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DOCTORAL THESIS

Deterministic and Simulation Based Planning Approaches for Advance and Logistic Processes in Mechanized Tunneling

submitted in fulfilment of the requirements for the degree of Doctor of Engineering (Dr.-Ing.) to the Department of Civil and Environmental Engineering of the Ruhr- Universität Bochum

BY

Dipl. -Ing. Ruben Duhme

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Interaction Modeling
Mechanized Tunneling

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List of Abbreviations

ABM	Agent Based Modeling
bdd	Block Definition Diagram
C	Empirical Coefficient for the CSM model
CAD	Computer Aided Design
CLI	Cutter Life Index
CPM	Critical Path Method
CSM	Colorado School of Mines
DES	Discrete Event Simulation
EMI	Earth Mechanics Institute (at Colorado School of Mines)
EPB	Earth Pressure Balance Tunneling Machine
DRI	Drilling Rate Index
F_{CH}	Cutterhead Contact Force
F_n	Normal Force
F_r	Rolling Force
F_t	Total or resultant force
ibd	Internal Block Diagram
IF	Influential Factors (advance rate)
k_1	Loading Factor (crane)
k_2	Performance Influence Factor (crane)
k_3	Operational Influence Factor (crane)
L_{seg}	Segment Length
M_{CH}	Cutterhead Torque
MSV	Multi Service Vehicle
N_d	Number of TBM Cycles per Day
n	Cutterhead Revolution Speed
NTNU	Norwegian University of Technology Trondheim
P	Power
p	Penetration of the Cutterhead
P_d	Daily TBM Performance
P^o	Pressure of the crushed zone
PERT	Performance Evaluation and Review Technique
Q_n	Actual Lifting Performance (crane)
Q_T	Theoretical Lifting Performance (crane)
R_{disc}	Radius of cutter
RPM	Rotations per Minute
s	Cutter spacing
SADT	Structured Analysis and Design Technique
sd	Sequence Diagram
stm	State Machine Diagram
SysML	Systems Modelling Language
tadv	Net Advancing Time
TBM	Tunnel Boring Machine
t_{cyl}	Total Duration of a TBM Cycle
T_d	Daily Working Hours
t_{disc}	Disc tip width
t_{ring}	Lining Construction Time
t_{stop}	Downtime
UML	Unified Modeling Language
v_{adv}	Net Advance Rate
μ_G	Utilization Rate (crane)
Φ	Angle of contact between disc and rock
Ψ	Constant for pressure distribution function
σ_c	Uniaxial compressive strength of rock
σ_t =	Tensile strength of rock

Abstract

Many tunnel construction sites deal with major time losses and low productivities. Often the actual productivities fall far behind the planned levels with insufficient or improper jobsite logistic systems being the reason. In such cases, there are many projects where it is unclear to the responsible staff, which countermeasures would actually improve the situation. Therefore, using better planning tools would allow improving the productivity in these cases.

The main reason for these deficiencies being so widely spread throughout the industry is the lack of structured planning methods as well as a lack of awareness for such methods in other industries that could be transferred to construction. Therefore, methods that could potentially be beneficial are often not applied. Furthermore, there is little reference data available to planners, which would be necessary to estimate the actual impact of changes in the logistic system.

In order to offer an approach to overcome these deficiencies, the logistical setup of several tunnel construction sites has been analyzed. The analysis has been used to derive an extensive set of reference data that forms a foundation for future planning. Subsequently, the most common planning methods, which are currently used by the industry, have been examined for their potential and limitations and a systematic approach for analytic planning of tunnel logistics has been derived. Furthermore, the use of process simulation for planning tunnel construction logistics is examined in detail and compared to analytic planning methods.

Using simulation based planning tools, construction managers can improve the productivity of their jobsites and decisions regarding additional investments in logistic equipment can be made transparently. The structured analysis of jobsite logistics can also help developing effective countermeasures in case a projects performance is below expectations due to logistic problems.

1 Introduction

Well managed logistics are a key element for fast completion of mechanized tunneling projects. With the mechanized tunneling industry maturing in general, modern planning and performance prediction tools become increasingly important. An unprecedented number of cities are planning and building new tunnel projects (Gu, Salland-Staib, & Zheng, 2014) which has led to a large increase in the number of contractors which are active in tunneling. Most of the planning expertise in the industry is present in form of personal knowledge of experienced staff. Due to the vast growth of the industry, many jobsites lack experienced staff for these planning tasks and subsequently encounter difficulties. There are few codified planning methods specifically for mechanized tunneling logistics that could help remedy this situation. The academic world and the vast majority of tunneling consultants focus their work on geotechnical aspects, excavation processes and ground support. Sophisticated process control and data logging systems exist in the market (Maidl & Staschelt, 2014). They allow monitoring all parameters and comparing them with their targets. To monitor a tunnel´s logistic network, such systems do not exist, yet.

A tunnel boring machine (TBM) must be permanently supplied with lining material, grout, grease, rails, tools, spare parts and personnel. The excavated muck has to be transported to the surface and disposed. Most deliveries must be performed just in time or just in sequence. Cranes, trucks, trains, conveyors, moving platforms, pumps and other systems are used for these transport operations (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011). There are physical and economical restrictions, which narrow the practical choice of possible technical solutions. In many cases, significant productivity losses due to logistic problems can be observed. Considering the daily operation cost, these losses come at a hefty price tag. Therefore, planning efforts which aim at reducing delays and waiting times pay off quickly. This is a strong inventive for the use of simulation as a planning tool.

Currently, almost all planning regarding the site layout and the logistics equipment is done using a combination of computer aided design (CAD) drawings and self-made spreadsheet tables. They focus on the location of switches, the cycle times of cranes and trains as well as the internal transport processes within the backup system. These planning tools vary greatly in quality and practicality. Many cases have been observed, where they were used incorrectly. The industry’s standard planning tools often reach their limits with increasing complexity of process interactions as it occurs in most real life logistic networks. In addition, statistical effects such as they occur when different processes depend on each other and interact are not reflected by these calculations (Halpin & Woodhead, 1998) (Weigl, 1993). Nonetheless, they have their well-deserved place in practical planning.

For planning aspects where these traditional methods are insufficient, process simulation offers an alternative which is increasingly used in many industries including construction (AbouRizk S. , 2010). Process simulation has been used in tunneling since the development of the Cyclic Operations Network (CYCLONE) by Daniel Halpin in the 1970s (Halpin, 1977) Most applications however, have been designed for management purposes and are not able to support eliminating deficiencies on the operational level. In order to utilize process simulation on this level of detail, studies about process interactions on several jobsites have been conducted to determine the actual process structures as well as their variability. A standardized approach to collection of information has been developed to procure this information.

Modern planning methods like process simulation easily create the false illusion of accuracy if not employed carefully. They must be based on systematically structured reference data. Here lies the danger of overestimating their results without exactly knowing the quality and suitability of input parameters and modeling. Creating transparency for the selection of input parameters and the modeling process is therefore important to allow judging the quality of a planning process.

The study presented in this thesis develops a set of planning aids for the TBM industry and aims at giving a practical guideline for the usage of the planning techniques for logistics in TBM tunneling with special attention to introducing process simulation into the planning processes where necessary. A fictional example project that closely resembles typical urban metro projects is used to illustrate the various methods and tools. This shall help planners in their desire to achieve higher production rates in mechanized tunneling as well as allowing the industry to predict the actual tunneling performance more realistically.

2 Problem Definition and Methodology

Delays on tunnel jobsites are often caused by a lack of suitable planning instruments. This chapter introduces three typical examples of reasons for delays that can be observed on many projects. The first two examples are linked to the transport networks on the surface and within the tunnels. The third one deals with delays caused in the TBM backup system itself. While the first two problem types can be found more often in metro and train tunnels, the last one is more typical for large diameter machines. These examples illustrate the bandwidth of planning problems. After introducing them, the solutions offered by this thesis are discussed and the methodology of their development is outlined.

2.1 Logistic Problems on TBM Jobsites

Logistic problems on TBM jobsites range from barely noticeable time losses due to slightly delayed or slowed processes to frequent waiting periods of hours or days which are caused by major planning errors. Often the reasons are structural, meaning that the structure of the logistic system does not allow higher performances even if the individual processes could be operated at increased speed. In other examples, the structure is suitable, but the individual performance of one or several components of the logistic network is not sufficient for the overall system to reach its performance targets. The visible differences between highly efficient and disastrously inefficient jobsites can be very subtle and small nuances in organization or structure can have a big impact on performance. Following examples give an impression of the nature of the problems that are typically encountered.

2.1.1 Problem Example 1: A Bottleneck in the Shaft

Metro projects often feature two, sometimes even three parallel tunnels starting from the same shaft. As metro networks are predominantly built in urban areas, floor space is often very scarce. That means that the shafts are small, cranes and storage areas close to each other and there is little room for maneuvering at the shaft bottom. Often there is a gantry crane that lifts the muck buckets from the shaft bottom to the muck pit and a crawler crane to lower segments onto the train at the bottom of the shaft. Such a scenario is shown in Figure 2-1. The gantry crane and the crawler crane cannot access the shaft at the same time because they block each other’s movement paths. The train usually consists of one or two segment cars, a locomotive and several muck cars. That makes it much longer than the shaft floor. To access the train cars for loading and unloading by crane, it is necessary to break up the train and shunt the wagons. This process requires at least a switch in the rails, often also a shunting platform. Overall, the coordination and execution of these processes is difficult and often not achieved in the required cycle time. This causes delays in the TBM operation.

Figure 2-1: The gantry crane and the crawler crane can block each other's access to the shaft.

2.1.2 Problem Example 2: Advance Slowed by the Tunnel Logistics

Tunnel jobsites utilize either trains or trucks as means of transport in the tunnel. Additionally, belt conveyors or pipelines may be used to transport the muck continuously. If not, muck cars must be waiting under the machine belt discharge in order for the TBM to advance. At the point in time when one car leaves, the next one should already be there. Otherwise, the advance would be interrupted. There is little space for trains and trucks to pass each other in the tunnel. When the tunnels become longer, switches or widened road sections must be installed to allow vehicles passing each other. A good example for the impact of the tunnel logistic system on the project duration is the comparison be-tween the 3,500m long Bözberg tunnel and the 4,250m Murgenthal tunnel. Both have been built using the same TBM. The projects differed in terms of segment width which was 1.5 m length of ring in the Murgenthal tunnel compared to 1.25 m for the Bözberg tunnel. While mucking was done by trucks at the Bözberg tunnel, a conveyor system has been installed for the construction of Murgenthal tunnel. The advance rates for both are shown in Figure 2-2. While the Bözberg tunnel reached only an average of 54m per week, it was possible to mine 85m in average per week in Murgenthal. Maidl attributes this remarkable performance increase to the use of continuous conveyor transport instead if intermittent transport by dumpers (Maidl, Schmid, Ritz, & Herrenknecht, 2008).

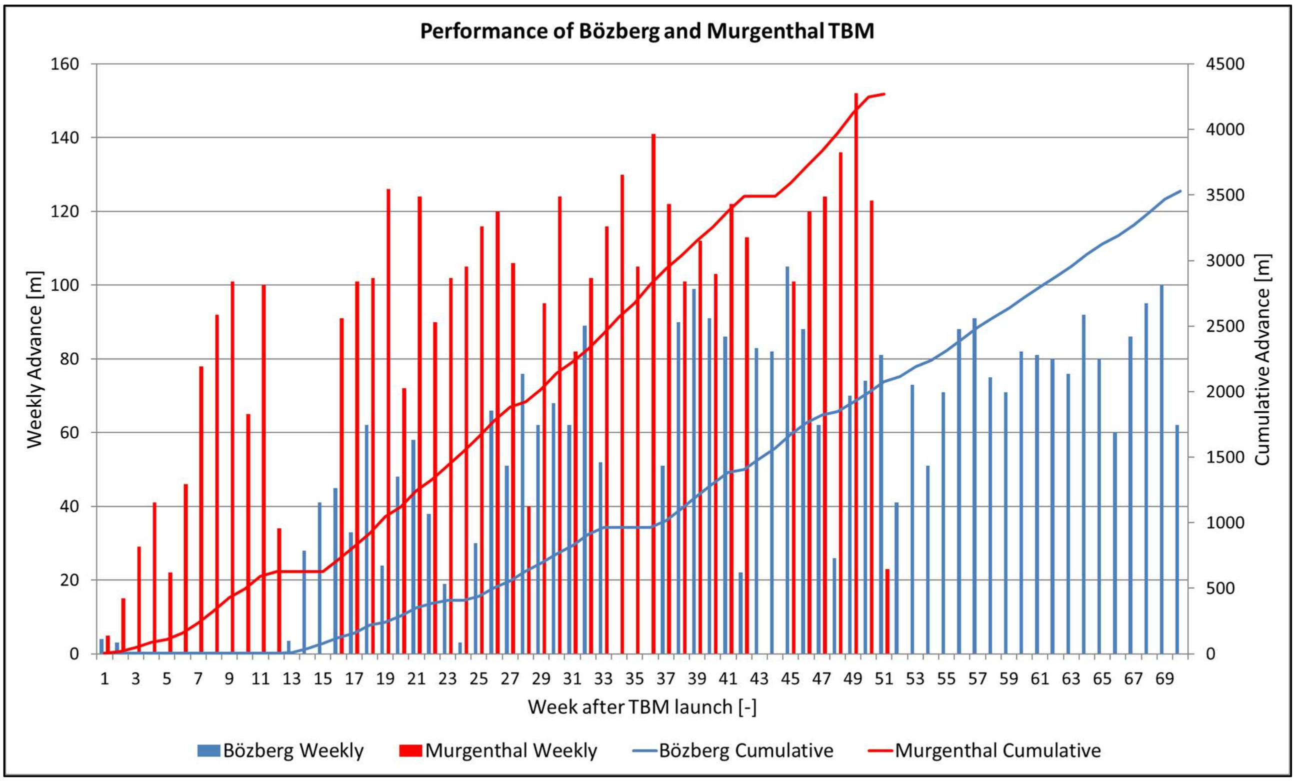


Figure 2-2: Weekly and cumulative performance comparison of Bözberg and Murgenthal tunnel drives (Maidl, Schmid, Ritz, & Herrenknecht, 2008)

2.1.3 Problem Example 3: Backup Internal Logistics

After successfully planning efficient logistics on the jobsite surface and within the tunnel, all material handling within the TBM backup system itself must be managed properly. Especially large diameter machines tend to feature complex internal logistic systems that can be a limitation for the performance of the TBM. In case the segment transport requires several steps, the segment delivery can quickly turn into a bottleneck. The transport components may consist of several cranes, shuttles, lifting and shunting tables, turntables and the segment feeder. At the German Katzenberg tunnel, mucking was done by belt conveyor and segments were delivered by truck; a setup which usually allows a high productivity from the logistics perspective. Each segment had to be transported from the end of the TBM by crane over a distance of 140m within the backup system to cross a bridge area, below which the invert was built. This crane would place the segment onto a shunting table (Figure 2-3 at the bottom), which moved it sideward into a position where a second crane could pick it up to place it on the segment feeder. According to the measurements presented by (Schmitt, 2006), the fastest transport process for a full ring took longer than the excavation of a rings length. The segment transport within the backup system had become the bottleneck for the overall cycle duration.

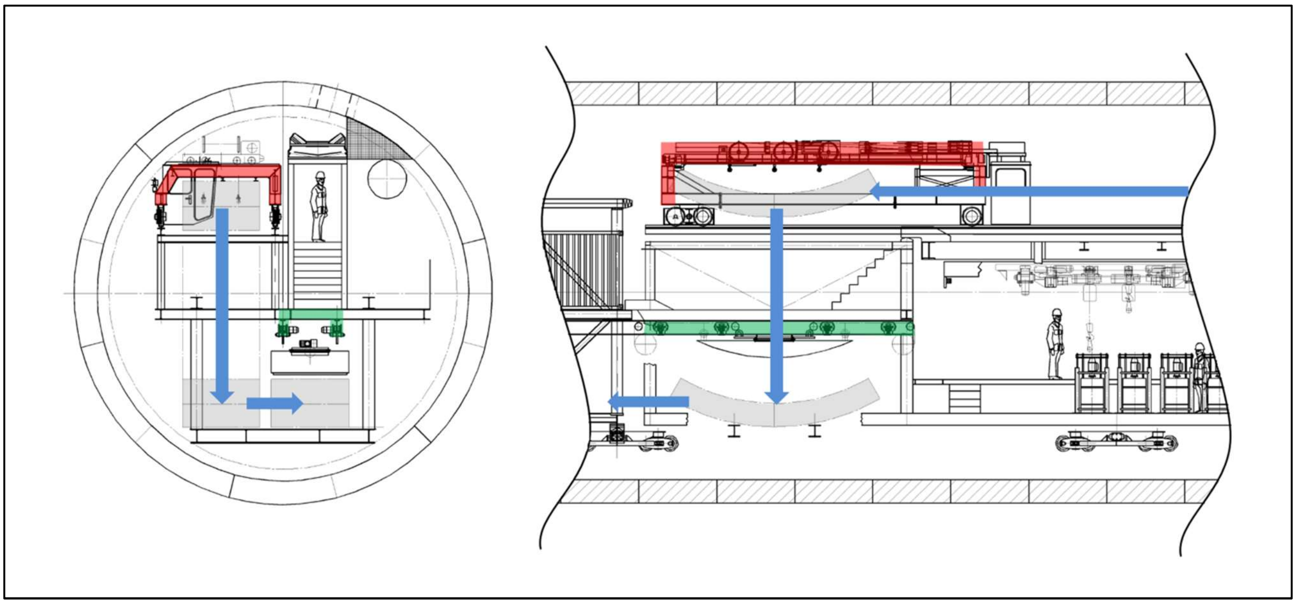


Figure 2-3: Segment transfer using segment crane 1 (red) and segment crane 2 (green)

2.1.4 Planning Aspects for TBM Jobsite Logistics

To summarize planning aspects, literature offers a number of checklists for planners by authors such as (Girmscheid, 2008), (Maidl, Schmid, Ritz, & Herrenknecht, 2008), (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011), (Bruland, 1998). Following list extracts the most prominent aspects that have to be addressed during planning stage:

- All necessary goods and their required quantities, batch sizes, handling aids, lead times, weights and dimensions must be identified and characterized.
- The layout of the jobsite with storage areas, driveways, crane coverage, shafts, assembly and work areas as well as their changes throughout the different project stages must be clarified.
- The structure and mutual dependencies of logistic processes including time and space constraints must be understood.
- All the equipment that is necessary to perform the logistic tasks must be identified including its performance data.
- All process durations and their stochastic parameters must be known.

- Communication structures within the jobsites, including supervisors, light signals, control rooms, signalmen, phone and radio connections but also the responsibilities of key personnel must be outlined.
- The interfaces between different planning responsibilities such as internal and external logistics have to be defined.
- Sensitivity analysis for the main influences on performance shall be carried out.
- Specific work instructions, which allow putting the plans into practice and allow the involved personnel follow a guideline have to be developed.

2.2 Research Goals

Little theoretical knowledge about process interactions, logistics theory and the structure of material supply systems flows from the academic world to the practical day to day work of tunnel construction planners. There are many different aspects of construction planning covered by researchers. Practitioners often use other tools than those discussed in research. This thesis aims at building a bridge between academics and professionals. While developing a systematic approach to logistics planning for mechanized tunnel construction, the practical usability of the approach shall not be forgotten. The proposed planning methods shall support an optimized design of the TBM´s support and supply processes and allow the performance comparison between alternative logistic systems. The proposed methods shall be feasible for actual jobsite conditions with all their restrictions. Based on existing methods used by the industry today, best practices are identified and further developed into a systematic approach. As planning can only be done based on the data from past projects, a practical survey approach has been developed on the base of the existing practices for the retrieval, structuring and usage of reference data for process durations. Furthermore, this work clarifies the limitations for classic planning tools and explains how the usage of process simulation can support planning processes where traditional instruments aren't feasible. Based on an artificial example project the successful integration of process simulation into the planning of tunnel jobsite logistics is demonstrated. The result of this work shall be available to planners to improve their practices and help the industry to achieve higher performances and efficiencies. In summary this results in the following three key objectives:

- Develop a structured analytic planning approach for jobsite logistics and performance prediction of TBM projects; including templates and guidelines for their use on site.
- Develop a body of structured reference data for process durations and methods for data collection, structure and usage.
- Demonstrate a systematic approach for the integration of process simulation as a planning aid for TBM jobsites.

2.3 Methodology

The basic line of thought started with system analysis, followed by a review of existing planning methods. Subsequently a simulation based planning methodology has been developed, applied and validated. The following steps reflect this idea as they built on one another in logical order and provide an overview of the activities and related results that have contributed to this work. The steps have not been executed in a purely linear manner but rather in an iterative process.

