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# Process simulation as a tool for TBM jobsite logistics planning

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ABSTRACT: Many TBM tunneling projects do not reach their planned performance and are struck by severe delays due to deficiencies in their jobsite logistics. The reasons lie within the planning methods which are used throughout the industry. They neither base their estimations on in field measurements nor do they consider the complex interaction of the logistic processes on site. The authors propose a planning approach which is based on a standardized assessment of the logistic equipment and processes and subsequently utilizes process simulation to deliver realistic performance estimates for TBM operations. The approach is demonstrated by analyzing an improvement proposal for a metro construction project with three EPB machines which experiences dramatic logistic problems.

## 1 INTRODUCTION

### 1.1 *The logistics of TBM jobsites*

On construction projects where tunneling machines are used, the supply of construction materials and removal of muck are greatly influencing the overall performance of the jobsite. Tunnel segments, rails, grease and grout must be supplied on time to the TBM whereas the excavated muck must be removed from the machine synchronously with the advance of the machine. If these logistic operations cannot be performed with sufficient speed, the net advance rate of the TBM sinks drastically due to waiting periods. On metro construction projects typically trains are used to transport material within the tunnel. Due to the small shaft footprints which are typically seen in urban projects, the length and therefore the capacity of the trains is usually restricted to only one third or even one fourth of a ring. Longer Trains must be uncoupled before they can be unloaded. Even with these short trains, the muck cars often have to be uncoupled and maneuvered onto parallel tracks to bring them within reach of the crane. One or several cranes lower and lift material between storage areas on the surface and the shaft bottom. While on most jobsites the excavated muck is transported in containers by train to the shaft where the containers are lifted up and emptied into the muck pit by crane, some jobsites use a belt conveyor within the tunnel and a vertical or inclined conveyor in the shaft. This lowers the workload for the cranes which then can focus on supplying the machine with construction material.

### 1.2 *Performance analysis and planning*

Planning of the layout and type of logistic equipment on TBM jobsites is largely experience driven. Typically construction managers choose layouts which gave them positive experiences previously. Some jobsites use Excel based calculation sheets for the workload and capacity of TBM's the supply chain. Gantt charts are often developed to show how the different consecutive processes interact over the length of one or several tunneling cycles. However much of the input data which is used to perform these calculations is estimated and not backed by actual data from in field measurements. Furthermore the complexity of the processes is not reflected in these calculation approaches and therefore many delaying effects are not captured.

### 1.3 *Logistic problems*

Many jobsites run into unexpected logistic problems. For metro projects, especially with EPB shields, which use purely rail bound transports within the tunnel, long waiting periods are regularly encountered. Due to the space constraints in the shaft and the small capacity of the muck trains, the cycle times for emptying the muck cars is often much longer than planned. Additionally the processes for lowering segments into the

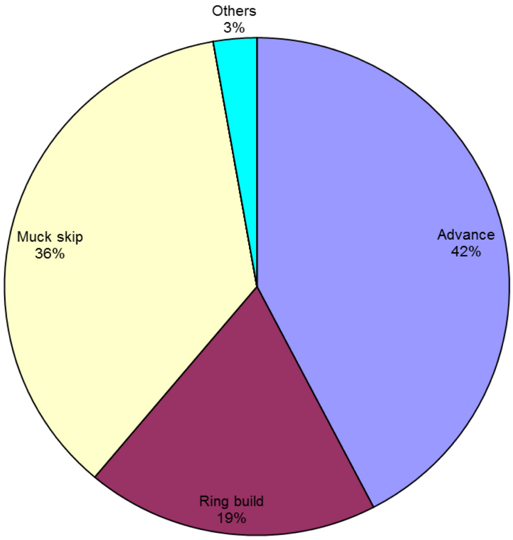


Figure 1. Typical weekly time distribution of a project with large logistic problems (One of three TBMs supplied through one shaft).

shaft and for removing the muck often interfere with each other which causes additional delays. This mutual influence means that just adding another crane would not be beneficial as the additional crane would further increase waiting times due to cranes blocking each other's movement paths. The severity of these problems varies from case to case.

