A Review of Planning Methods for Logistics in TBM Tunneling

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1. Introduction

One of the often overlooked but crucial factors for quick TBM project completion are correctly dimensioned and managed logistic systems. As Mechanized tunnelling is applied in more and more projects worldwide, professional and standardized planning methods as well as reliable performance prediction methods become increasingly important as well. The outstanding records regarding safety, performance and tunnel quality in the light of the ever faster urbanization in developing countries have made the number of Tunnel Boring Machine (TBM) tunnelling projects skyrocket over the past decades. A large number of cities are planning and building new metro systems. This also leads to a fast growth in the number of contractors in the tunnelling market. Most of the planning expertise in the industry is present on form of personal knowledge of experienced managers. There are only very few methods and planning procedures which build on theoretical foundations. There are many jobsites which experience performance losses due to the layout and choice of their logistic systems. This can often be traced back to the planning methods which are used. When observing the academic efforts made on mechanized tunnelling it becomes obvious that research regarding face stability, excavation control and design of segment lining is dominating the discourse. Very sophisticated process control systems exist in the market as well [1]. They allow constantly monitoring the excavation parameters and comparing them with a target to allow tight control of all aspects and high safety standards. Such systems are not yet available for the logistic processes in the construction sector although a wide range of difficulties can be observed regarding jobsite logistics. They can range from smaller errors which cost a few minutes to large problems where each shift loses several hours of working time due to delayed material delivery. This is usually most difficult when special constraints are tight such as in inner cities, where often several TBMs are launched and supplied from one jobsite. The reasons for logistic problems can often be found structurally, meaning that the structure of the logistic system does not allow higher performances due to process interference. So even if the individual processes could be sped up, the overall performance would not increase significantly. In other examples, the structure is correct, but the performance of one or several individual components of the logistic network is not sufficient to reach performance targets for the overall system. The visible differences between highly efficient and delay plagued jobsites can be very subtle and small nuances in organization or structure can have a big impact on performance. TBMs must be permanently supplied with segments, grout, grease, rails, tools, spare parts and personnel in order to work. The excavated material must be removed and brought to the surface. All this material must be delivered to site, stored and brought to the correct place on time in order for the TBM to advance steadily. Cranes, trucks, trains, conveyors, moving platforms, pumps and many other systems are used for these transport operations [3]. Which exactly can be used is subject to technical and economical boundary conditions. The economic conditions often lead to sub-optimal solutions being used which may lead to significant performance losses. This sometimes is more expensive than using better systems as the productivity losses ultimately mean waiting time and longer project durations. That means that usually increased effort for planning pays off easily by allowing better performances. Today the industry is using a wide number of different tools and
methods for logistic planning which mostly are timetables, manual transport volume estimations and several times of cycle diagrams. They allow planning with various degrees of detail and can, if applied correctly, estimate the performance of a logistic system. One of the key factors to their use is always reliable reference data which must be available. Gathering this reference data is often neglected as it is time consuming and only pays off over the course of several projects. Once a large body of data is available, it must be structured and stored in a suitable way to be used for future planning. This paper summarizes the methods which can be used for data collection and the necessary steps for structuring. Furthermore, an overview of the different types of planning methods as well as indications for their correct use is given. A small outlook on future application of process simulation tools for logistics planning is given as well.

2. Challenges in Jobsite Logistics

There are many different types of logistic problems on TBM jobsites. In order to make them more tangible, this chapter introduces three examples of such difficulties which can all be regularly observed in the industry. The first two examples are taken from the supply chain of the TBM whereas the third one in an internal problem in the TBM. The first two examples can be mostly found in smaller tunnels where transport in tunnel and shaft is often restricted in terms of space. The third one is typical for large diameter machines where the complexity of the logistic system is a main challenge.

2.1 Example 1: A Bottleneck in the Shaft

Metro projects often feature two; sometimes even three TBMs launched parallel from the same shaft. Metro systems are usually constructed in areas which are already built up so special constraints are usually leading to jobsites with a small footprint. This leads to small shafts with little space for manoeuvring inside, small storage areas and possible traffic congestions. Often gantry cranes are used to lift muck skips out of the shaft and an additional mobile crane supplies segments and other small goods. Such a situation is shown in figure 1. The gantry crane and the crawler crane can block each other's access to the shaft. Although thought to bring twice the performance of a single crane, they cannot access the shaft at the same time and therefore difficulties arise. When trains are used for tunnel transport, they usually consist of one or two flat cars, a locomotive and a number of muck cars. In small shafts, the trains are often longer than the shaft and must be broken up in order to make all cars accessible to the cranes. This requires a switch and often also a shunting platform in the shaft. The coordination of these processes often leads to delays as breaking up the trains takes longer than planned. Often there is also no standard procedure for this which can be followed by the workers. Possible countermeasures can be separating the access path of the different cranes to the shaft or adding a second parallel track in the shaft floor.