- Analysis of the basic principles of tunnel logistics and related operations and boundary conditions. Process analysis on several jobsites including all transport processes, their structure and mutual dependencies.
- Development of a simple, “ready for jobsite” form for identifying and describing the logistic processes and equipment of a jobsite. Later, this has been used in several field studies.
- A stochastic analysis of jobsite process durations based on video observations, shift protocols, TBM data and manual measurements. This data has been structured such, that it could be used for the estimation of process durations within the TBM operation.
- Collection and analysis of existing planning tools for jobsite logistics and a detailed discussion about their usage with several construction managers. This step clarified the boundary conditions within the tunnel construction industry and helped defining requirements for practically usable planning aids.
- Review of existing planning tools and their application and development of a set of generally applicable planning aids in spreadsheet software.
- Comparative studies of the logistic situation on several construction sites. These works delivered a clear picture of practical logistic problems, the related causalities and countermeasures as well as detailed data regarding process durations and interactions. The study’s results also contain detailed reference data, which in future can be used for planning logistic systems.
- First steps of building a modular simulation model which could be customized to several projects using Siemens Plant Simulation. While most research on this field came from the academic world either focusing on the details of simulation software or on management aspects, this work was aiming at using process simulation as a design aid for the TBM manufacturing industry. Based on this step, concepts for modularity and reusability of simulation models were developed based on the SysML modeling language.
- Implementation of tunnel logistics simulation models in Anylogic led to a clear understanding of the requirements for simulation tools in TBM tunneling.
- Implementation of a simulation model for TBM logistics and performance prediction in the Anylogic simulation software for a complete reference project. Comparison to using traditional planning aids.

3 State of the Art

There are a number of different fields this thesis builds on. Some are well documented in literature, such as the advances in the development of simulation techniques. Others are less frequently discussed in the academic world, for example, the methods and planning tools that are used by tunnel managers on site. The following fields are relevant for this thesis:

- Practical methods and tools for TBM jobsite logistics planning as planners throughout the industry use them.
- Methods for TBM performance prediction and their advances as they are used by the industry in academics.
- Simulation systems in construction planning and their development.
- Specific applications of process simulation to tunnel construction planning.

3.1 Commonly used Planning Aids for TBM Logistics

Many of the observed logistic problems on tunneling jobsites can be traced back to the planning methods that have been used. Often wrong methods are used or incorrect reference data is the base for decisions. In many cases, human factors and the influence of communication are neglected, as planners focus on technical data and specification sheets. However, nontechnical factors such as organization quality, environmental factors or human factors have a major influence on performance (Girmscheid, 2004).This chapter introduces the common planning techniques in the industry. General project planning techniques that are not specific to TBM tunneling are omitted in this place. The planning methods that are used in tunnel construction are mainly techniques for estimating material volumes and validation techniques to check if a certain proposed logistic system is capable of delivering the necessary performance to deal with this volume. The following sections introduce the most common types. They mainly originate from practitioners, but are discussed in literature as well (Duhme, Rahm, Thewes, & Scheffer, 2015).

3.1.1 Transport Volume Tables

Contractors need to plan the transport volumes on site (Saturn-Group, 2005). Knowing what has to be transported throughout a project is the foundation for planning the layout of any logistic system. Therefore, the material throughput must be assessed for each section of the jobsite. This is typically done using transport volume tables. Starting from the TBM, the material flow is assessed step by step along the transport route. The main sources of information to prepare transport volume tables are the tunnel design, TBM design and the preliminary plans of the logistic system. They determine the type and amount of required materials per tunnel meter or time unit. The TBM design calculations contain most information on the necessary amount of building material and consumables. Additionally, checklists and reference projects should be consulted to gather a complete list of required material. This list is often organized as a table listing consumption per ring, available storage volumes on the machine as well as transport batch sizes. Subsequently the necessary transport intervals can be derived. These intervals must be adapted to a practical pattern that matches the available logistic equipment. After completing this process for each TBM supplied by the same shaft and the tunnel transport system, the tables for the shaft are created as the cranes might require different batch sizes than the tunnel vehicles. The same applies to the deliveries to and from the jobsite. Therefore, separate transport volume tables should be created for these processes as well. Often the transport tables are integrated into the method statements for TBM operation (Atkins - Doha Red Line South, 2012).

As there is always a degree of uncertainty attached to the estimated performances, all transport volumes should be checked for average and maximum performance of the TBMs. Only if there are still safety buffers assuming maximum performance, it is possible to run all TBMs on site with their design advance speed.

The main result from preparing the transport volume tables is an overview on which materials are to be transported from where to where using what kind of transport method. However, they are no possible interferences considered yet. Examples for transport volume tables applied to a realistic planning situation are presented in section 7.2.1.

3.1.2 TBM Cycle Charts

Before designing the supply chain on site, the internal process cycle of the TBM and its backup system must be planned. Material volume tables contain information on the goods to be transported. However, they still contain no information on the related schedules. This is added by TBM cycle charts. The key questions to answer while designing the TBMs operation cycle are:

- Are there any bottlenecks in the internal logistic system of the TBM that could affect the planned advance rates?
- Which logistic operations must be planned and performed regularly within the backup system?
- Which supply schedule has to be maintained to guarantee uninterrupted operation of the TBM?

TBM cycle charts are either supplied by TBM manufacturers or created by contractors themselves. They either focus solely on the backup gantry´s internal logistic operations or include transport processes within the tunnel (Atkins - Doha Red Line South, 2014), (Ordowski, 2012). Especially in combination with overview drawings of the backup system, they reveal a detailed insight into the interaction of different logistic processes.

The first stage of planning the logistic processes within the backup system is collecting information on all material handling operations. Typically, this is structured in a method statement that includes geometrical and organizational information where and with which equipment, which goods are moved (Atkins - Doha Red Line South, 2014), (Girmscheid, 2008). In addition, several manual installation processes that might interfere with logistic operations must be considered. Furthermore, regulatory requirements such as equipment functional safety (ISO, 2007) may lead to additional constraints. To get an overview of the handling processes, one starts with the transport volume tables introduced in Section 3.1.1 and lists all handling operations for each item. This considers the steps duration and the required resource. An example of the resulting table is shown in Table 3-1.

Table 3-1: Processes within the TBM backup system (Herrenknecht, 2015)

Process	Estimated Duration [min]	Resource
Advance	35	TBM
Load Muck	35	Belt Conveyor
Ringbuilding	45	Erector
Unload Segment on Feeder	3	Segment Crane
Feed Segment	2	Segment Feeder
Unload Train Rails	3	Segment Crane
Unload Gantry Rails	3	Segment Crane
Load Gantry Rails	3	Auxiliary Crane
Disassemble Gantry Rails	15	Manual
Unload Bolts & Clamps	3	Manual
Unload Grease Barrel	4	Grease Crane
Unload Pipes	5	Pipe Crane
Extend Pipe	10	Manual

After summarizing the processes, their order of necessary precursors has to be determined and listed. This is done using elements of classic scheduling techniques such as the critical path method (CPM) (Halpin & Woodhead, 1998). TBM cycle charts are essentially Gantt charts and therefore showing the processes durations linked to their predecessors and successors. Other than in typical project planning, the TBM cycle is a repetitive process instead one defined by a single beginning and single end. This requirement rules out using most common project management software tools for calculation and visualization, as they do not support cyclical processes. As not each operation occurs during every ring, there is a choice to make, which operations are to be included into the cycle charts. Showing all processes would lead to excessively long charts, which decreases the readability massively. The planner has to choose a scenario that is assumed being a representative or critical example. Typical charts contain a half or full day of operation. They can be drawn for different scenarios such as varying excavation speeds (Schmitt, 2006) or considering additional logistic requirements such as the need for extra shotcrete in fault zones for open TBMs. This proves a powerful method to identify critical paths and bottleneck resources.

One of the key advantages of Gantt charts which are created with modern scheduling software is the integrated logic which automatically adapts the chart when the underlying process information changes. This easily allows examining the consequences of any scenario. Logically if one of the main advantages of using Gantt charts lies in the automatic adaption to changing input parameters, this quality is lost if they are not dynamically programmed but drawn by hand in spreadsheet software. Here lies one of the main risks for TBM planners. Often in the tunneling industry, the TBM cycle charts are drawn by hand or semi-automated in spreadsheet files and therefore are not adapted to various scenarios and possibly variable information.

An example for such is shown in Figure 3-1. The chart is decoupled from the logical relation between the different processes that lie underneath. Sometimes, project planners and TBM designers develop elaborate spreadsheets that calculate the duration for different processes from the sum of all their sub-processes and automatically create Gantt charts from the results. However, due to the nature of these spreadsheets, they do not contain the logical order of predecessors and successors. Therefore, change management becomes hard. The input information for cycle charts is normally just estimated manually which means that comparing different setups or scenarios results in excessive manual work and is often not done in detail. Figure 3-1 shows such an example of a TBM cycle chart for a large diameter shield. The chart contains the main processes within the backup system during the construction of four rings. These include advancing and ring building as the core processes, the segment and grout transfer, as well as resetting the invert slabs on which the gantries are rolling.

The risk hidden in this approach lies in the comprehensive visualization of the results. It might cloak the shortcomings in the underlying logic, as this approach does not force the planner to check process conflicts explicitly. If all input data such as timings and logic relations are assessed correctly though, TBM cycle charts are an ideal method of visualizing the logistic operations. As for all other planning tools, the choice of reference data and input data has the largest influence on the quality of results.

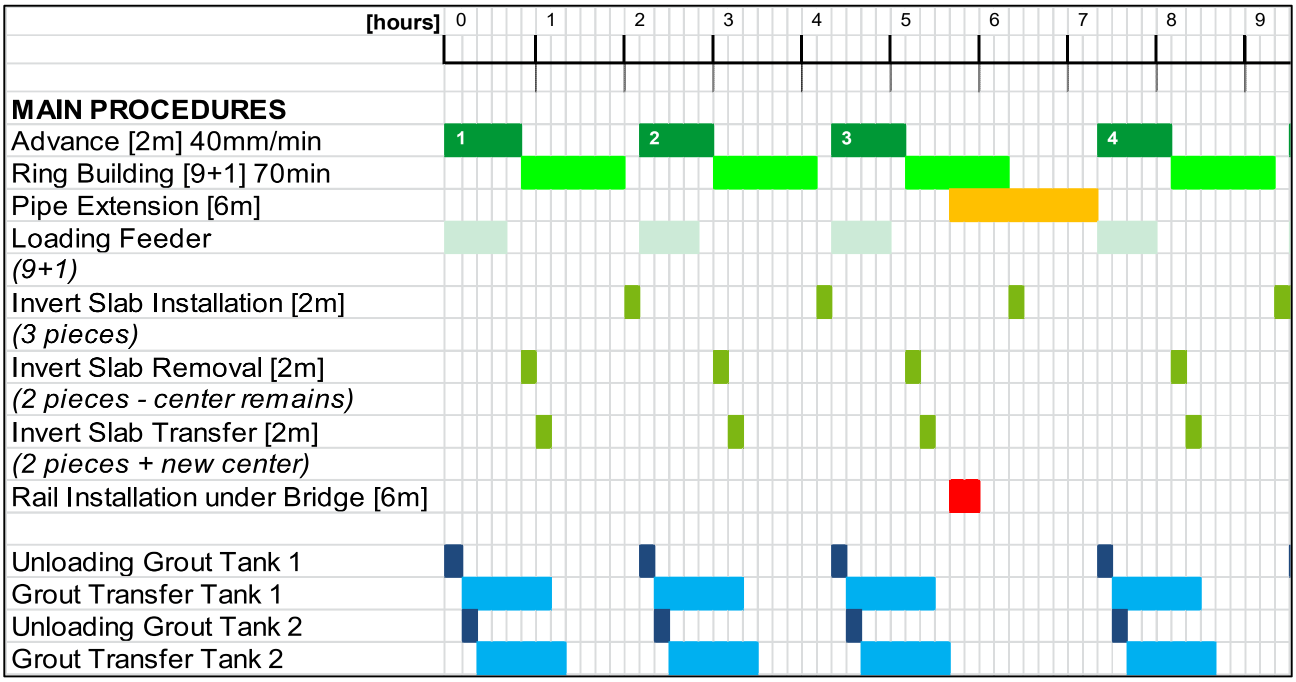


Figure 3-1: TBM cycle chart for a large diameter shield (Herrenknecht, Planning Documents for Wuhan SanYang Road Tunnel, 2010)

3.1.3 Vehicle Timetables

Vehicle timetables help coordinating the movements of different vehicles such as trains or trucks. They are used to schedule vehicles, cranes and other moving elements of the supply chain in the tunnel and at the surface. The tunnel transport follows the same cycle as the TBM itself. Therefore, the results from the TBM cycle design form the initial values for the cycle design of the tunnel transport. For the tunnel transport, there are a number of design approaches that are essentially different views on the same design procedure. All of them require the technical data of vehicles, TBM cycle times and the road or track layout as input values. Furthermore, it is necessary to assume a preliminary duration for loading and unloading in the shaft, although this has not yet been determined in detail at this planning stage. Either the cycle can be designed graphically, by calculation or using a mixture. Whichever way is chosen, the main goal of this step is answering the following questions:

- Which transport infrastructure must be installed within the tunnel?
- How many trains or trucks are necessary?
- Is there a bottleneck in the transport system and how big is the influence on the TBM?
- How many vehicle passing positions are necessary and where are they to be placed?

The simplest way to graphically determine the necessary number of train and switches is a train timetable or train cycle diagram. It uses the train speed, tunnel distance and waiting times at both ends in order to determine if and where california-switches must be placed and how many trains are necessary. The movement of the vehicles is drawn into a coordinate system with time on the x-axis and position in the tunnel on the y-axis. It translates to inclined lines for driving into the tunnel and declined lines for driving outwards. Standing in one position for waiting, loading and unloading is drawn as a horizontal line. An example for such a timetable is shown in Figure 3-2.

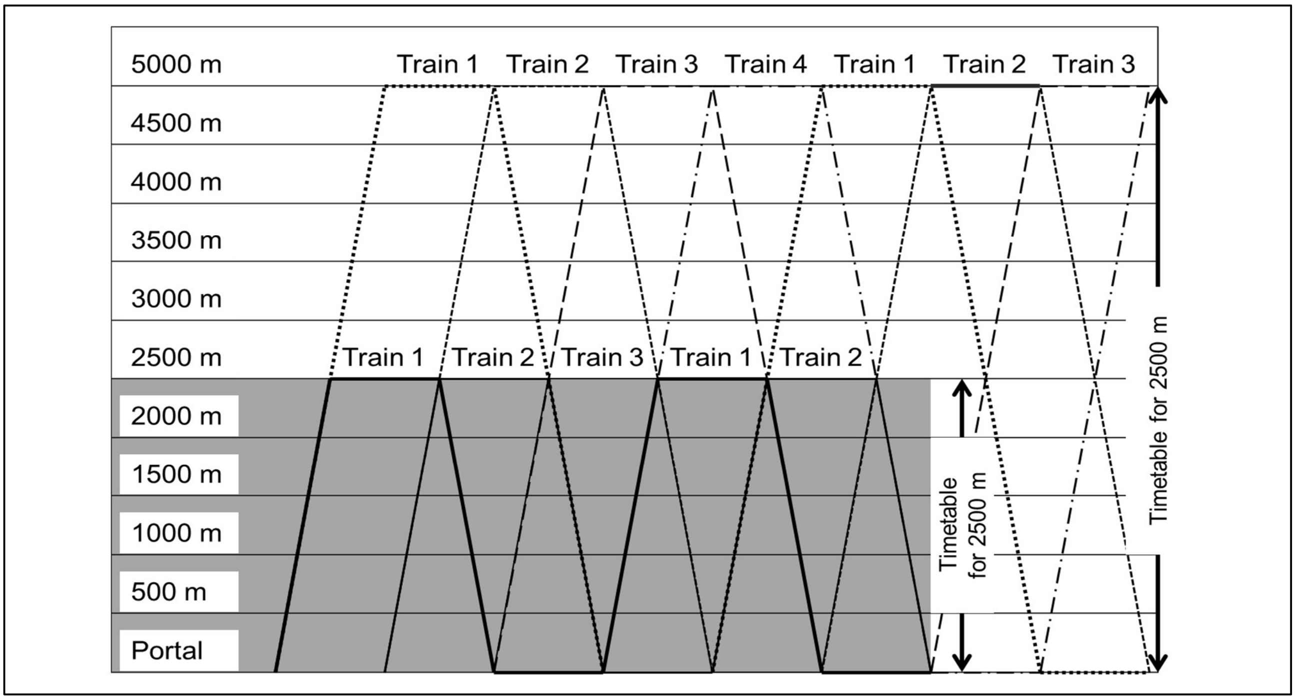


Figure 3-2: Train timetable (Maidl, Schmid, Ritz, & Herrenknecht, 2008)

The first train is drawn into the diagram, “drives” on the inclined line into the tunnel to the TBM and remains waiting while being loaded and unloaded. When this train leaves the TBM, the next train should arrive on time. This requirement defines the starting point for train 2. Additional trains are being added to the system until the trains that have gone in and come out once and waited to be loaded outside can arrive at the machine on time. This determines the necessary number of trains to supply the TBM. This model assumes that there is a possibility for the vehicles to pass each other at the TBM and at the portal. There are locations in the diagram where the movement paths of the vehicles cross each other. These are the positions where passing points must be installed. In Figure 3-2 such a point can be found at 2500m. Some planners add vehicle waiting times at the predefined locations of switches (Atkins - Doha Red Line South, 2013). However, as the nature of actual construction processes is probabilistic, the additional buffer this represents can also be modeled by extending loading durations at both ends.

3.1.4 Dynamic California Position Tables

When excavating longer tunnels, there are several theoretical and practical limitations to Train cycle diagrams. These shall be discussed to give a guideline for planning procedures. Firstly, cycle diagrams only depict a photographic moment in time. As the TBM advances, the passing points will have to move as well. When it advances further, additional passing points must be added. The cycle diagram does not explicitly show the addition and movement of these theoretical passing points over the course of a project. In order to get information about the development of the points while the TBM is advancing, an infinite number of cycle diagrams would have to be created. In addition, the varying number of switches for different train speeds cannot be seen in diagrams such as Figure 3-2. In order to visualize this, it is necessary to draw a diagram showing the number of switches related to the net penetration rate and tunnel length such as in Figure 3-3.

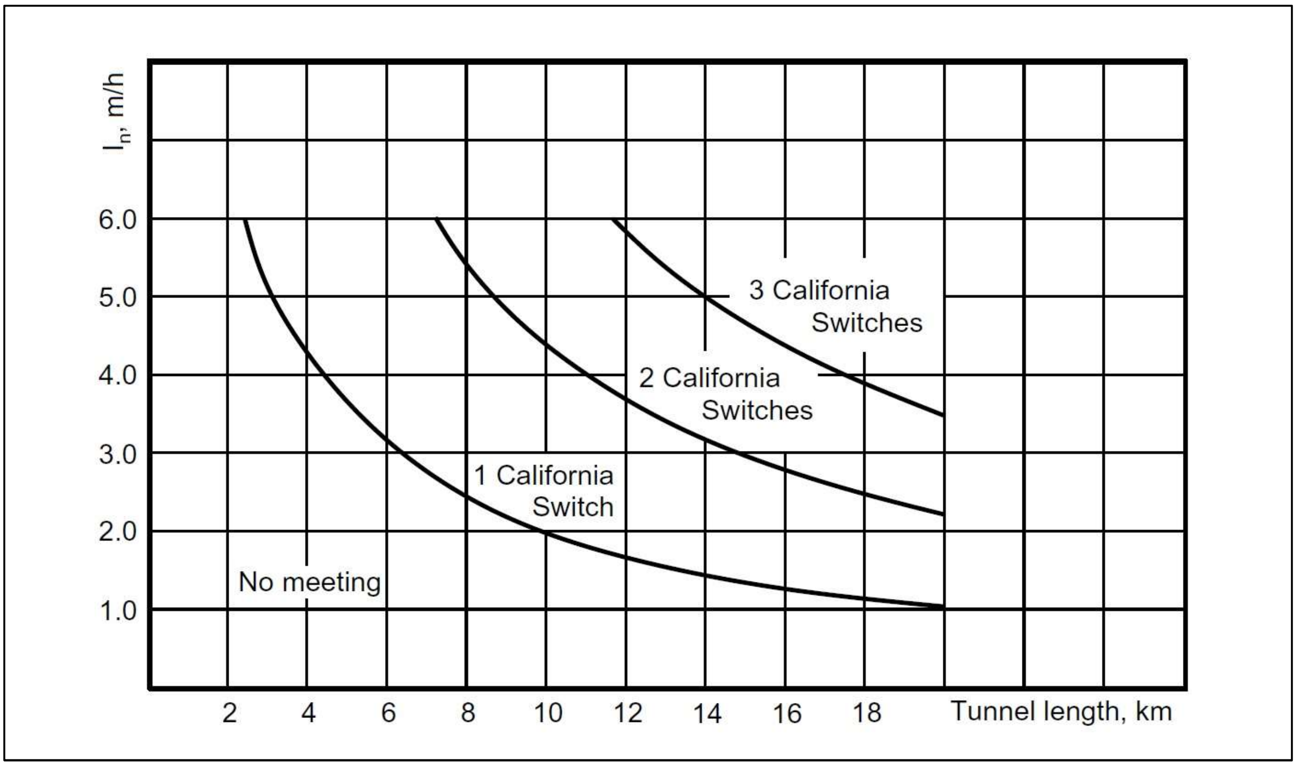


Figure 3-3: Switches depending on net penetration rate and tunnel length. (Bruland, 1998)

This type of diagram results from the synthesis of a large number of train timetables (Bruland, 1998). As this requires either rather complex computing or extensive manual calculations, this is hardly done by site planners. Furthermore, this is still an idealized scenario. In reality all input data is subject to stochastic distributions and there might be different speeds for loaded and for empty vehicles. There might be different types of vehicles with different speeds and different loading times, vehicles might slow down in certain sections of the tunnel for safety reasons and there might be unscheduled extra deliveries for personnel or spare parts. The advance rates can differ significantly between different sections of the tunnel. All this is impossible to depict in the vehicle cycle diagrams. Are these cycle diagrams useless then? Far from that; if conservative parameters are assumed, they will deliver a realistic guideline for the necessary number of trains and passing points in simple projects. However, if the structure of the logistic system gets more complicated, mere timetables are not enough to derive a realistic picture of the transport situation.