Projects where these waiting times add up to a quarter or a third of the overall durations can be observed especially among metro projects where two or more earth pressure balance shields are supplied via the same shaft. Figure 1 shows an example from such a project. The 36% time share for "muck skip" means that over a third of the week was lost due to waiting for muck containers.

## 2 OBJECTIVE

### 2.1 *Development of data acquisition methods*

The planning aids which are used throughout the industry as well as most of the published simulation based approaches from the academic world are mostly relying on performance estimates for the throughput of individual logistic components. Therefore methods for structured in-field data acquisition must be developed which allow measuring the actual performances and realistic availabilities of logistics equipment. As most relevant data is not automatically measured and logged, this means identifying possible sources of information and developing monitoring methods which generate representative data. As often different parties have different interests when recording and reporting performances, only a sound and independent analysis of data from different sources can generate a holistic picture. In order to allow a practical use on jobsites, the tools and methods for data collection must be simple and efficient enough for use on site by the existing personnel.

### 2.2 *Understanding process structures*

Process structures are often poorly understood. The logistic chain within a tunnel seems to be very linear being built from consecutive rather than concurring processes. But this is not always the case and the process interactions between the different steps are hardly planned at all due to their complexity. Mutual influences of processes are highly dependent on the actual site layout and must be assessed and planned for each project individually. Furthermore many of the aspects which are relevant to possible process interactions are found on a detail level which is below the planning level of most projects and are therefore not detected during layout planning and procurement of the equipment. A clear understanding of the process structure is necessary to focus possible simulation studies onto the areas with the biggest leverage.

### 2.3 *Quantifying the effect of technical changes*

The existing planning tools for jobsite logistics have several drawbacks. First of all, complex process interactions cannot be considered realistically as static, linear tools are not capable to quantify the effect of the interactions on individual process performance. Furthermore, the influence of stochastic distributions of single process durations onto the whole chain cannot be estimated by them. Concurring processes and parallel paths through the logistic network are not represented in static performance calculations for logistics as well. Process simulation can fill the gap which is left by the traditional planning methods and can therefore support building a realistic forecast of a logistic systems performance. This allows quantifying the effects of changes in equipment and therefore if either additional investment in equipment is justified or if the existing equipment can be used in a more efficient way by improving communication and organization of the transport processes. Therefore a simulation model must be developed which allows performance analysis with interchangeable components.

## 3 LITERATURE REVIEW

### 3.1 *Performance estimation*

Performance estimation of TBMs is mainly experience driven. Comparative studies like (Osborne 2008) mostly focus on relating geologies and the main technical data of TBMs to the achieved performance. This approach can supply valuable information for risk managers and planners. Nonetheless, often the detailed reasons for delays are not covered in a way that makes their probability of occurrence deterministically transferrable to future projects.

There are several calculation models available for the performance of tunneling machines. The most prominent ones are the Colorado School of Mines Model (CSM-model) (Rostami 1997) and the NTNU Model developed at the University of Trondheim (Bruland 1998). Both focus on the actual drilling process and use lump sum factors for availability and machine utilization which are based on experience. These approaches can be used to perform a detailed analysis of the drilling processes but are not suitable to analyze and improve the logistic processes and their influence on overall productivity.

### 3.2 *Process simulation in TBM logistics*

In 1993 Weigl (Weigl 1993) presented an approach implemented in the simulation software Micro Cyclone (Halpin and Riggs 1992). He simulated several tunneling projects in Munich, Germany, with simulation parameters gathered from on-site data acquisition. The stochastic modeling of input data tremendously increased the usability of the results. The simulation model allowed the performance estimation of the logistic setup and the identification of beneficial modifications.

A simulation model focused on the logistics of a hard rock TBM was presented by Liu et al. 2010. The authors investigated the muck removal of a 20 km tunnel. The main interest was the number of muck cars per train, number of trains and switches applied. The approach is modelled on a rather abstract level in the simulation framework Cyclone. The model does not reflect the earlier mentioned interdependencies between several supply chain elements.