2.2 Example 2: Delays caused by Tunnel Logistics

Either trains or trucks are used for the tunnel transport. They deliver segments, muck and all other materials which are necessary to operate the TBM. When no tunnel belt or slurry circuit is used to extract the muck, the muck cars must wait at the TBM below the machine belt to be loaded which defines the standing time of the trains at the TBM side. Either each train can load the muck of a full ring or it is distributed on several trains. Figure 2 shows such a train. When one train leaves, the next one should immediately arrive. Otherwise delays arise. As there is little space for the
trains or trucks to pass each other in the tunnel, it is necessary to arrange positions where they can pass each other. For trains this are so called california switches and for trucks an elevated road section is constructed which is wide enough to fit two trucks. The amount and positions of these passing location must be properly planned to ensure a constant supply of the TBM with material.

An example for how different logistic systems in the tunnel can affect the productivity is the comparison between the Bözberg tunnel and the Murgenthal tunnel. They have been built with the very same TBM but using different logistic systems. Furthermore the width of the segments was different. The Murgenthal Tunnel was using 1.5m wide segments whereas the Bözberg Tunnel was using only 1.25m wide segments. Murgenthal used a tunnel belt for mucking and the Bözberg tunnel was built using trucks to transport the muck. Figure 3 shows the advance rates which were reached in comparison. While on Bözberg only 54m per week could be achieved, it was possible to increase the performance to more than 100m per week consistently. “Conveyor transport, with its continuous operation, has led to remarkable performance increase compared with a comparable use of dumpers with their intermittent transport.” [4]

**Fig. 2** A tunnel train with two flat cars, a locomotive and six muck cars

**Fig. 3** Comparison of advance rates in Murgenthal (left) and Bözberg (right) tunnels

### 2.3 Example 3: Internal Logistics of the TBM

Besides the deliveries on site and in the tunnel it is also crucial to manage the internal logistics in the backup system of the TBM. As the backup systems especially of modern large diameter TBMs are highly integrated systems, most of their performance is influenced by the initial design and little can be changed after launching the machine. These complex logistic systems can be a limitation to the machines performance. Especially if the segment transfer is built using many consecutive steps such as several cranes, shuttles, lifting and shunting tables, turntables and the segment feeder. Then it can quickly turn into a bottleneck. At the German Katzenberg tunnel EPB TBM mucking was done by belt conveyor and segments were delivered by truck; a setup which allows a high productivity from the tunnel logistics perspective. Trucks were delivering the segments from the surface to the TBM. A crane was unloading them and transported them across the bridge under which the road was constructed. The distance to be covered by this crane was...
about 140m. The crane placed the segments onto a shunting table which moved them sideways to a position where a second crane could reach them. This crane subsequently moved the segments onto the segment feeder. This segment transfer process was effectively limiting the TBMs performance. While the advance duration of the TBM was slower than the transfer on some rings, on others the advance could be finished before the segments were completely delivered. A situation like this should be avoided and considered during the design stage of the backup system. Once the TBM is designed it is extremely difficult to change things like this. Possible design changes could be increasing the first segment cranes capacity to two segments which reduces the number of necessary transport cycles. This is done on many modern large diameter TBMs.

2.4 Planning Aspects for TBM Logistics

This chapter introduced a number of typical problems which can be observed on many TBM jobsites. How can the different aspects of jobsite planning be summarized? Literature offers a number of checklists for planners [6, 2, 1, 7]. Following list extracts the most prominent aspects which have to be addressed during planning stage:

- All necessary goods and their required quantities, batch sizes, handling aids, lead times, weights and dimensions.
- The layout of the jobsite with storage areas, driveways, crane coverage, shafts, assembly and work areas as well as the changes which will be necessary throughout the different project stages.
- The structure of logistic processes including mutual dependencies of transports, time and space constraints and the handling and transport steps.
- All the equipment which is necessary to perform the logistic tasks.
- The timing of the transports including performance estimations for individual processes and the whole system.
- Communication structures within the jobsites, including supervisors, light signals, control rooms, signalmen, phone and radio connections but also the responsibilities of key personnel.
- The interfaces between different planning areas, internal and external logistics as well as different equipment parts.
- Sensitivity analysis for the main influences on performance.
- Specific work instructions which allow putting the plans into practice and allow the involved personnel follow a guideline.