3.1.5 Combined TBM and Transport Cycle Diagrams

Another way of visualizing the transport cycles are combined time distance diagrams for TBM and vehicles (Maidl B. , 1994). They link the transport situation to the machine movement and can continuously track the situation in the logistic network. As they are drawn with CAD systems or in spreadsheets, the underlying logical information is not contained in the diagram. This makes adaptions difficult. Figure 3-4 shows a time-distance diagram for the tunnel transport linked to the TBMs movement. Although this type of diagram offers distinct information on the interaction of TBM and transport cycles, it lacks on one hand the level of detail which is contained in TBM cycle diagrams, on the other hand the overview capabilities of construction progress diagrams (Pollard, Green, & Conway, 1992).

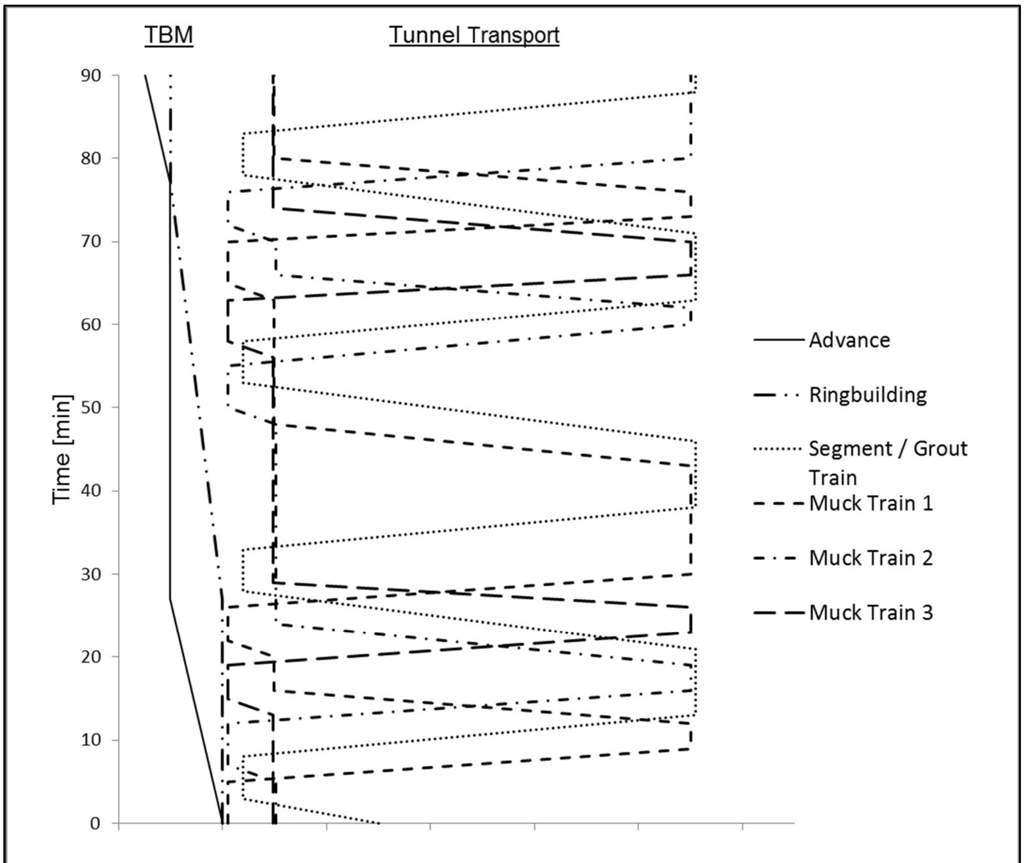


Figure 3-4: TBM cycle and transport schedule as combined visualization (Maidl B. , 1994)

3.1.6 Calculation of Lifting Capacity

The lifting performance of cranes Q_N is calculated by multiplying the theoretical performance Q_T with its influence factors (Girmscheid, Leistungsermittlungshandbuch für Baumaschinen und Bauprozesse, 2004).

$$Q_N = Q_T \times k_1 \times k_2 \times k_3 \times \eta_G \quad (1)$$

In this formula, k_1 marks the loading factor, k_2 the performance influence factor, k_3 the operational influence factor and μ_G the utilization rate. While this formula allows calculating the overall throughput of the crane, it does not yet indicate its cycle times. All cranes cycle durations are always made up of a similar pattern. It slightly varies between different types of crane kinematics but the principle of dividing the cranes operation into its individual elements is always identical. Figure 3-5 shows the principle of dissecting the crane cycle into its individual activities to determine the complete cycle time.

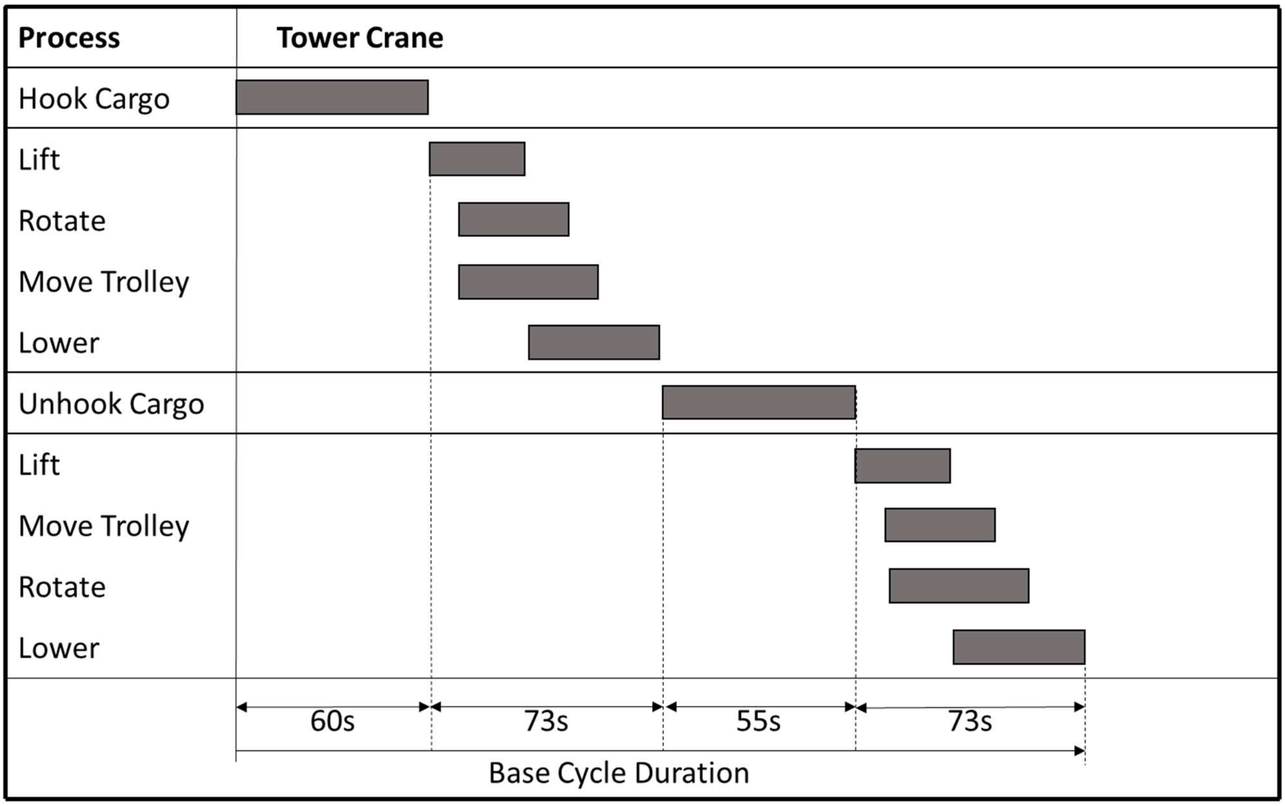


Figure 3-5: Cycle duration calculation for cranes (Girmscheid, 2004)

3.1.7 Limitations to Common Planning Tools

When analyzing the logistic problems on TBM jobsites there are several repeating patterns that can be tracked down to the prevailing panning tools and methods. Some can be traced back to just incorrect usage of planning tools; others would require completely different planning approaches. The following patterns emerge:

- Without a structured, step-by-step planning approach for TBM tunneling logistics, learning effects are difficult to establish throughout the industry.
- Planning is often based on unrealistic assumptions for the durations of individual processes.
- Ignoring process interactions and therefore mutual influences that slow down processes create overoptimistic scenarios.
- “Small processes” which may not represent considerable value or duration are often ignored during planning. Nonetheless, their share of resource usage is rather significant. The same is valid for unforeseen processes such as equipment failures, spare part transports or other irregular events.
- Disregarding dynamic factors that can change over time often leads to misallocation of resources. Especially larger projects require addressing this issue in a regular procedure (Pollard, Green, & Conway, 1992).
- For many planning aids, the level of abstraction is too high. Important operational aspects are neglected and the consecutive scenarios paint an unrealistic picture.
- The influence of process disruptions is neglected. They are represented by stochastically distruibuted mean time between failure (MTBF) and mean time to repair (MTTR).

Some of these issues are inherently rooted in the applied planning methods while others are rather due to improper application of per se suitable methods and tools. Generally speaking, the existing methods allow the estimation of general capacity requirements as well as planning and validating general transport concepts for low complexity projects with good results when applied properly. Their limitations are reached rather quickly when it comes to more complex projects with parallel material flows that are interfering with each other and generally more network shaped than linear.

3.2 Prediction of TBM Performance

Predicting TBM performance consists of estimating its individual process durations. Drilling and lining installation are productive and thus core processes. Their durations can be estimated fairly precise, whereas machine availability is more difficult to predict. The prediction of TBM performance is subject to a large number of studies with different focuses. “Performance prediction included prediction of instantaneous penetration (cutting) rate, cutterhead torque requirement, machine thrust requirement, cutting tool consumption rate, machine utilization time, and daily advance rate” (Copur, et al., 2014). TBM Performance is typically measured in monthly, weekly or daily production. In (Maidl & Wingmann, 2009) the following formulae are stated to describe the daily performance of a TBM in softground:

$$P_d = N_d \times L_{Seg} \tag{2}$$

including:

$$N_d = \frac{T_d}{t_{cyl}} \tag{3}$$

$$t_{cyl} = t_{adv} + t_{ring} + t_{stop} \tag{4}$$

$$t_{adv} = \frac{L_{Seg}}{v_{adv}} \tag{5}$$

$$v = p \times n \times IF \tag{6}$$

The daily performance P_d is made up of the number of advances per day N_d, multiplied with the segment length $L_{seg.}$ The number of advances per day depends on the daily working hours T_d *and the duration of each cycle* t_{cyl}. Each cycle consists of net advancing time t_{adv}, ringbuilding time t_{ring} and downtime t_{stop}. To determine the net advancing time, one has to divide the segment length L_{seg} by the net advance rate v_{adv}. The net advance rate again is made up by the cutterhead penetration p, cutterhead revolution speed n and an influential factor IF. This factor is composed of support pressure, cutterhead wear and conditioning quality. The model suggests penetration rates depending on geology and ringbuilding time depending on learning curves and tunnel diameter.

A similar approach is proposed in (Bruland, 1998) for hardrock machines. While it follows the basic principle, the influence factors are adapted to hardrock tunneling. What all performance estimation models have in common is the division of performance into drilling, lining installation and downtime (Leitner & Schneider, 2005), (Rostami J. , Performance Prediction of Tunnel Boring Machines (TBMs) in Difficult Ground, 2015). Most studies focus primarily on the penetration rate and develop models that allow correlating ground parameters to the achievable penetration rates by multiplying the calculated advance rate with a theoretical machine utilization rate.

Among those studies, approaches covering hardrock tunneling outnumber by far those analyzing softground tunneling (Maidl & Wingmann, 2009). This results mainly from the fact that “with the introduction of machines that could deal with mixed face of soil and rock, the relationship between the excavated material and the excavation rate changed as a result of innumerable influences” (Tarkoy P. , 2009). Due to this complexity, an analytic prediction system for soft soil has not been developed yet. Nonetheless, performance prediction methods have evolved from rather simple formulae to complex systems of interdependent factors (Leitner & Schneider, 2003). They include many factors such as “rock support, changing cutters, repairs and not least the efficiency of the back-up logistics for removing the muck from excavation and delivering construction material and supplies” (Maidl, Schmid, Ritz, & Herrenknecht, 2008).

Several studies have already investigated human productivity factors influencing ringbuilding durations such as learning curve effects (Maidl & Wingmann, 2009). In (Wachter, 2001), learning curves from several tunneling projects have been determined. They form an exponential function that can be derived from the individual daily performances. Figure 3-6 shows an example of such a curve. As the learning curve is exponential, no abrupt end can be determined. Therefore, a lower threshold is defined by (Wachter, 2001), above which the terminal performance range is reached and the learning phase is defined as complete. Beyond this point, the stationary performance phase is beginning.

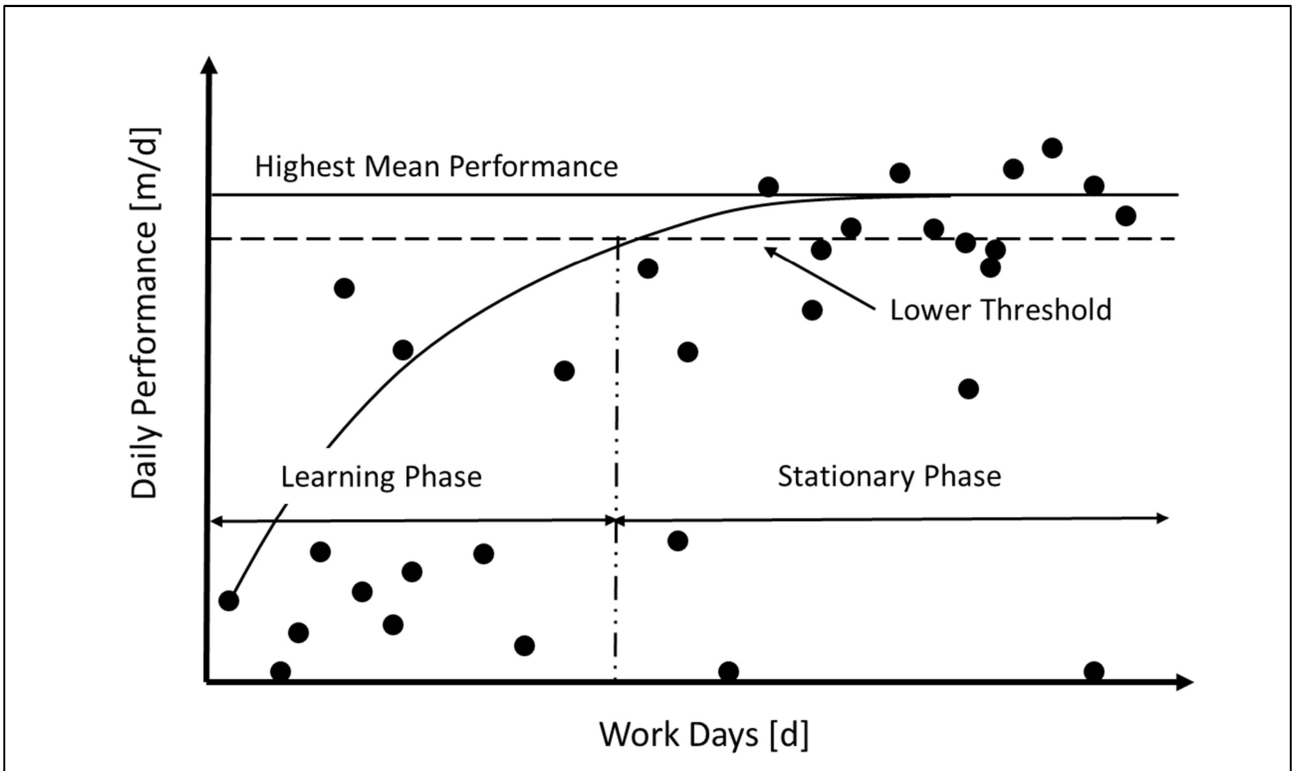


Figure 3-6: Learning curve model for TBM tunneling (Wachter, 2001)

The most advanced performance prediction models exist for hard rock tunneling. They can be divided into two distinguished approaches. The analytic method is based on the cutting forces acting on the individual cutters and the empirical one is based on the achieved performance of the machine in the field as a whole system (Rostami, Ozdemir, & Nilsen, 1996). Both apply estimated utilization rates to the determined raw advance rates. The empirical models can be distinguished further into those, which correlate rock conditions to penetration rate and those, which correlate them to the actually achieved advance rates (Ramezanzadeh, Rostami, & Kastner, 2004). In (Rostami, Ozdemir, & Nilsen, 1996) a comparison of the two most common models, the analytic Colorado School of Mines (CSM) model and the empirical University of Trondheim (NTNU) model (Bruland, 1998) has been presented that is shown in Table 3-2.