A third approach to analyze the logistics of a TBM project must be mentioned. Ebrahimy presented in 2011 the Simphony Supply Chain Simulator (SPSS), which extends the functionality of the original Special Purpose Simulation for Tunneling (introduced by AbouRizk et al. 1990). The SPSS focuses on the supply with prefabricated tunnel lining. Especially, the production, storage, and transportation of the segments are modeled in great detail. Thus, an essential part of the TBM supply chain is simulated to further enhance the results gathered with the original SPS for Tunneling.

## 4 CONCEPT

Three pillars form the foundation of the presented planning approach for TBM logistics. First methods for data acquisition must allow getting a realistic picture of the actual situation and the actual performances of the equipment. Second the actual interactions between the planned processes must be found and depicted in a clear way. Lastly a planning tool must be developed which is able to consider actual process performances as well as their interactions in a realistic way.

| Resource | Material | Start | End | Process | ID |
|---|---|---|---|---|---|
| Gantry Crane 1 | Muck car | Shaft bottom (front) | Muck pit 1 | Mucking | GC1_1 |
| | Muck car | Muck pit 1 | Muck pit 1 | Emptying muck car | GC1_2 |
| | Muck car (empty) | Muck pit 1 | Shaft bottom (front) | Mucking | GC1_3 |
| | Segments | Shaft Top | Shaft bottom (front) | Segment delivery | GC1_4 |
| | Auxiliary material | Shaft Top | Shaft bottom (front) | Aux mat delivery | GC1_5 |
| Gantry Crane 2 | Muck car | Shaft bottom (rear) | Muck pit 2 | Mucking | GC2_1 |
| | Muck car | Muck pit 2 | Muck pit 2 | Emptying muck car | GC2_2 |
| | Muck car (empty) | Muck pit 2 | Shaft bottom (rear) | Mucking | GC2_3 |

Figure 2. Process Overview Table for the Gantry Crane Processes.

### 4.1 *Data acquisition methods*

When analyzing standstill times of TBM's, usually the available shift reports show an incomplete picture as they focus on the TBM and do not explain detailed problems in the logistic chain. Their content can be analyzed in order to get statistical data about events within the TBM such as the reliability of different components or the working speed of the personnel. In order to retrieve a representative amount of data about logistic processes, a set of time lapse video cameras has been erected on jobsites in order to monitor a condensed observation period from several areas. This footage can be used to create detailed Gantt-charts and Process Lists for all relevant elements of the logistic system. On most jobsites, the availabilities which typically can be found differ significantly from theoretical values which are assumed during their planning stages, as many smaller activities are usually performed which are seldom considered during planning stage but sharply lower the availability for the main tasks. In order to support the analysis of ongoing projects, a set of simple forms was developed which guide jobsite personnel while documenting the logistic setup and the ongoing processes. The result of this documentation is a process table as shown in Figure 2.

Furthermore standard templates for process analysis and time studies which are based on time lapse videos have been developed. These allow the analysis of ongoing or planned projects and guide the personnel to provide the necessary data for further analysis. In case a future project is planned, the standard forms must be filled according to the planned setup.

### 4.2 *Analysis of process structure*

Poor understanding of process structures is one of the main reasons for the regularly found logistic problems. Two problematic areas are regularly observed: Firstly a lack of knowledge about which processes actually take place, secondly the patterns of their interaction. In order to structure observation results, information enriched layout plans which define the nodes of the logistic network as well as process interaction charts (Fig. 3) have been developed. They support structuring observation results of a running project or planning a hypothetical project. The information which is condensed in these charts is specific and precise enough to be used as data for a simulation study.

| ID | GC1_1 | GC1_2 | GC1_3 | GC1_4 | GC1_5 | GC2_1 | GC2_2 |
|---|---|---|---|---|---|---|---|
| GC1_1 | | | | | | | |
| GC1_2 | | | | | | | |
| GC1_3 | | | | | | | |
| GC1_4 | | | | | | | |
| GC1_5 | | | | | | | |
| GC2_1 | | | | | | | |
| GC2_2 | | | | | | | |

Figure 3. Process interaction table of gantry crane one and two with color coding for different patterns of interaction.