3. Planning Methods for TBM Logistics

The tunnelling industry is using a number of common tools to plan and check the logistic systems which are allowing the jobsite to operate. Mostly they have been developed and shared by tunnel managers, TBM designers and consultants inside the industry. Very little academic work has been dealing with TBM jobsite logistics. But these works hardly offer any practical advice but rather discuss different planning principle on a level of detail which is often too low to directly transfer them into practice. Many of the planning aids which the industry is currently using allow proper planning if used correctly but also may cause difficulties when not used correctly. Examples for
both are abundant. Also the use of unsuitable methods can be observed. One challenge that is regularly faced is the lack of reliable planning data. References of process durations are often not clearly documented and it therefore becomes difficult to judge if reference data from past projects is applicable to a new project or not. The following sections will introduce basic methods of reference data collection as well as the most important planning methods which are applied. The planning procedure follows always the same steps which can be iterated until a desirable result is achieved.

1. Estimating the expected gross machine performance of the TBM.
2. Determining the necessary transport volumes and batch sizes as well as storage volumes.
3. Preliminary jobsite layout planning.
4. Analysis of the TBM’s internal working cycle
5. Calculation of the transport cycle times of trains, trucks, cranes and all other major logistic components.

The main idea behind this procedure has been developed by Bruland [7] is compartmentalizing the different sections of the jobsite into individual sections while assuming no mutual influences between them but only directed dependencies. Therefore it is possible to start at the TBM with estimating the required delivery capacities and work cycle by cycle through the jobsite until covering the whole system. This principle is shown in Figure 5. For each section of the transport an individual cycle can be calculated and designed. Although there are many effects which cannot be considered by such a planning approach, it delivers good results when followed thoroughly.

![Fig. 5 The consecutive transport cycles developed by Bruland](image)

### 3.1 Data Acquisition

Unknown processes cannot be planned. Therefore the availability of applicable reference data is one or the cornerstones for successful planning. This includes the right type of data and the right format and structure. The main data which should be available is:

- Performance parameters of the planned machinery
- Process durations and atomized durations of their sub processes
- Failure rates and reliability of machinery
- Parametrization of data elements
- Stochastic properties of the datasets

All performance values are a result of the specific jobsite conditions where they are measured. This restricts the transferability between projects to some extent. In order to make performance data transferable, it is necessary to determine the factors influencing performance and consider them. They must be quantifiable. That means that the duration of a process like emptying a bucket of muck must be atomized into individual steps like lifting, horizontal movement and positioning. The factors which define the individual steps duration like distances, accessibility, and
experience of the worker must be estimated or measured and stored together with the durations. This allows the future adaption to differing conditions.

There are a number of different methods to acquire data on and off site. They are well established in the construction sector and often used to collect information for estimating purposes. The main sources are:

**Historical Records:** If the system and structure is comparable to past projects, it is in many cases possible to use data and parameters which have been obtained on reference projects. Because the records already exist, this method does not require real time data collection. This may appear a very attractive option for the practitioner but bears the risk that the historical system is not comparable for any reason and the data differs from the system which is planned.

**Manufacturer Specifications:** One of the main sources for performance data are the specifications of the equipment on site. However the specifications show theoretical performance under laboratory conditions but not the actual performance which can be obtained on site. Whether the theoretical performances can be achieved on site is often questionable.

**Vendor Claims:** The vendor or distributor claims will probably fall between the manufacturer’s specifications and reality. The vendor or distributor should already have some experience with the type of system that is being considered.

**Operator Estimates:** Operators of existing equipment can be a valuable data resource when the practitioner does not have the time or data collection resources to collect actual data. If the operator is knowledgeable about the system, it may be possible to obtain some performance estimates that can be used as input data. For example, the operator could be questioned on the shortest, most common, and longest processing times for a particular operation. Operators also offer valuable information on why certain processes can be sped up or slowed.

**Management Estimates:** The practitioner may also consider soliciting managers or engineers associated with the system. Though these individuals probably do not have the same proximity relationship to the process, their input may be helpful when an experienced operator is not available for input.

**Automatic Data Acquisition:** It may be possible to set up some sort of automatic data capture system. This is analogous to the traffic volume monitors that are frequently encountered on the road. These monitors count the frequency of cars passing by a specific point over a given time period. TBMs are generally equipped with data management systems which monitor a large number of processes and can contribute a lot of information. However they usually cover only a small part of the whole logistic system.