Table 3-2: Factors considered in performance prediction models (Rostami, Ozdemir, & Nilsen, 1996)

Influence Factor	**Analytic Models**	**Empirical Models**
Cutter Forces	Yes	No
Cutter Geometry (type, shape, etc.)	Yes	No
Cutting Geometry (spacing & penetration)	Yes	Partially
Machine Design Issues	Yes	Partially
Face Layout	Yes	No
Diagnostics & Design Modifications	Yes	No
Adaptability and the Ability to Develop new Technologies	Yes	Very Limited
Ability to Exchange Information between different Excavation Systems	Yes	No
Rock Strength and Physical Properties	Yes	Partially
Rock Property Indices	Partially	Yes
Ground Conditions	Indirect	Yes
Rock Mass Properties (joints, faults, etc.)	Indirect	Yes
Performance Prediction	Yes	Yes
Cutter Cost Estimation	Yes	Yes

It is obvious that the different approaches have different strengths and weaknesses. While the analytic methods are more useful for machine design and technology development purposes, empirical and stochastic methods are most suitable to give a global view onto projects for estimation and planning purposes. The subsequent sections give an overview of the following methods:

- Analytic methods for drilling performance prediction
- Empirical methods for drilling performance prediction
- Prediction of ringbuilding durations
- Prediction of utilization rates

3.2.1 Analytic Prediction of Excavation Speed

The basic idea behind analytic performance prediction methods is a very elegant one. *"To start from the individual cutter forces and determine the overall thrust, torque and power requirement of the entire cutterhead […]"* (Rostami, Ozdemir, & Nilsen, 1996) means that this approach can be widely used in the design process of drilling machinery. Equations that govern the cutting process have been obtained from extensive full-scale laboratory cutting tests. When applied to the actual TBM, the most influential mechanical parameters include thrust, cutterhead rotations per minute (RPM), disc spacing, disc geometry and maindrive power. In combination, they specify a certain penetration rate that can be achieved in a certain type of rock with a certain cutting technology. Since the middle of last century, a wide number of studies on understanding this cutting process have been conducted (Leitner & Schneider, Penetration Prediction Models for Hard Rock Tunnel Boring Machines, 2003), (Ramezanzadeh, Rostami, & Kastner, 2004). Today the most commonly used analytic model for TBM performance prediction is the Colorado School of Mines (CSM) model which has been developed at the Earth Mechanics Institute (EMI) of the Colorado School of Mines over the course of the last 30 years (Ozdemir, 1977), (Rostami J. , 1991), (Rostami J. , 1993). While the model has initially been developed using data of intact rock, the CSM model has been modified to consider rock fractures and brittleness (Yagiz, 2006). The following formulae calculate the cutting forces per disc in the CSM model:

$$P^o = C \times \sqrt{\frac{S}{\Phi\sqrt{R_{disc} \times t_{disc}}} \times \sigma_c^2 \times \sigma_t} \tag{7}$$

$$F_t = \frac{P^o \Phi \mathrm{R} t_{disc}}{1 + \Psi} \tag{8}$$

$$F_n = F_t \times \cos\left(\frac{\Phi}{2}\right) \quad \text{and} \quad F_{nr} = F_t \times \sin\left(\frac{\Phi}{2}\right) \tag{9) (10}$$

The crushing pressure P^o in the crushing zone directly under the disc is calculated from geometric parameters and rock parameters. The geometric parameters are the empirical coefficient C, cutter spacing S, the contact angle Φ, as well as disc radius R_{disc} and tip width t_{disc}. The rock parameters are the uniaxial compressive strength of rock σ_c and the tensile strength of rock σ_t. From the pressure in the crushed zone, the total force F_t is calculated. This requires again the geometry parameters of the disc as well as the constant pressure distribution factor Ψ. This force can be distinguished into the normal force F_n and the rolling force F_r for each cutter. In the next step, the forces for each individual cutter can be added to determine the excavation parameters for the whole cutterhead.

$$F_{CH}{}^{*} = \sum_{1}^{N} F_n \tag{11}$$

$$M_{CH} = \sum_{1}^{N} F_{ri} R_i \tag{12}$$

$$P = 2 \times \pi \frac{M_{CH} \times RPM}{60} \tag{13}$$

The necessary contact force for the cutterhead F_{CH} can be determined by summarizing the individual contact forces for the number of N cutters. The necessary torque M_{CH} is calculated by summarizing the product of individual rolling forces and disc assembly radii. The necessary power can be calculated from those two together with the rotational speed of the cutterhead. Ideally, a maximum penetration rate is reached with the model. There are limits to increasing the rate though by the technical design of the machine. These come from the maximum contact force of each disc, the available maindrive torque and the maximum rotation speed of discs and cutterhead. When using the CSM model, it is used in an iterative process until one of the limits is reached. These limitations are shown graphically in Figure 3-7. Today the CSM model is the most widely applied analytic calculation method for hard-rock TBM advance rates.

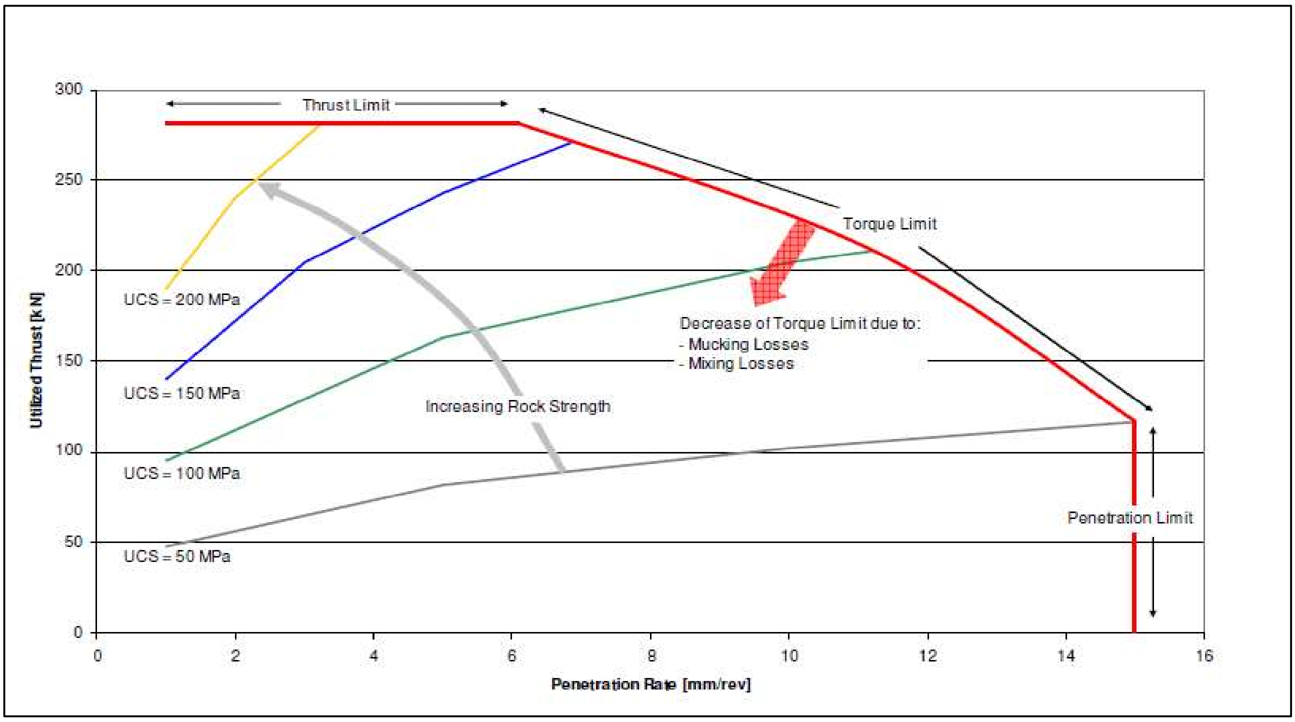


Figure 3-7: Limitations of the CSM model calculation process (Bäppler, 2009)

3.2.2 Empirical Prediction of Excavation Speed

Empirical performance prediction methods are based on references from the past. Typically, the models are condensed into a series of geological and technical graphs that have been obtained from project data. The most referenced of these methods is the NTNU method (Lislerud, 1988), (Bruland, 1998), (Nelson, 1983) which has been developed and refined over the years at the Norwegian University of Science and Technology. The Total Hardness Method (Tarkoy P. , 1975), (Tarkoy P. , 2009) is less commonly used today although it offers fast and inexpensive prediction. One decisive advantage of these empirical methods is their inclusive consideration of the whole tunneling system. Even unknown effects are included in the overall numbers. On the other hand, they are inherently unable to consider innovation. As the body of reference data is valid for existing systems, empirical models cannot be used for determining the potential performance of new machinery designs (Rostami, Ozdemir, & Nilsen, 1996).

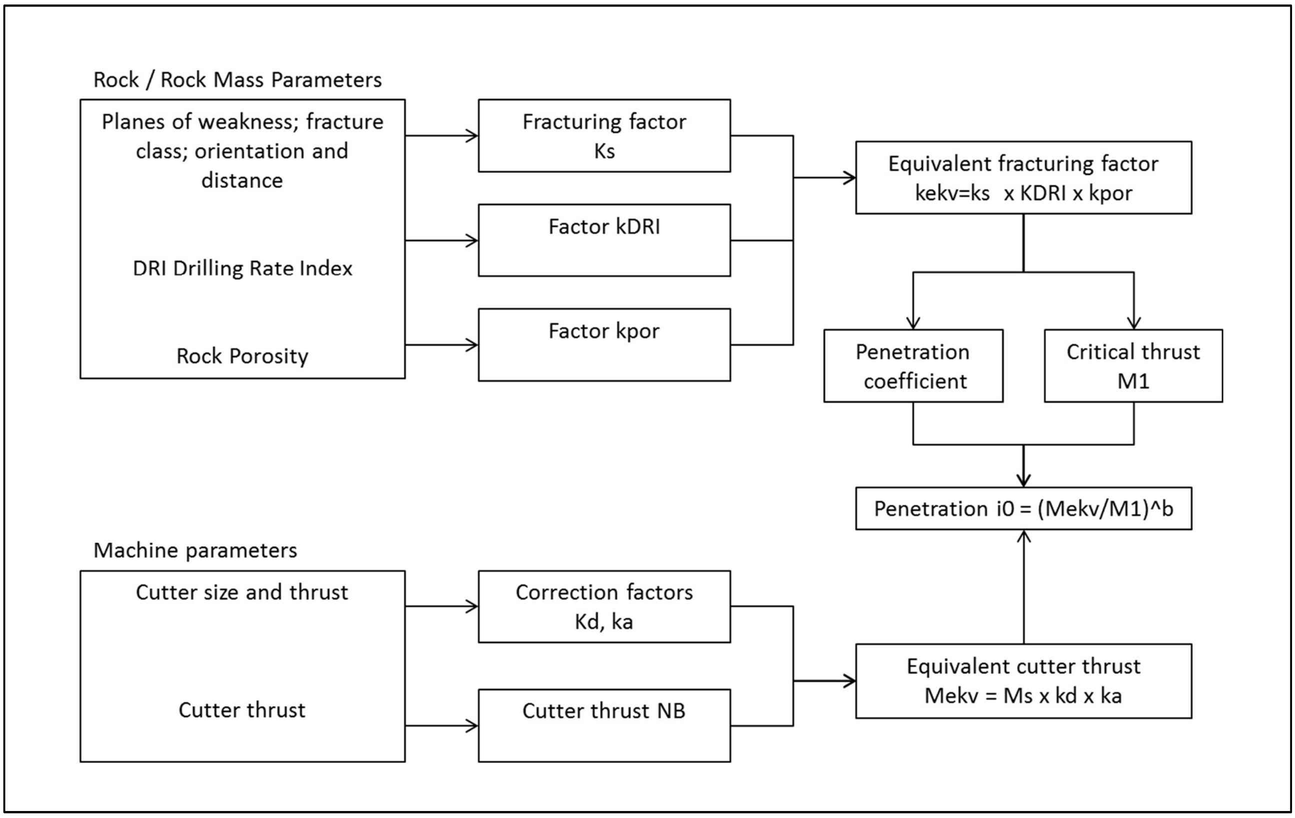


Figure 3-8: Workflow of the NTNU model, (Leitner & Schneider, 2003)

The NTNU model uses several rock property indices, namely the Drilling Rate Index (DRI), the Cutter Life Index (CLI), as well as the degree of fracturing and combines them with machine parameters such as thrust, cutter spacing, installed power and cutterhead RPM to derive the achievable penetration. Subsequently, the actual daily advance rates, cutter consumption and construction cost can be derived by using standard utilization rates. Over time, referencing charts starting out with different geological parameters have been developed within the NTNU model. Figure 3-8 illustrates the workflow of the NTNU performance prediction model. While on one hand the rock property indices are modified with several factors for geometry and fracturing, the raw performance parameters of the machine are modified with correction factors on the other hand. Subsequently, both are united in the penetration index.

As the geotechnical parameters of soft ground are more complex to classify, empirical models are the best choice to predict advance rates. In (Maidl & Wingmann, 2009) a model that uses different influence factors that are applied to a raw advance rate is proposed. This raw advance rate is the result of an empirical analysis of past projects data. The raw advance rates shown in Table 3-3 are subsequently modified by applying influence or reduction factors for support pressure, conditioning and the cutterhead state. This allows a good practical estimate although many factors such as TBM size or operational aspects are not yet considered.

Table 3-3: Advance rates of EPB in various ground conditions (Maidl & Wingmann, 2009)

Soil Type	Net penetration [mm/rot]	Net Rotation Speed [RPM]
Sand	30 - 40	1.2 - 2.0
Gravel and Gravel Sand	15 - 30	1.2 - 2.0
Compact Clay	30 - 40	1.2 - 2.0
Stiff Clay	40 - 50	1.2 - 2.5
Soft Clay	40 - 50	2.0 - 3.0
Soft ground with boulders	15 - 20	1.2 - 2.0

When encountering mixed ground conditions, the soft ground generally allows higher penetration rates than the rock, causing a risk of cutter damages. In (Thewes, 2004) an approach is presented to calculate the maximum penetration for the rock sections on the base of the CSM model to limit the forces on cutters. In many cases, the penetration rate is lowered even further to reduce the risk of damages further.

While these figures are generally valid, they do not factor in the local conditions of a specific project. A practical solution are local comparisons of past project performance in the same geology (Shirlaw, 2015), (Osborne, Knight Hassel, Tan, & Wong, 2008). They are able to reflect the local geological conditions and their specific challenges. Furthermore, any existing artificial influences on advance rates such as prescribed support pressure levels are included in such references.

3.2.3 Prediction of Ring Building Durations

There have been several studies on the duration of ring building durations. Learning curves are an important aspect of ring building duration (Wachter, 2001). A similar learning curve that gives an indication on the spread of the durations is proposed in (Maidl & Wingmann, 2009). Using an 11m diameter TBM with 6+1 segment design as an example, the durations shown in Table 3-4 have been derived. However, if the technical parameters of the tunneling project differ, there parameters must be modified accordingly. As the ring building process is composed of several individual steps, analysis on their individual durations has been made to understand the key influences and how to speed up the process efficiently (Schmitt, 2006), (Gelbrich, 2012).

Table 3-4: Ring building durations (Maidl & Wingmann, 2009)

Tunnel Length [m]	Average Duration [min]	Duration Range [min]
0 - 200	90	75 – 120
0 - 500	72	55 – 100
0 - 1000	63	45 – 90
0 - 2000	54	35 – 75
< 2000	45	20 - 60

The following list has been proposed by (Maidl & Wingmann, 2009) as main influences on ring building durations. However, without an analytic method to derive a definite duration from these influence factors:

- Number of segments per ring
- Segment length, width and weight
- Tunnel length
- Number and type of connections
- Type of coupling (gripping) system
- The precision and the speed of erector and supply system
- Requiements for installation tolerances
- Degree of experience and practice of the personnel

3.2.4 Estimating Utilization Rates

According to (Tarkoy P. , 2009), (Bruland, 1998), the overall utilization of a hardrock TBM can be defined as the portion of machine operating time per shift time. This includes the lining erection as productive. This matches the definition for segmental lining TBMs (Copur, et al., 2014), (Maidl & Wingmann, 2009). The estimation of downtime is a crucial though highly difficult task involving lots of past experience. In literature, a large catalogues of possible downtime reasons and general clues how to assess them can be found (Bruland, 1998), (Namli, et al., 2014). However due to the high effort of manual recording and contractual relevance of the data, there is very little actual data available in literature. Therefore, the prediction of utilization rate (+/-20%) is less precise than of the penetration rate (+/-5%) (Tarkoy P. , 2009). One example is shown in Figure 3-9 for a hardrock TBM. It becomes obvious, that the classification of time consumption can be prone to a rather large margin of error. In many cases, the category “other errors” is much larger and cannot be further distinguished with the existing data (Bilgin & Balci, 2005). Detailed classification systems for downtime have been developed and should be applied systematically (Leitner, 2004), (Tarkoy P. , 1999), (Tarkoy & Wagner, 1988), (Scheffer, 2012). This allows using downtime data to estimate relative downtime resulting from planning decisions on future projects (Jencopale, 2013). Obviously, the actual boring time makes up less than half of the project duration while lining installation, maintenance, downtime and other issues account for a total around 60% of the time. Considering this ratio, the importance of forecasting downtime becomes clear. As detailed data is not publicly available, (Copur, et al., 2014) suggest to define different global scenarios based on expert interviews. This leads typically to values between 20% and 50% utilization rate. Beyond this global approach, it is possible to make a more detailed estimation though. It is necessary to identify and classify the main influences downtime depends on, (Delisio, Zhao, & Einstein, 2011).

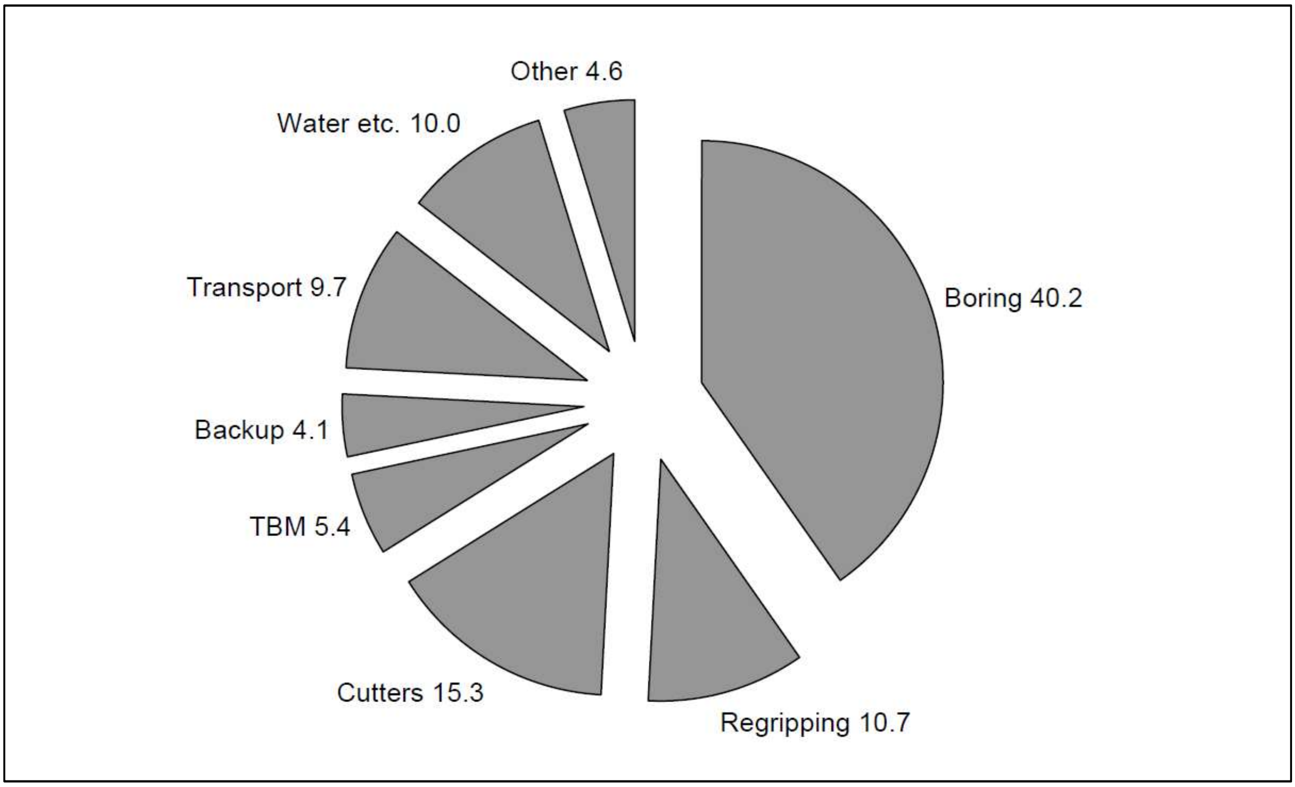


Figure 3-9: Time consumption portions at the Meraaker tunnel (Bruland, 1998)

Generally, downtime can depend on the advance in meters, such as regripping, utility extension, mucking delays or ground support installations. Especially in open TBMs, the geology has a major influence on downtime (Raschilla & Bartimoccia, 2009). Approaches to develop a unified model for documentation and categorization of downtime are under development (Hofer, Kluckner, & Schubert, 2015). Downtime can also be time dependent e.g. maintenance operations or excavation dependent, such as tool wear. Additionally, stochastically distributed downtime due to material failures must be considered. Checklists help to address these issues as completely as possible (Maidl & Wingmann, 2009). As can be seen when comparing the actually achieved utilization rates of the first and second line of the same TBM with predicted values in Table 3-5, it is obvious that the precise prediction is difficult. However, the data shows also that using direct references is the best approach. Generally, there is often a tendency for overly optimistic estimation of utilization rates as the reasons for slowdown are complex. The performance of line 1 is far below expectations.

Table 3-5: Comparison of predicted and real downtime (Namli, et al., 2014)

Parameter	**Prediction**	**Line 1 Actual**	**Line 2 Actual**
Advancing [%]	29 – 38	17	21
Specific Energy [kwh/m³]	5.5 – 7.7	6.8	7.3
Waiting Days [d]	34 – 38	20	30
Avg. daily progress incl. stops [m]	8.0 – 12.3	8.4	11
Avg. daily progress without stops [m]	15.3 – 28	10.6	21.2
Job termination days [d]	62 - 99	97	62

The improvements of line 2 can be attributed to learning effects. They not only span through a single project as described in (Wachter, 2001) but also influence consecutive projects through organizational learning. The values displayed here are very typical. Throughout literature, utilization rates between 15% and 60% can be found (Namli, et al., 2014), (Bruland, 1998), (Copur, et al., 2014), (Maidl & Wingmann, 2009). Depending on TBM type, geology and mucking method, there are different estimates available (Rostami J. , 2015), (Leitner, 2004). Tool wear and time necessary for interventions can be estimated based on local references as well (Shirlaw, 2015), (Zhao, Gong, & Eisensten, 2007). However, this is often done only for the TBM and not for the complete jobsite (Weigl, 1993). From available literature, one can summarize that the estimates vary greatly and although the general influence factors on utilization rates are known, it is not possible to perform any analytic calculation. The actual percentage and distribution of different types of downtime depends mainly on very project specific boundary conditions and can hardly be transferred from one project to a totally different one. Personnel experience, contractor experience and ground conditions as the most influential parameters on utilization rate (Copur, et al., 2014).