### 4.3 *Simulation based planning approach*

As opposed to static planning methods, a simulation-based approach can handle stochastic variation and reflect the real complexity of a logistic system. It enables the identification of alternative paths in the logistic system based on probabilities and boundary conditions. The authors developed a modular simulation model in the simulation software Anylogic which allows flexible exchange of components. Thus, the impact of technical changes within the system can be compared. This way, several setups can be compared easily yet transparently concerning their performance. Additionally, the presented simulation approach explicitly models disturbances during project execution. Thus, a specific setup can be evaluated concerning its capability to compensate the influence of such disruptions. The more robust a certain setup is the less is its sensitivity towards disruptions. This holistic analysis of a project reveals logistic bottlenecks and transparently supports the decision processes concerning setup changes or alternatives. A robust and powerful supply chain guarantees the performance of a TBM project and thus allows for effective budgeting.

## 5 CASE STUDY

To demonstrate the abilities of proposed planning approach, a construction project with relatively severe delays due to logistic problems is analyzed with the proposed set of methods. Based on a simulation study possible countermeasures are evaluated.

### 5.1 *The reference metro project*

The chosen reference project is a metro project with three EPB-TBMs starting from one shaft. Trains commute between the shaft floor and the TBMs and California switches within the tunnels allow trains to pass each other. Each train has one segment car which is also used for auxiliary materials, a locomotive and two muck cars during the early stage of construction. Later a second train with only muck cars is added to each tunnel in order to reduce the necessary commuting. Each muck car has a capacity of 6 $m^3$ whereas a whole ring produces a volume of 48 $m^3$. When in the

Figure 4. Muck containers on train cars are being emptied while moved aside on a sliding platform.

shaft bottom, two gantry cranes can reach the two muck cars and empty them into two muck pits. If segments are to be supplied, the muck cars must be uncoupled and moved aside with a sliding platform so the segment car can move within the reach of the cranes. The segments are lowered into the shaft either by one of the gantry cranes or by an additional mobile crane. As the three TBMs are assembled after each other, often tunneling and assembly operations are taking place simultaneously. This study is only examining the final steady state with all TBMs assembly finished. According to the shift report of the example projects, roughly one fourth of the whole project time is lost due to logistic problems. The reports state missing segments or mucking problems, but do not specify the detailed reasons.

### 5.2 *The logistic system*

The logistic system on the example jobsite is dealing with considerable difficulties. Muck removal and segment delivery cannot be performed on time. Especially the transport situation in the shaft is a major bottleneck. The three TBM's trains which must be supplied by three cranes have four access points where the cranes can reach the train cars. By systematically naming the nodes of the transport network, defined processes can be derived and their time consumption quantified. This information is firstly collected in timetables. After conducting a stochastic analysis of the process data, the processes can be characterized by their typical time distributions.

### 5.3 *Logistics process structure*

The complex structure of the logistic system has been the main difficulty in planning the performance of the crane and train interaction. The fact that several concurring and mutually influencing paths through the network prohibits a purely excel based approach and

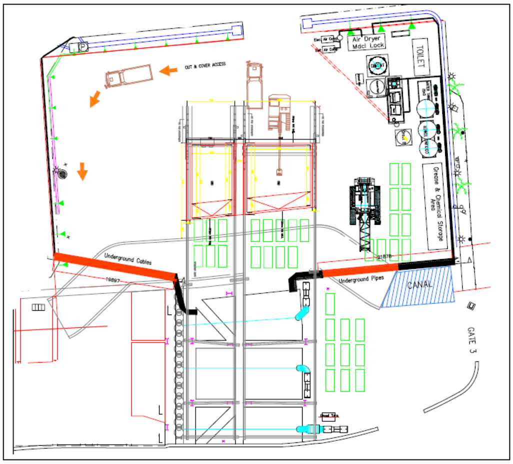


Figure 5. The shaft with three tunnels and the cranes at the surface.

requires a detailed description of the process interaction. An additional difficulty is the ongoing change of the system due to parallel assembly operations. This is not addressed in this study explicitly but will be subject of further research. The interactions are collected in a process interaction matrix such as Figure 3. As can be seen, several of the crane processes block each other. Furthermore due to the short shaft size, the train cars have difficulties, being reached by the cranes without lots of maneuvering, uncoupling and recoupling. These processes and their interactions have not been considered in the initial planning stage and therefore cause difficulties.