**Jobsite Observation:** The most physically and mentally demanding form of data collection is direct observation. This is where the practitioner or another individual actually goes to the location of the system and visually collects data. The data are collected by pen and pad or perhaps with some technological assistance. If the low-tech pen-and-pad approach is used, the practitioner may want to develop some sort of data collection form to keep the process as organized as possible.

**Video Recordings:** Positioning cameras at different places on site and analysing the footage is a very good method to collect actual data. Time lapse cameras may save time when looking through the footage. The analysis is time consuming though. There is video analysis software which can automatically detect different processes but this is a very complicated approach. If access to cheap labour is possible, manually writing tables with process durations from the footage is the easiest option.

**Microphone Recordings:** Many processes differ in terms of their sound. Microphone recordings can be a source of data which can be automatically analysed easier than video recordings. For several processes they allow precise measurement and automatic analysis over longer periods.

**Mobile Data Acquisition Systems:** These mobile systems are often seen in factory floors and storage yards. They allow also collecting data on site and installing a complex data acquisition
system is costly but the best option to gather large scale data on process durations. This will probably help and pay off when the processes can be analysed and sped up.

Which data acquisition methods are chosen depends on the available manpower and targets for data quality and precision. Often a combination is necessary to gather different aspects of the processes. Automatic systems for example are the best when large amounts of detailed data is necessary but cannot gather the metadata like working conditions and other factors which are important to know. The storage of the obtained data should be systematic and structured to allow later usage and make it interpretable for persons which have not been involved in the origin project.

### 3.2 Planning Tools

Many problems which can be observed on jobsites originate from a lack of planning or wrong planning. Wrong planning methods or the use of incorrect reference data may support business decisions which are not optimal. In many cases especially the influence of human factors is not considered and the resulting delays from improper coordination and communication are forgotten. Nonetheless there are a number of planning aids which are often used with varying levels of detail and success which have developed into industry standards. Often they are Excel based tools which have been developed by jobsite managers and are shared between colleagues. Most of them are based on academically developed planning methods like the critical path method or Gantt charts [6]. This chapter introduces the most commonly found methods and explains their principles.

**TBM Drilling Performance Estimations:** Based on theoretical models such as the CSM model, the NTH model or reference projects with similar conditions planners can estimate realistic performances which can be achieved [5]. Usually experiences and reference projects outweigh the influence of theoretical calculation methods. The TBM performance prediction has been subject to a large number of studies in the past decades “Performance prediction includes generally prediction of instantaneous penetration (cutting) rate, cutterhead torque requirement, machine thrust requirement, cutting tool consumption rate, machine utilization time, and daily advance rate.” Most studies focus primarily on the penetration rate and develop models which allow correlating ground parameters to the achievable advance rates by multiplying the calculated penetration rate with a machine utilization rate. Among those studies, approaches covering hardrock tunnelling outnumber by far those analysing softground tunnelling. In softground projects it is common to work with project references and estimate the performance based on past experiences. Today the most common prediction tool in hard rock is the Colorado School of Mines model. The performance estimates which are derived from either a calculation or an estimate are forming the base for further planning of logistics and transport requirements. It is wise to develop different scenarios and plan for different cases such as high performance and average performance.

**Transport Volume Tables:** Contractors plan the necessary number of transports to supply and discard material. The tables break down the key material including batch sizes and storage capacities. The result of this analysis is the number of different transports to be made. Possible interferences of the different logistic operations or changes in the TBM's advance speed are not considered. Also varying batch sizes cannot be reflected in an Excel based table. Nonetheless it is a simple yet very useful method. Ideally the necessary transport volumes should be prepared assuming different tunnelling speeds. If the assessment is done for maximum performance as well as for an average performance assumption, it is possible to design processes subsequently for a balanced assumption. The batch sizes for tunnel transport, handling on site and delivery to the jobsite are usually different from each other. Therefore the transport volumes and the related number of transport cycles should be calculated for different parts of the jobsite separately. One table can reflect transports from the shaft to the TBM as it is often done by trains and trucks. Another table can be prepared for the cranes on site and a third set for the deliveries to the jobsite and the removal of muck to a dump site. An example for a volume estimation is shown in figure 6. Material consumption, batch sizes and the arrival intervals of the material on different vehicles is clearly calculated by this table. This will form the base for further analysis on how to actually deliver the calculated materials and batch sizes by the means of vehicles or continuous conveyors.
The supply chain of the TBM has to be matched with the requirements of the machine. Therefore the working cycle of the TBM must be known because it defines the batch sizes and arrival interval for all elements of the supply chain. The planning tool which is used to do this are TBM cycle charts. They are basically Gantt charts which show different operations on a time scale. As TBM operation follows a cyclical pattern with not all processes occurring during every cycle, they usual show several cycles which together give a representative picture of the operation. After collecting data and visualizing all relevant individual processes, possible conflicts as well as possible waiting times which should be eliminated. Figure 7 shows an example.