3.2.5 Limitations to TBM Performance Prediction Models

Analytic and empirical prediction models for TBM performance are useful tools to predict TBM performance. However, as both focus on the actual drilling process, they only indirectly take the organizational and logistic aspect of performance into account. By referring to utilization rates of reference projects, they are inherently unable to consider the project specific conditions of the logistic systems that determine performance. Since organizational aspects, jobsite communication structures and the potential interference of processes lead to performance limitations in many construction sites, a large array of performance relevant factors remains to be considered when using existing performance prediction models. One possible approach to solve this issue is presented in this thesis. An analytic prediction model is used to estimate the TBMs drilling performance. Subsequently the logistic system is analyzed separately with the goal of designing it in such a way that it is able to fully support the TBMs performance. Another possibility is including the results of TBM performance prediction models into simulation models for the logistic system of a jobsite.

3.3 Scheduling and Process Modeling

Analysis and modeling of processes are at the core of every planning task. Military planning and large-scale construction projects have been the origin for a number of techniques such as Gantt-Charts (Clark, 1923) and the Network Planning Technique (Halpin & Woodhead, Construction Management, 1998), (Austen & Neale, 1984) as they are used in modern project planning software. These methods offer practical planning and visualization aids and have been the base for many newer planning techniques.

In order to model all aspects of a construction operation as it is necessary for simulation purposes there are modeling techniques originating in software engineering. Most notably the Systems Modelling Language (SysML), which is applied as a modeling tool in this thesis.

3.3.1 Scheduling Techniques

Scheduling techniques are methods that allow linking processes in their logical order to determine the overall structure and duration of a project. Usually they consist of network- or bar graphs depicting the underlying logic. Today they can be implemented in software tools such as Microsoft Project or Primavera Project Planner.

Bar charts are among the most commonly used schedule visualizations because they are simple to understand and use. Their underlying logic is formed by the network planning technique (Halpin & Woodhead, 1998). A basic example is the Gantt-Chart in Figure 3-1 showing the logistic processes in a TBM backup system. Their simplicity makes them very useful for milestone and summary schedules, which are used for global control at the project management and executive level (Wilson, 2003). At the working level, charts that are more detailed may be used. In a bar chart, time is shown on the horizontal axis. Different processes are then shown as horizontal bars that are drawn from starting time to ending time.

When drawing bar charts, the first step is preparing a list of all activities that are to be shown in the chart. These are usually the top hierarchy level activities. Each can be detailed as much as desired though. Subsequently, the activities durations are estimated and the logical sequence is indicated. Significant milestones and deadlines should be marked. As a result, the time buffer that is available to start processes earlier or later can be determined. This buffer is called float. Many activities and details can be added, but from a certain point on the bar chart loses its simplicity. Therefore, usually a maximum of 20 activities is normally shown in one chart. A method to show more details can be hierarchical charts. They allow focusing of small details or on the grand picture equally. Bar charts are also used for project controlling. The current progress of a process can be depicted by marking the bars portion relatively to the current progress.

Network planning is based on graphs that contain the logical structure of a project. Once all activities are depicted in a diagram and connected by arrows according to their order of execution, planners can determine the necessary time schedules. The principle is shown in Figure 3-10. Each activity is identified by its label and its duration. Within the network the earliest and latest starting time as well as the earliest and latest finishing time of each activity is determined.

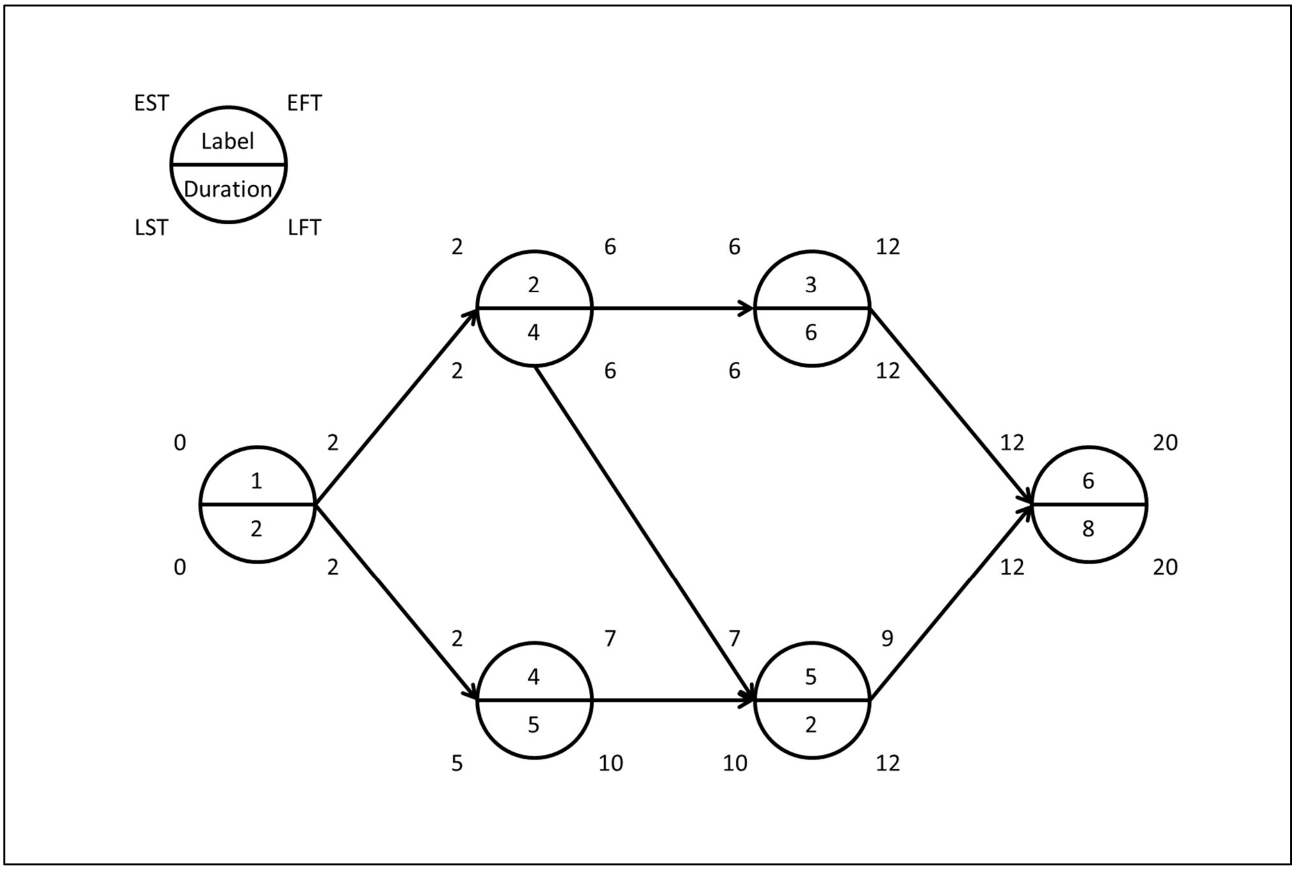


Figure 3-10: Schematic principle of network planning (Halpin & Woodhead, 1998)

In the shown example, the critical path follows the activities 1,2,3,6. A delay in any of them will delay the completion of the project. After calculating all activities once forward and once backward, the float is known for each activity (Pinedo, 2009). Using this principle is called the Critical Path Method (CPM). Compared to mere bar charts, it is far more suited to the construction industry as it permits the evaluation of alternative work programs, construction methods or types of equipment in a clearer way. The duration of activities may be decreased by using more or costlier resources. When comparing different scenarios, this can be used to determine the desired balance between cost and time. To keep the overview in complex planning situations, such graphs can be built in a hierarchical manner. However, at this stage, this system does not yet account for uncertainty of durations and consequently possible changes in critical path. This feature is added by the Program Evaluation and Review Technique (PERT) (Hegazy, 2002).

PERT is a statistical tool for project management that originally has been developed by the US military to manage complex defense programs (Ahujia, Dozzi, & Abourizk, 1994). A key innovation compared to previous scheduling methods was the usage of optimistic, pessimistic and most probable durations and their statistical evaluation with regards to the overall project duration. Today all the methods introduced in 3.3.1 are integral parts of project planning software. They also form the logical foundation for the development of simulation (Halpin & Riggs, 1992). Today PERT is widely incorporated in available project planning software.

3.3.2 The Systems Modelling Language

Today among the most widely applied methods for system modelling are the Systems Modelling Language (SysML) and Structured Analysis and Design Technique (SADT) based methods (Object Management Group, 2012), (Marca & McGowan, 1986). Unified Modelling Language (UML) has become a widely accepted and used modeling standard for software development. It is a worldwide standard that is specified by the Object Management Group (OMG) and codified as an ISO standard (ISO/IEC 19501).

To extend the application range from software to systems engineering, UML has been evolved into the SysML language (Weilkiens, 2006). SysML is consists of a number of diagrams which show different aspects of a system. Figure 3-11 shows an overview of these aspects. There are diagrams describing the structure and diagrams describing the behavior of a system. Additional diagrams allow structuring further information such as external boundary conditions. The following sections explain those diagram types that are used in this thesis.

Block Diagrams are the central element to define the structure of a system. “The block is the modular unit of structure in SysML that is used to define a type of system, system component, or item that flows through the system, as well as conceptual entities or logical abstractions. The block describes a set of uniquely identifiable instances that share the block's definition." (Friedenthal, Moore, & Steiner, 2011) Blocks define the relation between structures and substructures as well as the quantifiable physical properties of an entity. There are block definition diagrams (bdd) which show the hierarchy of a block and internal block diagrams (ibd), which focus on the connections between elements. Ports allow defining how inputs and outputs can enter and leave a system or subsystem (Object Management Group, 2012), (Weilkiens, 2006).

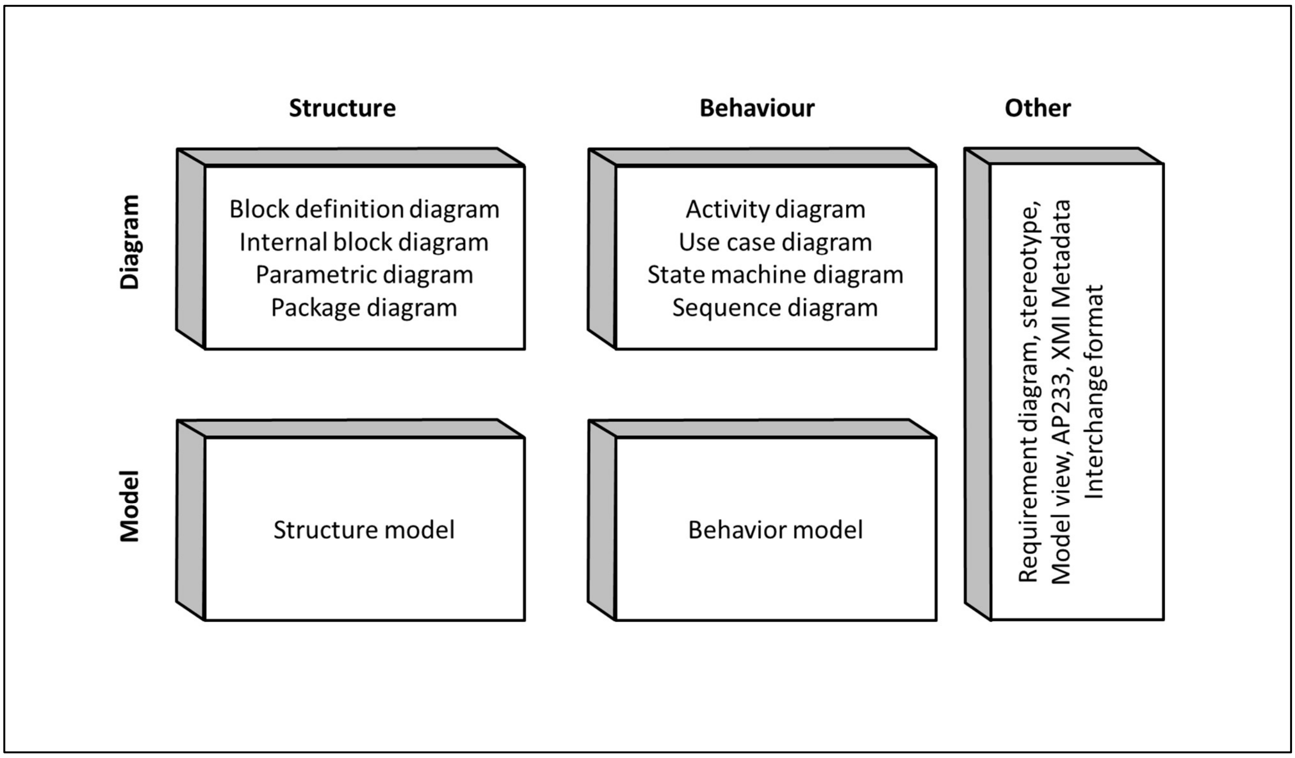


Figure 3-11: The SysML diagrams (Friedenthal, Moore, & Steiner, 2011)

State machine diagrams (stm) describe the behavior of a system with regards to internal and external events. They are essentially statecharts as presented in (Harel D. , 1987), (Harel D. , 2007). Statecharts are diagrams which can express complex behavior due to the aspects of hierarchy, communication and concurrency. The state machines of SysML define how the block's behavior changes as it transitions through different states. Whenever a state is entered or exited, there can be activities based on entry or exit. Transitions can be triggered by external events or internal logic. Hierarchy and branches, as well as other communication can model very complex behavior (Object Management Group, 2012), (Friedenthal, Moore, & Steiner, 2011).

Sequence diagrams (sd) show the interaction of different elements in terms of the messages they exchange (Weilkiens, 2006). They visualize how these messages trigger events and can create further communication or events among different model elements. “This representation of behavior is useful when modeling service-oriented concepts, where one part of a system requests services of another part” (Friedenthal, Moore, & Steiner, 2011).

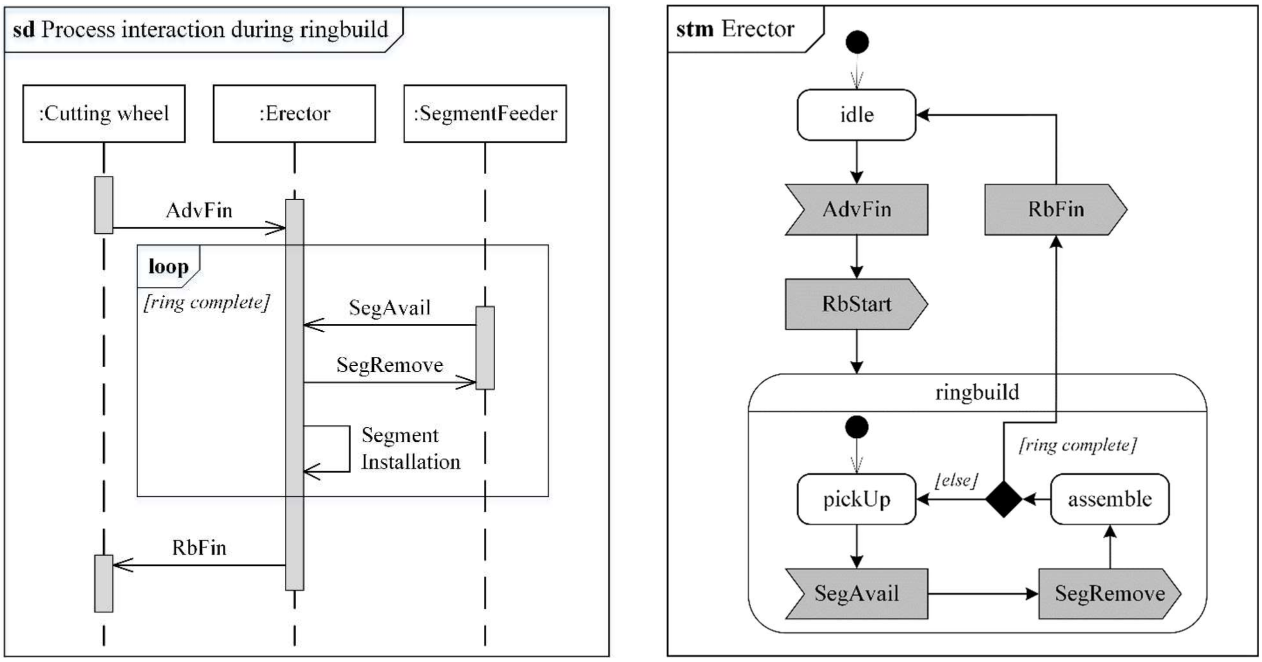


Figure 3-12: Example of Sequence Diagram (left) and State Machine Diagram (right) of TBM processes (Rahm, Scheffer, Duhme, Koenig, & Thewes, 2016)

3.4 Simulation in Tunnel Construction

Simulation is one of the technologies that are currently entering the construction industry and have the potential to greatly change the whole sector (AbouRizk S. , 2010). While in the manufacturing sector there are already large industry specific commercial frameworks available, the construction industry has no such foundation yet. Process simulation can add great value to designing efficient processes. Simulation studies allow the transparent evaluation of different scenarios with regards to time and costs. They provide a transparent foundation for management decisions regarding equipment and scheduling (König, 2011). The following sections will introduce:

- The different basic simulation principles
- Existing simulation frameworks used in construction
- Past applications of process simulation in tunnel construction

3.4.1 Basic Paradigms of Simulation

There are three distinctly different simulation paradigms. They differ in the ways their elements interact and their structure is formed. This makes them suitable for different purposes. They are system dynamics simulation, discrete-event simulation and agent based simulation.

3.4.1.1 System Dynamics Simulation

System dynamics modelling is a widely used modelling technique for processes that undergo dynamic changes such as flowing liquids or gases. System dynamics have been first introduced in the 50s as *“the study of information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise*” (Forrester, 1958). Today system dynamics simulation is used in a wide range of applications such as urban or social systems but also ecological or technical systems. In system dynamics the real world is represented by stocks and flows. Stocks can represent substances, goods, money, people, knowledge or ideas. They can flow between each other when the controls allow it. As it is possible to design internal feedback loops and interconnected systems, it is possible to model very complex real behaviors (Borshchev & Filippov, 2004). The underlying mechanism is a system of differential equations which model a systems time based behavior including the interdependencies between the different model elements.

3.4.1.2 Discrete Event Simulation

Discrete event simulation (DES) is a simulation paradigm which is typically used in manufacturing, logistics and other process and event centered applications. The method has been introduced in (Gordin, 1962) and is mostly used to model sequential systems. In a DES system, each event takes place at an instant in time and marks a change in the state of the system (Dang, 2014). Messages other events can trigger other events. This allows for interaction between the different system elements (Law, 2015). A DES simulation can be seen as state charts coming to life (Harel D. , 2007).

3.4.1.3 Agent Based Simulation

Agent Based Modeling (ABM) is a relatively new paradigm in simulation. The boundaries between traditional simulation and agent based simulation systems is not clear and subject do discussion (Macal & North, 2009). Effectively an agent is an object which contains rules that allow a reaction to certain mutual or external influences. This allows modeling of large systems with repetitive elements easily. Especially when elements have mutual influences, agent based simulation is a powerful tool (Borshchev & Filippov, 2004). There are a number of applications in construction (Sawhney, Bashford, & Walsh, 2003).

3.4.2 Simulation Frameworks in Construction

There are a number of simulation frameworks which are especially interesting for use in tunnel construction. Two basic simulation techniques which have paved the way for many other approaches are Petri Nets (Sawhney, 1997) and State Charts (Harel D. , 1987). There are several general purpose simulation frameworks such as Plant Simulation (Bangsow, 2008) and Anylogic (XJ Technologies Company Ltd., 2008) which have been used for construction (Duhme, 2012). Furthermore, there are specialized simulation frameworks which have been used for construction such as Cyclone, Symphony and Stroboscope. The cyclic network simulation framework (CYCLONE), introduced in (Halpin, 1977) was the forefather of many other approaches. Stroboscope (Martinez, 1996) and Simphony (Hajjar & AbouRizk, 1999), (AbouRizk & Yasser, 2000) are two important frameworks which are used in construction.