### 5.4 *Current situation based on actual data*

First, we modelled the current situation of the project. Therefore, we implemented a construction site that features rail bound and crane transport. The parallel operation of three TBMs is modeled by modifying equipment availabilities per TBM. Especially, the removal of muck is very time consuming and greatly slows down the progress. As discussed earlier, the muck excavated in one ring cannot be removed by the train in one go. The train must travel twice or thrice in order to remove the whole muck volume unless several trains are used. Considering the already confined space, interferences resulting from the three parallel operating TBM's decrease the performance even further.

In order to validate the model setup, actual data must be gathered and used as input data for the simulation model. Figure 6 compares the actual waiting time of the machine due to missing train recorded by the shift reports with the simulated waiting time. As can be seen the results match rather well. Therefore, we can conclude that the model is qualified to analyze the project and quantify the influence of specific logistic elements and the bottlenecks they establish.

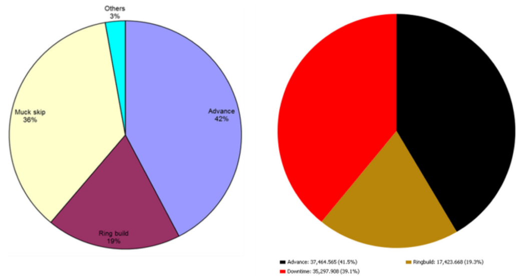


Figure 6. Actual waiting times of one TBM from the shift reports (left) and simulation results (right).

Figure 7. A tunnel belt removing muck from the TBM.

### 5.5 *Proposed modification of the supply chain*

As stated in the beginning, the biggest advantage of the presented approach lies in the possibility to replace elements of the jobsite setup and thus analyze possible alternatives concerning their performance. A major logistical bottleneck of the existing structure results from the confined space to remove the excavated muck. Furthermore, the machine must wait frequently to continue the excavation until a muck car is available. In the case study we chose a change in setup which provides great leverage to reduce waiting times of the machine and thus to increase the performance.

Therefore, we decided to alternate the muck car-based method of muck removal. A recently increasingly popular method is the application of conveyor belts installed in the tunnel to transport the muck from the excavation chamber right into the muck pit at the surface jobsite. Following that, the trains now only deliver material to the TBM. The whole process of material hauling is uncoupled from the trains. Thus, the excavation can now be continuous.

Figure 8 shows the newly calculated waiting time of the TBM. The waiting time could be reduced from over a third to below 10% if the conveyor-based muck removal is applied. Given the high daily cost of a jobsite with three TBM's, the time savings imply significant financial savings.

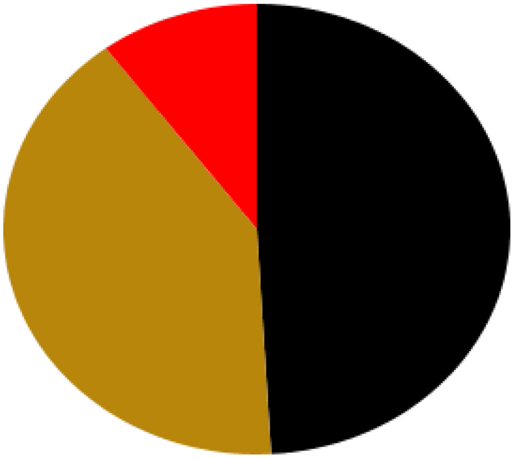


Figure 8. Simulated machine productivity of one TBM after installation of the tunnel belt.

## 6 CONCLUSION

When properly embedded into tunneling logistics planning methods, process simulation can be a powerful tool to evaluate the expected performance of a TBM. However there is a broad range of available performance data necessary to develop realistic predictions. The research presented in this paper demonstrated the ability of a structured planning approach to reveal weaknesses of a system and allow the evaluation of performance improving countermeasures. Further research is necessary to improve the adaptability on different projects and widen the available data basis of process durations to a statistically relevant extent. A major field to cover are the changes which the logistic system of a jobsite typically undergoes during the project. As they greatly influence the way the logistics work, they are another future field of research which follows this study.

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