![Fig. 6 Transport volume tables for assessment of material quantities](image)

![Fig. 7 TBM cycle chart of an EPB machine](image)

Of course cycle charts are limited as well in their application by the lack flexibility they offer. This is partly a question of using the right software. While most process scheduling tools such as MS Project offer great advantages in terms of their logical connection between the individual processes, they mostly do not support cyclic operations. Therefore in many cases Excel is used as a means to create and update cycle diagrams. This requires a lot of manual work and therefore creates a tendency to overly simplify systems or leads planners to neglect regular updating the charts according to changes in planning. A balance could be reached by creating Excel templates...
or using process simulation or customized scheduling software. Of course this also simplifies handling of stochastic data which is often more realistic than fixed durations planning.

**Vehicle and Crane Cycle Diagrams:** Both types of cycle Diagrams show time on the y-axis and the vehicle’s location on the x-axis. Loading and unloading are vertical lines while driving is an upwards or downwards inclined line depending on the direction. Due to this layout only one dimensional movement can be depicted. Vehicle and crane cycle diagrams allow determining if the chosen number of cranes and vehicles is sufficient to sustain a smooth operation. In case of vehicles they also allow determining the required number of passing points within the tunnel.

![Train Cycle Diagram](image)

*Fig. 8 Cycle Diagram with four trains and a tunnel distance of 3000m*

Such a cycle diagram with the example of trains is shown in figure 8. The shown example is based on the assumption that trains can pass each other at the shaft and at the TBM. Where the inclined lines are crossing, passing points need to be added. Therefore in this example one california switch should be installed at about 600m and another one at about 2200m tunnel length. There are limitations though for these diagrams. Once varying speeds, stochastically distributed process durations and different types of vehicles are to be considered, it becomes impossible to derive a clear diagram with defined passing points. Nonetheless vehicle cycle diagrams provide a good guideline for dimensioning.

### 4. Conclusions

The standard planning methods which are currently used by the tunnelling industry allow proper dimensioning and planning of logistic equipment. However there are many cases where delays and logistic problems lead to rising cost of tunnelling. There are several reasons which can be identified regularly:

- Planning is not based on actual process durations but on false and often overly optimistic estimates for process durations. In order to reduce the impact of these effects, it is very important to gather reference data in ongoing projects to build a database of references which can later be used for future planning.
- The effect of process interactions are neglected by planners. Delays caused by conflicted
processes are difficult to identify in early planning stages and often there are no iterations which allow checking the feasibility of previous assumptions. An important task to avoid negative process conflicts is iterating the preparation of cycle diagrams and cycle charts to regularly check if the planned or ongoing processes which should be executed simultaneously have any resource or special conflicts. That means that it must also be checked if all requirements for starting a certain process are fulfilled at the scheduled starting time. Furthermore the charts from the planning phase should always be compared to charts showing the actual situation which is observable after project start.

- Often seemingly small processes are ignored, although they have a considerable influence. A systematic approach to avoiding this error can be process studies on ongoing jobsites which help identifying the relevant processes. They can subsequently be included into the planning process of future projects.
- Disregarding changes in jobsite conditions or project progress often leads to the logistic systems not being adapted to changing conditions. This leads to the requirement of managing changes and constantly adapting and improving logistic processes according to changing needs.

Some of these issues are rooted in the nature of the prevailing planning methods, others in the high pressure and workload for construction managers and others can be traced back to the general level of development and culture in the construction sector or certain regions. There is a tendency that high labour cost has led to the development and implementation of more sophisticated planning methods in many industries. Also increasingly free and transparent markets as well as 21st century legal frameworks are a strong driver behind the modernization of planning and management techniques. The construction sector is currently undergoing a transformation with many new ideas being absorbed and implemented. Therefore a development to more sophisticated planning and controlling methods for jobsite logistics can be observed. The introduction of building information models, complex data acquisition systems, process simulation and real time monitoring of operational parameters are developments which currently indicate this change. They will help leading the industry to mastering the new challenges of the 21st century.
References

[8]