3.4.2.1 Petri Nets

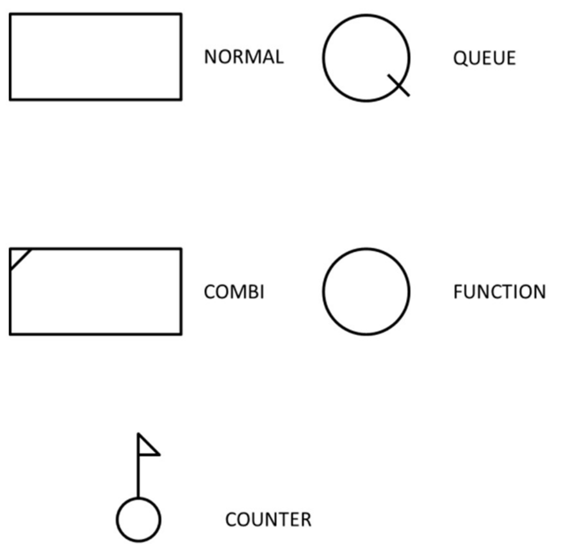
Petri Nets are a mathematical modeling language for the description of systems. A Petri Net is a directed graph where the nodes represent transitions. Directed arcs between the transitions show the order of events. They have been invented in 1939 by Carl Adam Petri to describe chemical processes (Petri, 1966). Petri Nets have been used as an alternative to classical CPM based planning techniques by (Sawhney, 1997) as they offer greater dynamic simulation capabilities. The basic principle of Petri Nets has been incorporated in dedicated construction simulators such as Cyclone.

3.4.2.2 State Charts

While originating in the 1040s, state charts in their modern form have been developed by David Harel (Harel D. , 1987). They are frequently used in computer science and are suitable to describe a systems behavior. Many simulation systems are based on the logic of state charts (XJ Technologies Company Ltd., 2008). They also form the theoretical foundation for SysML state machine diagrams as introduced in section 3.3.2. Statecharts are very intuitive and thus suitable as a graphical representation of logical structures.

3.4.2.3 Cyclone

The Cyclone simulation framework is the first dedicated contribution to the development of process simulation systems for construction. Most of the systems which have been developed throughout the last decades can trace their roots back to this system. Developed by Halpin (Halpin, 1977), it was specifically designed to simulate cyclic and repetitive construction operations by modeling the order of work tasks and move the required resources as entities through the model. The graphical elements which make up the model are shown in Figure 3-13. The NORMAL and COMBI elements are active elements. While a NORMAL element can be executed as soon as it is the next in the model, COMBI elements require certain conditions or resources to be fulfilled to be executed. They are thus delayed until the necessary amount of resources is available. For this waiting process passive QUEUE nodes are necessary. They allow the entities to wait before COMBI processes can be executed. ARROW elements then define the flow of entities between the other elements (Halpin, 1977). In later developments FUNCTION elements which allow additional more complicated logic like splitting or generating entities, as well as COUNTER nodes for counting entities have been introduced. While Cyclone has been a very important development step for the industry, there are a number of shortcomings. One key feature that was missing was the ability to explicitly model resources and their properties (Martinez, 1996).



NORMAL	A non constrain task. It is like a serving station with an infinite number of servers
COMBI	A task constraint by the availability of more than one type of resource. A resource arriving at a COMBI waits until all other required resources are available before it is processed
QUEUE	A waiting area for resources. A resource arriving at a QUEUE node will stay in the node until a COMBI is ready to process it
FUNCTION	Devised so it will provide some flexibility by allowing the creation of new elements
COUNTER	Keeps track of the number of time units pass it. It does not alter any of the resources or their properties

Figure 3-13: Cyclone modeling elements and their associated rules (Halpin & Woodhead, 1998)

3.4.2.4 Cyclone Based Frameworks

In order to improve in these areas, there were several developments taking place. Among them UM-Cyclone (Ioannou P. , 1989) and Micro-Cyclone (Halpin & Riggs, 1992) are the most prominent ones. Other further extended frameworks are Resque (Chang & Carr, 1987) as well as Coops (Liu & Ioannou, 1992). Coops is implementing object oriented programming techniques. During the execution of the simulation, the objects communicate via messages. Shi (Shi, 1999) developed the Activity Based Construction Simulation and Modeling approach (ABC). Disco (Huang & Halpin, 1994) features a pre- and post-processor visualization for Micro-Cyclone.

The next generation of construction simulation systems has been enabled by general advances in programming languages. MODSIM (Oloufa, Ideka, & Nguyen, 1998), is another object oriented framework which correlates construction objects with simulation objects. This makes the handling of the simulation more intuitive. (Odeh, Tommelein, & Carr, 1992) introduced Cipros (Construction Integrated Project and Process Planning Simulation). It is a knowledge-based system which extends the possibilities of characterizing resources even further and supports evaluating construction plans by relating them with design drawings and specifications.

3.4.2.5 Stroboscope-Based Frameworks

Stroboscope (STate and ResOurce Based Simulation of COnstruction ProcEsses) is one of the most widely used simulation frameworks today. It is an object oriented simulation framework which is based on activity cycle diagrams (Martinez, 1996). Therefore, the graphical representation is very similar to CYCLONE models. Resources can be differentiated by defining different entity properties. This can be extended by programming individual modules in high level compiled languages, such as C or C++. Built on the STROBOSCOPE Simulation Engine, Martinez introduced the EZStrobe software in 1998 (Martinez, 1998). EZStrobe is a simplified general purpose simulation engine which is built purely with graphical elements (Martinez, 2001). This allows users to build models which have no or little programming experience.

3.4.2.6 Simphony-Based Frameworks

Simphony is another object oriented simulation programming framework which sticks out for its wide practical use today. Developed by (AbouRizk & Yasser, 2000), it is especially suitable to develop special purpose simulation templates. Ruwanpura gives an overview of several of these templates including tunnel construction, geology modeling and pipeline routing (Ruwanpura & Ariratnam, 2007). Entities can be defined by programming their behavior in Visual Basic. Therefore, concepts of hierarchy and open interfaces can be realized. The recent version is called Simphony.NET and is built compatible with the High Level Architecture (HLA) framework (AbouRizk S. , 2010).

3.4.2.7 General Purpose Simulation based Approaches

Modern general purpose simulation frameworks such as Plant Simulation (Bangsow, 2008) or Anylogic (XJ Technologies Company Ltd., 2008) allow a wide range of development possibilities for tunnel construction simulation. Duhme (Duhme, 2010) has developed simulation modules for different TBM configurations and logistic systems to analyze the influence of TBM backup design and logistic system on the tunneling process using Plant Simulation. Scheffer has developed modular simulation models in the Anylogic simulation framework for the analysis of the jobsite layout and its influence on surface logistics performance (Scheffer & Rahm, Simulation der oberirdischen Baustellenlogistik beim maschinellen Tunnelvortrieb, 2013). Rahm et al. developed a simulation approach in Anylogic incorporating the influence or equipment failure rates using a multi-method approach with discrete event simulation and system dynamics elements (Rahm, Sadri, Koch, Thewes, & König, 2012). To support a reusable modeling structure, the model components have been developed using the SysML standard. Dang developed a special purpose simulation template called MISAS using Anylogic to analyze the influence of varying geology on the cycle times of three lots in the BV Recklinghausen Microtunneling Project in Germany. The system offers a graphical user interface and uncertain process durations to support the planning of the jobsite layout (Dang, 2014).

3.4.3 Simulation in Mechanized Tunnel Construction

Simulation modeling has been applied successfully in the planning of tunneling projects. Nonetheless a widespread acceptance throughput the construction industry is not yet reached. Most practical applications can be traced back to a handful of individuals who were exploring the possibilities of simulation in construction. Daniel Halpin and the following users and adaptors of CYCLONE have pioneered these developments. Halpin applied CYCLONE to analyzing the cycle duration of basic microtunneling processes (Halpin & Abourizk, 1991). Touran built already more complex models of TBM processes including tunnel and shaft logistics (Touran & Asai, 1987). However, in order to analyze different aspects of the construction project, different separate models had to be built. Brennan used CYCLONE to calculate cycle times for the construction of the Oakwood Beach Sever in New York and was able to obtain realistic results which could be validated during construction (Brennan, Hastak, & Yamashita, 2009). A very extensive study of the Munich project “Englischer Garten Fernwärmetunnel” was done by Weigl in his dissertation (Weigl, 1993). He built simulation models based on the experiences and work task durations of the first tunnel lot and applied the results to the planning of the subsequent lots. Nido et al. supported the planning of the Holes Creek Tunnel in Ohio, USA with an analysis based on CYCLONE simulation (Nido, Knies, & Abraham, 1999). In recent years, Liu et al. used a Cyclone model to analyze the muck trains needed for a hardrock tunnel project in Xinjiang, China (Liu, Zhou, & Jiao, 2010) and the influences of geologic uncertainty on the Jinping hydraulic tunnel (Liu, Xuan, Li, & Huang, 2014).

As STROBOSCOPE is commercially available there are a large number of application examples documented in literature. Marzouk et al. developed the decision support system TUNNEL_SIM (Marzok, Motassem, & Moheeb, 2008) for the construction of the Giza tunnel in Egypt based on STROBOSCOPE. Each alternative construction method has been modeled on the work task level and used to identify the most suitable construction method for each section of the tunnel. Ioannou et al. used STROBOSCOPE to determine the optimal allocation of resources for the Hanging Lake tunnel project in Colorado, USA (Ioannou & Likhitruangsilp, 2005). Based on the precedence logic and estimated process durations the overall construction time was determined by simulation. Messinella developed process models for the operation of road headers as well as drill and blast tunneling which have been used to analyze the construction duration of the Laval Metro Project in Italy (Messinella, 2010). A STROBOSCOPE based simulation was done to perform sensitivity analysis with regards to changing internal and external conditions.

Due to the efforts of Simaan AbouRizk SIMPHONY has been widely applied for construction projects in Alberta, Canada. The planning of the North Edmonton Sanitary Trunk (NEST) Tunnel has been thoroughly analyzed using simulation. Fernando et al. used Simphony to compare alternative solutions regarding the use of one or several TBMs and the configuration for shaft and logistic system with regards to project cost and duration (Fernando, Er, Mohamed, AbouRizk, & Ruwanpura, 2003). Al Bataineh et al. used a Simphony.NET based SPS template to perform a similar analysis on the construction approach including the comparison of different work shift arrangements and location of switches in the tunnel (Al-Bataineh, AbouRizk, & Parkis, 2013). Shahin et al. have developed an extension to Simphony to analyze the weather influence on the construction of NEST tunnels (Shahin, Abourizk, Yasser, & Fernando, 2013). The Simphony geology model has been used to determine the influence of different geology transition scenarios for NEST by Ruwanpura (Ruwanpura, AbouRizk, & Allouche, 2004). The South Edmonton Sanitary Sewer Tunnel (SESS) has been analyzed in a similar manner as NEST using Simphony as outlined by (Ruwanpura J. , 2001). For the Glencoe tunnel project in Calgary, Canada several alternative shaft layouts have been proposed. Al-Bataineh et al. have used a Simphony model to determine the cost / time optimum for these different layouts as well as the influence of different geology scenarios (Al-Bataineh H. , AbouRizk, Tan, & Fernando, 2006). In this study an extension, the Simphony Supply Chain Simulator has been developed which integrates the segment manufacturer into the simulation model. This module allowed analyzing the influence of tunnel production rates and storage capacities on the requirements for segment production and delivery. (AbouRizk, Ruwanpura, Fernando, & Er, 1999) have used the Simphony Tunneling Template to analyze the influence on shaft, muck car and crane site on the TBM´s productivity for the construction of the Mill Creek tunnel. Several applications of process simulation in tunneling have been developed based on the general purpose simulation framework Anylogic (Conrads, Thewes, Scheffer, & König, 2016), (Thewes, König, Conrads, & Scheffer, 2015). A number of works have investigated the use of simulation for improved performance prediction on TBM tunneling operations (Scheffer, et al., 2015) and (Duhme, Sadri, Rahm, Thewes, & König, 2013). An approach to quantifying the influence of component level disturbances onto the overall system and advance rates has been presented in (Rahm, Scheffer, Duhme, Koenig, & Thewes, 2016), (Thewes, König, Conrads, & Scheffer, 2015) and (Rahm, 2017). (Scheffer, Rahm, König, & Thewes, 2016) and (Duhme, Rahm, Scheffer, König, & Thewes, 2014) have analyzed the interaction of jobsite surface logistics and TBM production rate based on a general purpose simulation model. A number of works provide simulation based evaluation of TBM maintenance strategies including (Rahm, Duhme, Sadri, Thewes, & König, 2013), (Conrads, Scheffer, König, & Thewes, 2015), (Mattern, Scheffer, Conrads, Thewes, & König, 2016), (Scheffer, Mattern, Conrads, Thewes, & König, 2016), (Conrads, Scheffer, Mattern, König, & Thewes, 2017) and (Conrads, et al., 2017).

3.5 Evaluation of State of the Art

Stroboscope but especially Simphony and Simphony.NET are very powerful tools for construction planners. Nonetheless their practical application has been limited so far (AbouRizk S. , Role of Simulation in Construction Engineering and Management, 2010). Most applications have been executed by academics in an advisor role for the industry but not by practitioners themselves. Others focus mainly on cost comparison (Winkler, 2016). One of the main reasons is the gap between academics and practitioners in simulation specific skills. The existing applications have mostly been on a macro level to support management decision regarding the general construction approach. There have been very few applications of simulation to the actual design of tunneling technology. But on many TBM jobsites the micro level interactions of processes cause severe delays. Therefore, an approach to gathering the relevant data on this level as well as developing the relevant simulation systems is necessary. A special focus on the interface between simulation experts and practitioners can help gaining acceptance and allow the use of simulation to solve real practical problems. This includes the development of simple spreadsheet based planning aids which can solve some of the questions which have been typically analyzed by simulation experts. Since the industry already developed feasible solutions for many planning problems, simulation shall be used to solve those problems where analytic methods reach their limits. In summary, the following shortcomings can be identified:

- The industries existing planning aids do not exist as a coherent approach but rather as a patchwork of structuring attempts. Most of them are not available as a systematic planning approach.
- Observation data on micro-level processes is hardly available and therefore process durations and interactions are unknown.
- The existing simulation approaches have been mainly carried out on a management level and therefore lacked the level of detail which is necessary to support TBM and logistic system design.

4 Processes in TBM Tunneling

On TBM jobsites a multitude of interacting processes are necessary in order to keep the machine advancing. Depending on the type of equipment, the size of the project and the structure of organization there are many different possible process structures. Nonetheless, there are many repeating patterns as well. Lots of material must be supplied to the jobsite and removed away from the jobsite. It must be stored, processed and subsequently delivered to the point of use on site. The following section introduces the most common goods to be moved around on TBM jobsites as well as the major technical components that are involved in the logistic processes. Figure 4-1 shows a typical shaft including logistic equipment.

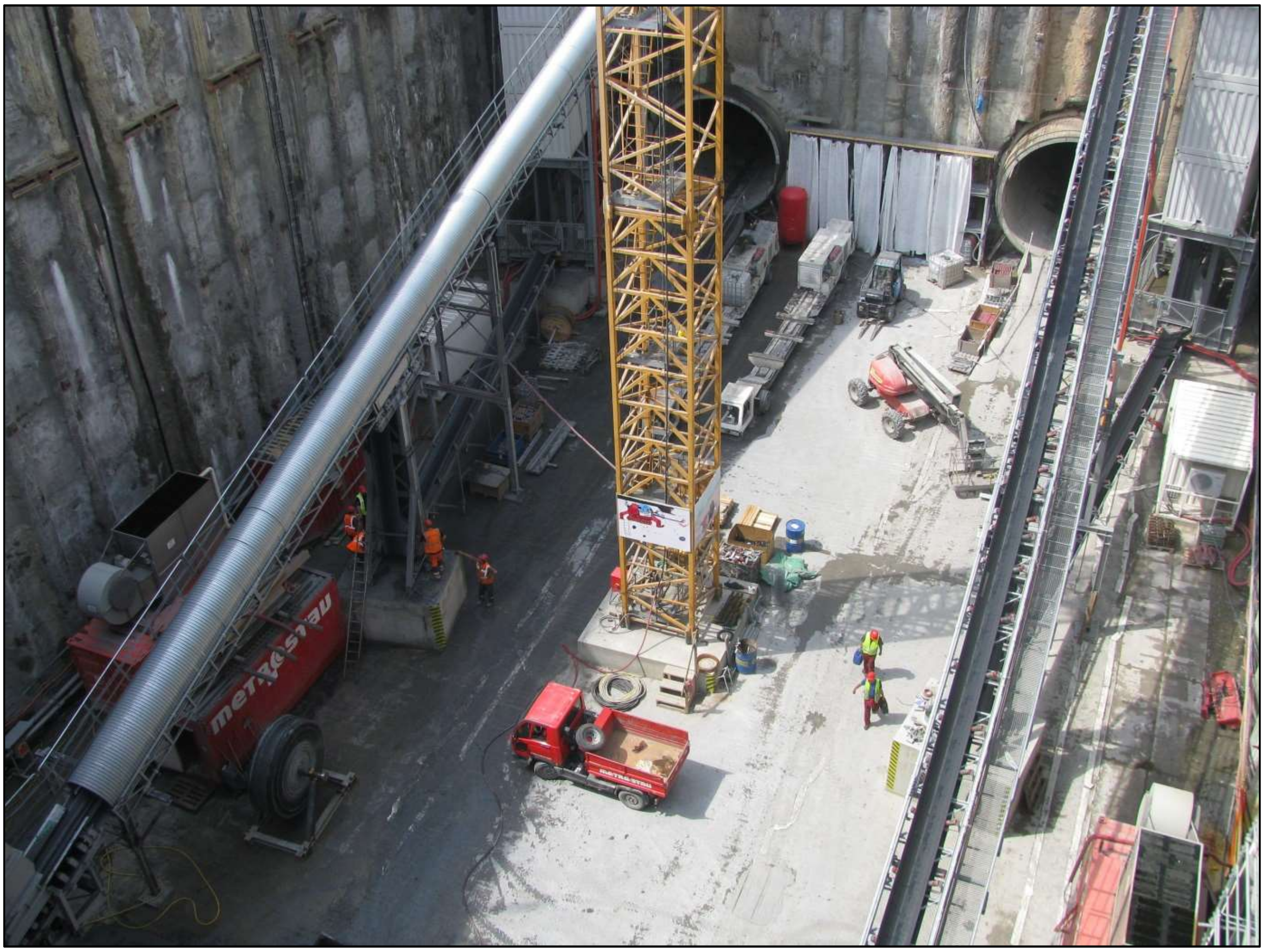


Figure 4-1: Tunnel shaft with crane, belt conveyors and delivery vehicles

In terms of their structure, processes in mechanized tunneling are quite unique within the construction sector. Halpin characterized the construction industry as project centered (Halpin & Woodhead, 1998). A low volume of products is built in small batch sizes. In contrast the manufacturing sector mass produces a large volume of goods in sometimes gigantic batch sizes. This is valid for the whole project but when observing the individual processes in mechanized tunneling, a high number of identical repetitive processes are executed. This repetitive nature of the processes in tunnel construction allows for a high degree of standardization of the production systems. Therefore, similar logistic elements as well as their related processes characterize all TBM jobsites.

The processes around an advancing TBM can be divided into different groups (König, et al., 2014). Firstly, the advance processes which are directly related to the advancing TBM and are performed by the TBM itself. They include advance and ringbuilding. Secondly, the support processes of the supply chain. They include all the processes in the backup system, the tunnel and on the jobsite, ranging from the storage on site to the cranes and trains delivering material to the TBM, which are necessary to support the operation of the TBM itself. Lastly, support processes such as maintenance are necessary to keep the machine in an operable state. Figure 4-2 provides an overview of this structure. Several publications offer a deep insight into TBM jobsites such as (Girmscheid, 2008), (Maidl, Schmid, Ritz, & Herrenknecht, 2008) and (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011).

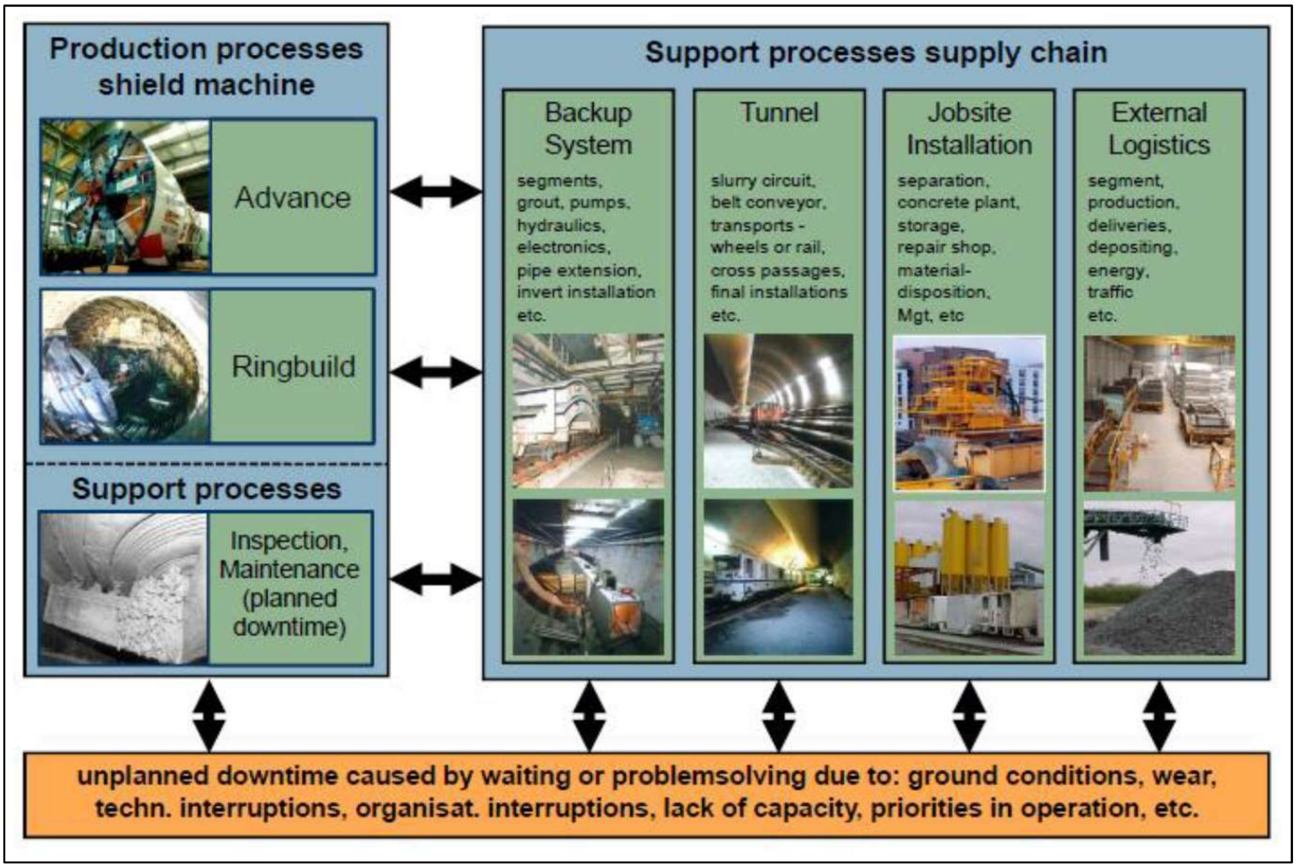


Figure 4-2: Interaction of production and support processes, (König, et al., 2014)

4.1 Production Processes

The TBM is at the core of the jobsite processes. One could say that everything that's happening on site is solely for the purpose of keeping the machine advancing. Of course there are further works on other parts than the tunnel which are executed at the same time, but usually building the tunnel is the dominating task of construction projects. There are different types of tunnel boring machine that are applied in different geologies. The most frequently used are the Earth Pressure Balance (EPB) machine, the Slurry Shield, also called Mixshield and Hardrock TBMs. In recent years, a number of hybrid and multi-mode machines have been developed to extend the classic application ranges of these machines. Although all these machine types differ significantly in some aspects, there are a few basic principles that are applied in all of them. First of all, every tunneling machine needs an excavation mechanism which in many cases is a full face rotating cutting wheel. The tunnel face must always be kept stable and therefore a mechanism for support pressure application is necessary wherever earth and water pressure require it. In addition, some form of lining has to be built in most types of geology. This can either be done by assembling prefabricated segments, which is the case in EPB and Slurry machines or by steel beams, rock bolts, wire mesh and shotcrete as it is done in Hardrock TBMs. Of course, there are provisions for material transport and muck removal as well as all the machinery related to the electric, hydraulic and pneumatic systems. Some of the equipment is passively part of the advance, while other requires regular active processes. There are several important processes worth explaining in more detail. This will be done by using an earth pressure shield as an example.

4.1.1 Excavation

The cutting wheel in the TBM front is loosening the soil and rock by rotating and pressing excavation tools against the tunnel face. The tools can be either disc cutters, cutting knives, rippers or buckets. A general classification can be made by separating into hard rock cutting (discs) and soil or soft rock cutting (knives and rippers). The range of available tools is immense and part of the know-how of their manufacturers. Cutting knives are made of steel bodies with hard metal inserts or hardened steel surfaces that do the actual cutting. Disc cutters have a hardened cutting ring that is rolling on the rock and thus breaking it. Once worn out, they can be exchanged. The bulkhead of the machine applies support pressure to the excavation chamber to keep the face stable. Thrust cylinders push the machine forwards, transducing the advance forces into the existing tunnel lining. While moving forward, the excavated muck must be removed from the excavation chamber. This is done by a screw conveyor in case of EPBs. The extracted muck is subsequently dropped onto a belt conveyor and brought to the back of the machine where it is handed over to the jobsite transport system. Due to bulking, its volume expands to typically 150-200% of the undisturbed volume (Girmscheid, Baubetrieb und Bauverfahren im Tunnelbau, 2008), (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011) (Maidl, Schmid, Ritz, & Herrenknecht, 2008). Figure 4-3 shows these components in a 3D model of a TBM.

Parallel to the excavation itself there are a number of support processes which have to be running in order to enable the excavation. There are sealings and bearings which are constantly lubricated with grease, such as the tailskin sealing, the main bearing sealing and the main bearing itself. The related supply systems must be operating in order for the TBM to advance. When the TBM moves forward, a gap is left between the completed lining and the ground. To prevent settlements, this gap must be backfilled with grout. This can be either a single component grout or a two-component grout consisting of a main component and a hardening agent. The TBM is equipped with tanks and pumps to allow synchronized backfilling.

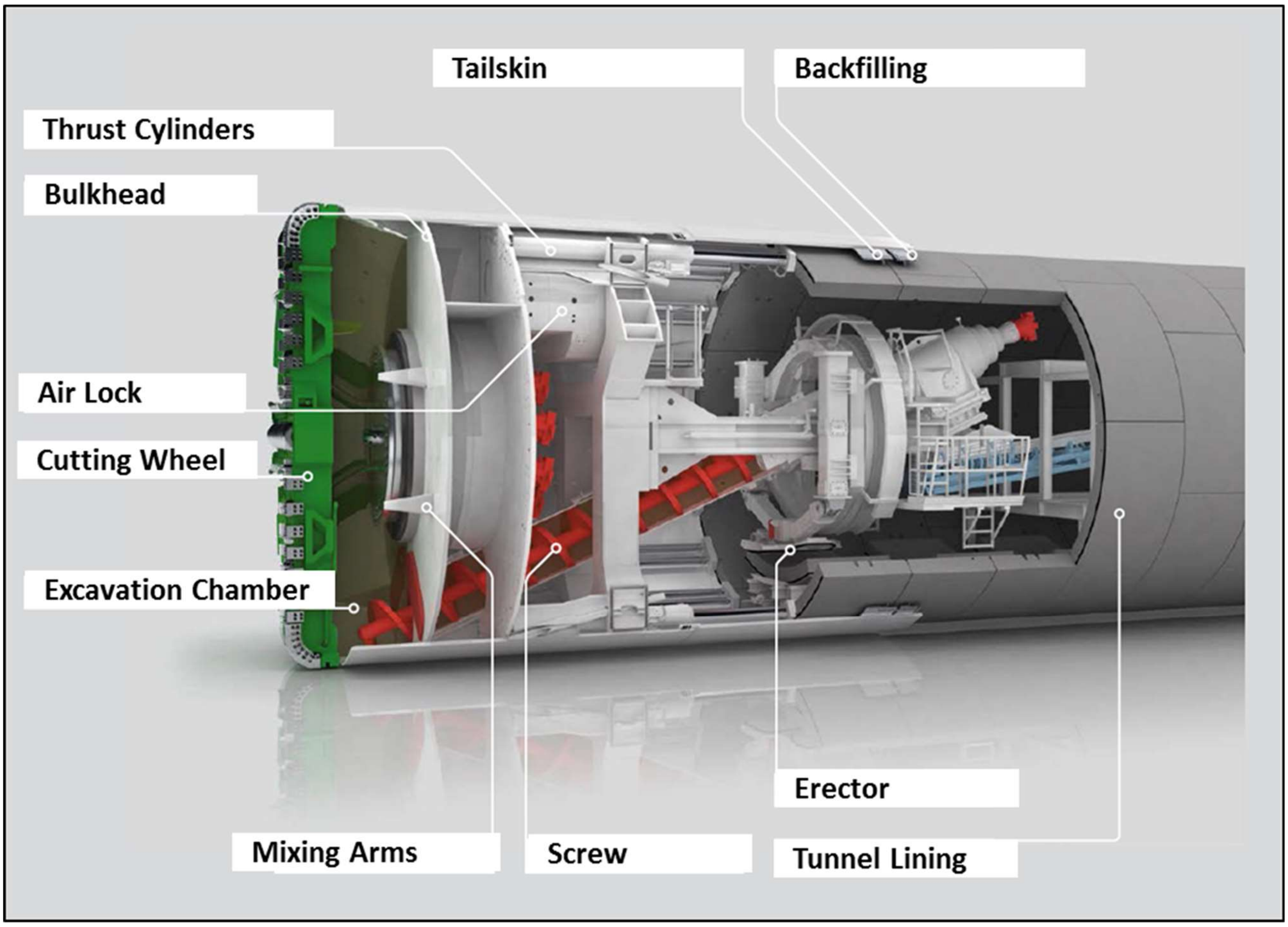


Figure 4-3: Schematic structure of an EPB TBM (Herrenknecht AG, 2015)

4.1.2 Ringbuilding

Tunnels which are driven by TBM either have a segmental lining, built from precast concrete segments or a lining consisting of anchors, ring beams and shotcrete in case of Gripper TBMs. In hard rock projects, the lining is usually built only when the geological conditions actually require stabilization. Therefore, it is a less cyclical process especially because it is depending more on actual rock conditions than on organizational aspects. This thesis focuses on TBMs with segmental lining. The segments are assembled one by one using the erector, a manipulator arm with 6 degrees of freedom that can pick them up and position them correctly at the tunnel circumference. A segment feeder is handing them over from behind the machine to the erector. The lining segments are produced from reinforced precast concrete. Figure 4-4 shows an example from the EOLE tunnel in Paris. Assembly features such as threads, nuts or sealing grooves are cast directly when molding to ensure a high degree of standardization and ease the assembly. The segments are shaped asymmetrically to allow the negotiation of curves. In terms of distinct processes, the ringbuilding is characterized by the erection of the segments, the manual work necessary to connect and fix them, as well as the delivery process on the segment feeder (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011). These processes can only take place on time if a powerful logistic supply chain is supplying everything in the right order at the right time.

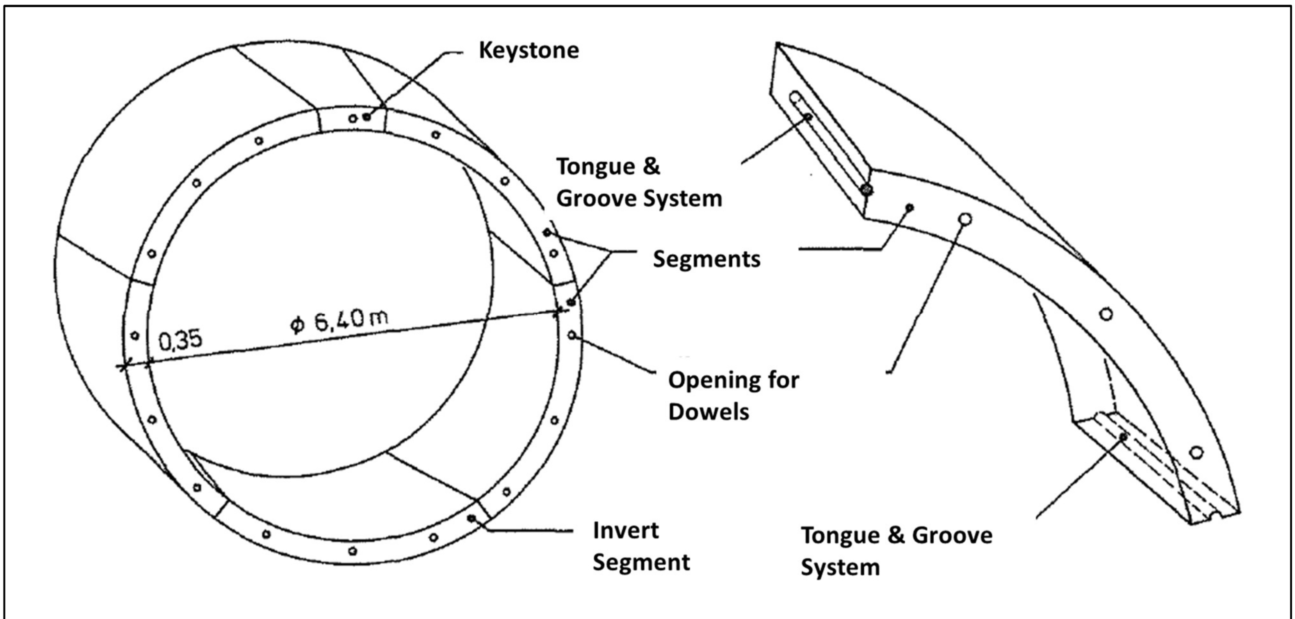


Figure 4-4: Tunnel segments with assembly elements (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011)

4.2 Support Processes of the Supply Chain

During advance, the TBM must not only be supplied with construction material and consumption materials, the excavated material and other waste must be removed from the tunnel as well. Both add up to a considerable amount of material that has to be handled. The logistic supply chain is responsible to guarantee availability of all required materials. Table 4-1 gives an overview of these materials.

Table 4-1: Building material and consumables to be transported

Material	Description
Muck	The excavated material can be solid or liquid. Depending on the consistency, there are various transport options.
Lining Material	Most TBM tunnels are lined with precast concrete segments. But in hardrock tunnels there are also anchors, steel beams, nets and shotcrete used.
Backfilling Material	The circular gap between segments and geology is filled with single- or two component grout or with pea gravel.
Invert Construction	Especially in larger tunnels the invert is built from precast segments, cast in situ or a mix of both methods.
Grease Barrels	Different types of grease are used for lubrication and greasing purposes and are delivered in barrels.
Additives / Conditioning Agents	Mainly in EPBs the soil is conditioned by using foam, polymers, or bentonite. The material are delivered in barrels, tanks and containers.
Rails and Sleepers	When using trains, rails and sleepers are laid in the invert.
Ventilation Hose	The ventilation hose comes in cassettes which are replaced regularly
Pipes	Pipes for Bentonite, Water, Wastewater or Grout must be laid in the tunnel.
Electricity Cables	The TBMs high voltage cables and communication lines are laid in the tunnel and come on a reel or in a tray
Belt Conveyor Structure	In case a tunnel belt is used, its substructure must be extended regularly
Feed and Slurry Lines	On Slurry shields the feed and discharge lines must be extended regularly
Others	Spare Parts, Wear Parts, Tools and Personnel come in different transport batches and methods

4.2.1 Processes within the Backup System

All TBMs are equipped with a backup system consisting of several gantries on wheels that are housing all the equipment that is necessary to operate the machine. This includes electrics, hydraulics, ventilation, greasing, control systems and logistic equipment. Especially the logistic equipment must be well coordinated to ensure the efficient delivery of all material. Depending on the TBM diameter, the general layout of the backup systems can differ significantly. While metro sized TBMs often feature rather similar designs, especially large diameter TBMs show a great variety in terms of logistic structure. There are open type backups and closed type backups. There are those with a large bridge where the invert is constructed in the machine area and some, where the invert is built behind the machine. Some feature just very straightforward logistic systems, some rather elaborate ones with many interconnected elements such as cranes, moving tables and shuttles that might interfere with each other. Especially larger machines require heavy-duty support systems for the backup gantries. Some run on special invert slabs that distribute the weight onto the tunnel and are built in the erector area. After the TBM has passed, they are disassembled and brought back to the front to be reassembled. One of the main design criteria besides the diameter is the link to the chosen tunnel transport system. The backup system must be matching the transport systems to accommodate, load and unload the selected transport vehicles and systems for the tunnel. This also includes the pipe and cable extensions, which must be performed regularly to keep the machine connected to its supply lines. Figure 4-5 shows the backup system of an EPB TBM for a Singaporean metro project including the following elements:

1) Bridge
2) Belt Conveyor
3) Grout Tank
4) Tenside Tank
5) Hydraulic Station
6) Electric Cabinets
7) Transformer
8) Cable Drum
9) Hose Garland
10) Segment Feeder
11) Quick Unloading Station
12) Control Cabin
13) Grease Station
14) Bentonite Tank
15) Compressed Air System
16) Ventilation Cassette

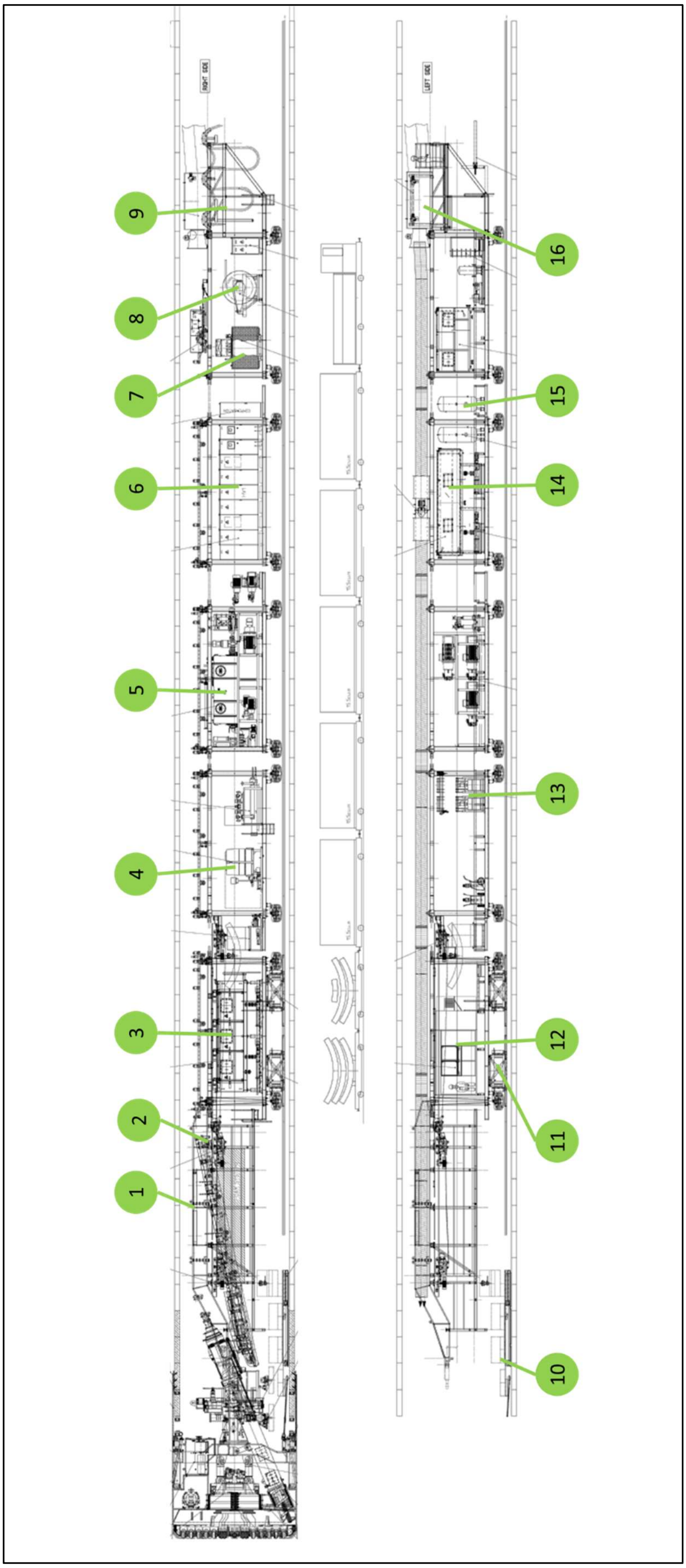


Figure 4-5: Backup system of an EPB TBM (Herrenknecht AG, 2015)

Of the processes within this system the most prominent one is the segment transfer which delivers segments from the transport system used in the tunnel to the erector where the tunnel is built. This is typically done by one or several cranes, a segment feeder and in some cases moving platforms or turntables. Of course the material which has been excavated must be removed. Within the backup, there are usually belt conveyors or pipes which continuously allow muck transfer to the tunnel transport system.

The ring gap, which remains between segments and geology must be backfilled with grout. The grout must be stored in tanks. Either the complete full tank is brought to the TBM and brought back to the surface for a refill when used up, or a transfer pump transfers the grout from a train or truck to the backup. In some cases, the grout is pumped to the TBM through a pipe directly from the surface. In EPB machines, a soil conditioning system is ensuring proper plasticity and mechanical properties of the soil. This is done by producing and injecting foam, polymer and bentonite into the soil. On the backup system there are tanks, mixing systems and pumps to facilitate this. The related consumables are delivered in barrels and containers and mixed with water and air in situ. In the back of the last backup trailer there is an area where the supply pipes are built into the tunnel and continuously extended. Also the tunnel belt, electric lines and ventilation pipes are extended here.

Barrels with grease for the tailskin sealing as well as the maindrive sealing must be unloaded and connected to the related barrel pumps. All these processes must be coordinated in such a way that they don’t hinder each other in terms of space or personnel requirements. In order to provide an overview of all the goods that have to be handled, the following section lists them.

4.3 Surface, Shaft and Tunnel Logistics

Within the jobsite, all storage, handling and transport processes must be assigned and coordinated. The material flow planning consists firstly of reserving areas for storage, assembly, traffic and other mechanical and civil works as well as managing the correlating capacities. All the transport routes and the material handling equipment must be planned subsequently. Especially in the shaft and tunnel, the transport capacity must be planned carefully as special constraints easily lead to bottlenecks.

4.3.1 Storage and Work Areas

A large number of different storage and work areas are necessary on site. This ranges from segment storage, general storage and workshop areas to grout batching plants and the muck pits. The two main aims of site storage are controlling the number of items necessary for construction and acting as a buffer against delays and uncertainty. For general purposes such as assembly operations, repairs, spare parts and general material storage there is a certain amount of space necessary. To negotiate curves, there are differently shaped segment types necessary. The storage area for segments must either be large enough to keep different segment types in sufficient numbers in stock or there is a larger segment storage site near the production facilities and the jobsite holds only a small buffer storage. The segments are usually supplied to the TBM in stacks already reflecting their assembly order. If not, the order must be shuffled in the tunnel before placing them onto the segment feeder which costs extra time. Usually the muck pit is located next to the shaft. It must be large enough to act as a buffer in case the disposal is delayed. In case waste water treatment is done on site, there might be space for a basin necessary.

The required storage areas for grout, foam, polymer, grease and oil depend mainly on the machine type and size. Usually these goods come in containers or barrels. If tunneling is done under pressurized conditions, compressed air equipment is necessary as well. This can range from a compressor station to complex systems such as saturation diving plants. All storage areas should be planned in accordance with the crane range to allow easy loading, unloading and material movement.

Figure 4-6: Access shaft that allows only one single lifting process at a time

4.3.2 Transport on site

Forklifts, excavators, trucks and cranes are used to move material around on site. One of the main goals while planning the layout is avoiding too much interference between the different transports. So trucks should not need to turn, key transport roads should not be blocked by other processes or civil works. For cranes, it is important that they do not block each other. If several cranes are operating in the same area, they have a high risk of blocking each other with reduces their capacity and complicates planning and communications. It is also important to make sure that transport batches are sufficiently sized so that the number of necessary crane cycles is not increased by smaller goods. The design and coordination of lifting processes often creates bottlenecks on site. Figure 4-6 shows a shaft which allows only a single lifting process at a time. In such a situation segment delivery and mucking cannot be performed concurrently.

4.3.2.1 Cranes

Cranes are an integral part of every TBM jobsite logistic system. They perform lifting, loading and assembly operations. Especially when several TBMs are launched from one shaft, they may become a bottleneck. Cranes can be classified according to several criteria. According to (Girmscheid, 2008) following types can be differentiated:

- Gantry cranes consist of a bridge that rests on two lateral support structures. These can move along a predefined track on parallel tracks. A hoist trolley on the bridge performs the lifting operations. On TBM jobsites gantry cranes are often used for mucking.
- Tower cranes are one of the most common crane types in construction. A load carrying jib and counter jib are resting on a central mast that can rotate. There are different kinematics depending on the detailed design. Generally, all tower cranes service rather large, circular areas.
- Mobile Cranes are often the method of choice due to their high degree of flexibility. TBM assembly, segment delivery and various loading operations are often done by mobile crane. Also they can be rented by a contractor for shorter periods of time if additional lifting capacity is necessary.

4.3.2.2 Vertical Conveyors

In order to allow continuous material transport in vertical sections, sidewall belt conveyors can be used. Their design allows an S-shaped arrangement with horizontal feeding and discharge positions and a vertical transport stretch. As soon as the material is on the belt, the walls on the side and the horizontal steps on the belt keep it in place. Because of the increased loads on the belt, its components must be made from high strength materials with steel wires and high performance textiles embedded into a special rubber matrix. While the investment for such installations is rather high, they can help separating different material flows and greatly improve possible productivity. In cohesive ground though, the pockets of vertical conveyors bear the risk of clogging though.

4.3.3 Transport in the Tunnel

The interface between surface logistics and tunnel logistics is usually located at the bottom of the shaft. Normally there are areas for temporary storage of smaller goods at the shaft floor. The logistic operations can be separated into the transport of muck and deliveries of construction material and consumables to the TBM. According to (Girmscheid, 2008) there are several distinct systems for mucking:

- Continuous transport systems (belt conveyors, slurry lines)
- Rail bound transport systems (train, conveyor train, etc.)
- Rail free transport with MSVs, dumpers and trucks

All of them have advantages and disadvantages and are more or less prevailing with different TBM types or applications. Continuous transport systems reduce traffic and ease logistic planning. Vehicles which are going back and forth into the tunnel usually require a way to pass each other. Switches and parallel tracks –so called “californias”- allow trains to pass each other. They are placed in regular distances within the tunnel. If trucks are used for mucking and delivery; there are sections where the road in the tunnel is widened in order to allow the trucks to pass each other.

Which type of transport system is effectively used, depends not only on technical considerations but in many cases also on the available equipment stock of the contractors. While rail bound transport requires more infrastructure for sleepers, rails etc. The cost of locomotives and rolling stock is lower than for MSVs let alone the cost for tunnel belt systems or liquid pumping transport systems.

4.3.3.1 Tunnel Belt Conveyors

Tunnel belts are used for continuous disposal of muck from the TBM to the surface. Today generally, extendable belt conveyors are utilized. The advantages of tunnel belts include low dust development, continuously high transport capacity, low maintenance and operation intensity as well as decoupling of inbound and outbound material flows. An extendable tunnel belt consists of the return roller on the TBM backup, the substructure at the tunnel wall, a belt extension system at the portal as well as the belt itself that is typically made from steel reinforced neoprene. While the TBM is advancing, every few meters a new piece of belt substructure is installed underneath the belt. The belt extension system which continuously allows the belt to be extended and follow the movement of the TBM is located in in the shaft or launching cavern. Such a system is shown in Figure 4-7. It consists of the machine belt (1) and the return roller (2) on the TBM side. The belt (6) covers the tunnel distance. On the shaft side there are the belt storage (4), the drive (3) and the belt discharge. (5). Once the capacity of the belt extension storage is reached, The TBM must be stopped and a new section of belt conveyor is added. Typical belt storages can accommodate up to 600m so time consuming extensions are only necessary in longer intervals. Tunnel belts help decoupling mucking out from vehicle traffic in the tunnel. Usually this leads to considerably higher performance potentials. Especially for longer tunnels, the additional cost for tunnel belts can quickly be compensated by higher performances.

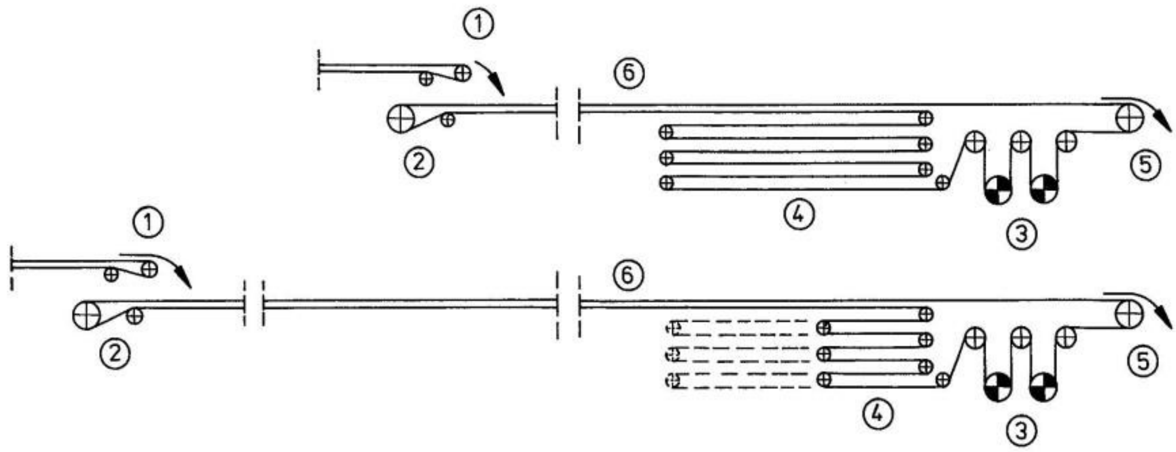


Figure 4-7: Tunnel belt extension system (Maidl, Schmid, Ritz, & Herrenknecht, 2008)

4.3.3.2 Rail Bound Vehicles

Globally, rail bound vehicles are the most commonly found transport methods in tunnel jobsites as they are cheap and simple. They are either propelled by diesel engines or battery powered electric motors. Due to the cheap operating cost and high robustness and reliability of diesel engines, batteries and electric motors are found seldom today and only used in environments where emissions should be avoided. Muck cars in their simplest form are built by just placing a container on a chassis with wheels. More sophisticated solutions can accommodate hydraulics for independent emptying or internal belts which allow distributing the loaded material without moving the train along the discharge point. Muck cars accommodate typically a volume of 5 to 20m³, depending on tunnel size and crane capacity. Ideally, one train can load the muck volume of a full excavation stroke. Otherwise, several trains are loaded intermittingly; although this usually leads to severe losses in performance. There are two ways to load the trains in the gantry area. Either the train slowly passes under the conveyor belts discharge point or a movable loading belt distributes the muck on the train. As trains run on fixed rails, it is necessary to build sleepers and rails in the tunnel invert as well as providing switches for the trains to pass each other. Traffic is generally restricted by the narrow space in tunnels. In larger tunnels, two parallel tracks might be constructed. One for inbound and one for outbound traffic. The coordination of the trains is also an important issue. For large projects such as the Channel Tunnel or the Gotthard Base Tunnel, there were large railway networks with centrally controlled signaling systems installed. “In the Channel Tunnel, the entire transport system failed to achieve the necessary performance while operating under sight rules, and this slowed the advance rates down. Not until the operation was changed over to a railway system with signals was the necessary performance achieved” (Maidl, Schmid, Ritz, & Herrenknecht, 2008). Table 4-2 provides an overview of advantages and disadvantages of rail bound logistics in the tunnel.

Table 4-2: Advantages and disadvantages of rail bound tunnel logistics

Advantages	**Disadvantages**
• Relatively low energy consumption per transport capacity	• Rails are bound to fixed routes
• Relatively high capacity per train	• Low gradients possible
• Low personnel requirements	• Tracks might hinder other works on site
• Low risk of damage to the tunnel structure	• High cost for rails and sleepers
• Low exhaust gas emissions	• Low flexibility regarding transport route

4.3.3.3 Tire bound vehicles

Tire bound vehicles are very attractive because of their flexibility. They also allow transporting goods in steep tunnels as trains are limited to gradients of little more than 3% while trucks can be used up to 7% incline. Roughly, 7-8m road width is necessary for regular trucks to pass each other and a bit less for special tunnel vehicles. These multi service vehicles (MSV) are custom built for application in mechanized tunneling. They fulfill specialized roles such as segment delivery, grout transport, personnel transport or as a flat car. Often tire wheeled trucks also allow higher speeds than trains unless the rails are installed with very high quality. On some larger TBMs where mucking is done by trucks, rotating tables are available to turn the trucks around at the TBM. The most common scenario of MSV usage is segment delivery by truck and mucking by belt or slurry circuit.

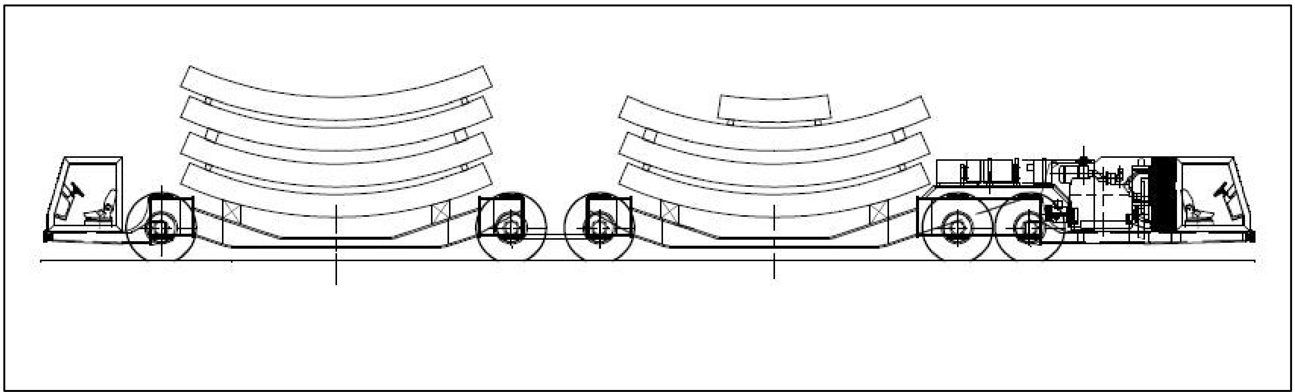


Figure 4-8: MSV for bidirectional driving, (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2011)

The question if tire bound transport is economically feasible depends a lot on the road conditions in the tunnel. If the material in the invert tends to become muddy and there is a lot of road maintenance work to be expected, rails might be the more economic choice. In addition, the tunnel diameter and the vehicles possibility to pass each other has a strong economic impact. An aspect which makes the use of MSVs very attractive especially on larger projects is that the complex rail networks and terminals become obsolete which saves cost and adds a great level of flexibility.

4.4 External Logistics

The first prerequisite for the smooth operation of any construction site is the sufficient supply and removal of material to and from the site. This means road access, railroad access or conveyors or pipes leading to a dumpsite. Especially for larger projects, the necessary number and frequency of trucks can easily reach hundreds per day. To sustain the design advance rate of a 15m EPB machine, there are almost a thousand trucks per day necessary. This amount of traffic must not just be accustomed but also coordinated. All kinds of possible external influences such as changing traffic conditions, production lead times, environmental regulations or weather influences must be considered when planning the sites access to external logistics. For the German Stuttgart21 project for example there has been a special access road built to the city center jobsite to minimize the traffic impact for the general public (Deutsche Bahn AG, 2016). For the disposal of wastewater there are strict guidelines regarding pollution which affect the necessary on site facilities for storage, cleaning and disposal. For the supply of material to the jobsite, the lead times of all articles must be considered. There different options how to facilitate the external logistics for a jobsite:

- **Road Access:** Most jobsites use trucks for external logistics. All goods are supplied to the jobsite and all waste and muck is disposed via the road. That means that traffic restrictions as well as traffic jam and weather conditions affect the deliveries. Also cleaning facilities for all trucks which enter public road are necessary to limit the pollution of public road. Sometimes special roads only for the construction logistics are leading from the jobsite to a public road access point further away. This can help lowering the traffic load in areas adjacent to the site.
- **Railway Connection:** Some jobsites have direct access to railway tracks. This allows using trains for supply and disposal. For large volumes especially for the muck on large jobsite this can be a very good system. But due to the large cost for building railway tracks it is rather rare to see and only recommendable for megaprojects like the Gotthard or the Channel Tunnel or if railway access is given anyway. On the other hand, in some railway tunnels, the project owners prescribe railway as the preferred supply system in the project tender.
- **Conveyors:** On some large jobsites conveyor belts are not only used in the tunnel but also to transport the material away from the jobsite to a disposal site. This allows reducing traffic and also the need for vehicles significantly which again improves safety and can help lowering cost.
- **Connection to the Grid:** Water and electricity are supplied by cables and pipes to the jobsite. Water is necessary to produce concrete, bentonite, foam, for cleaning and other purposes. Depending on the quality of local utilities, either the supply can be guaranteed directly from the water mains or if the necessary amount of water exceeds the mains capacity, supply from nearby open waters or wells is necessary. In most cases wastewater is led into the regular sewer system. If this is not available, cleaning facilities must be provided on site before water can be led into any rivers. Electricity is the main source of energy for TBM construction sites. Therefore, connection to sufficiently large public grid is necessary. This is usually 10kV or 20kV. Transformers and distribution stations are necessary.

4.5 Planned and Unplanned Support Processes

Planned support processes include all maintenance processes that are necessary to uphold a high operational availability of the TBM. Additionally unplanned support processes, namely repairs have to be executed. They take place as a reaction to equipment failures. The following sections give an introduction to the disturbances in the tunneling system as well as to maintenance and repair operations.

4.5.1 Disturbances

According to (Rahm, Scheffer, Duhme, Koenig, & Thewes, 2016), disturbances can be classified into different types. Production disturbances are those, which directly affect the main elements of the TBM that are associate with advance and ringbuilding. They include downtime in the erector as well as in elements such as the hydraulic system, maindrive or grouting system that must be in working order to perform advance or ringbuilding. These disturbances directly interrupt the production of the TBM and lead to downtime until repaired. Another class of disturbances are supply chain problems. In case the supply chain is not able to deliver or remove material fast enough from the TBM, the production cycle is interrupted. This disruption can either originate in equipment failures such as a crane breakdown, or in process interactions. If a crane cannot deliver segments to the train because the access to the shaft is blocked by another crane performing lifting operations, such a disruption arises. In some cases these disruptions affect the production process. In other cases they may not lie on the critical path and do not affect the production cycle. A third class of disruptions are cascading disturbances. If downtime in one process triggers subsequent downtime in another process, a cascading effect occurs. An example for such an event could be a problem tn the TBMs hydraulic system during advance. Although by the time the problem is fixed, advance could theoretically resume, grout in the TBMs tanks could have hardened in the meantime and must be replaced, before advance can recommence. Such cascading effects cannot be explicitly modeled, but arise from the logical order of other processes. A detailed review of the influence of disturbances on tunneling systems is presented in (Rahm, 2017).

4.5.2 Maintenance and Repairs

Like any other technical system, TBMs need regular maintenance and repairs. The most prominent example is changing the cutter tools. The excavation tools are subject to wear and must be checked and replaced regularly. How often depends strongly on ground conditions and the operation of the machine. The Colorado school of mines model is a possible method to estimate the frequency (Rostami J. , 2015). If the tools are severely worn out or damaged, changes might require more additional work. One of the most influential factors for the duration of such changing work is the machines operating pressure. If the excavation chamber is pressurized, diving techniques must be used to allow people entering and working in the chamber. Pressurized air diving can be used up to 4 bars, up to 8 bars mixed gas diving can be done and for higher pressures saturation diving is necessary (Herrenknecht & Bäppler, 2007). Depending on the pressure this will substantially slow down the work process. If maintenance is neglected, repairs become necessary more often and especially more severe damages often lead to exponentially growing work for repairs. This is not only valid for tools but also for the whole range of equipment on a TBM. All the components need regular maintenance on a ring, daily, weekly or monthly basis. How often exactly and which operations must be performed is subject to the maintenance handbook. This handbook is usually transcribed into checklists which contain all the maintenance operations to be performed each shift, daily, weekly or monthly. This regularity means that maintenance is to be included into the processes defining productivity. In addition to planned maintenance processes, repairs must be performed in response to equipment failures. While failures are statistically characterized by the mean time between failure (MTBF), the related repairs are characterized by the mean time to repair (MTTR). Since statistical data on component level is not available for MTBF and MTTR, re related downtime is addressed in this thesis by referring to global average values.

5 Acquisition and Evaluation of Reference Data

A strong foundation of suitable reference data marks the cornerstone of successful planning. Especially in simulation studies the right data has to be used in the right way to foster sound results. Therefore, one of the key objectives in this thesis is obtaining actual activity durations. For mechanized tunneling planning there are several key areas which must be contained in reference data:

- Performance parameter of the technical systems on site
- Process durations for jobsite activities
- Probability distributions for the available data
- Soft performance factors such as worker productivity

The key challenge lies in extracting the performance defining factors and their dependencies from the available data. Activity durations are on one hand subject to the type and build of the actual equipment and on the other hand depending on many variable factors such as process interactions and local conditions. Especially these are regularly ignored or underestimated during planning. The acquisition process and data structure must take these factors into account when measuring as they are hard to estimate analyticly .

5.1 Data Sources in General

Data acquisition is a seemingly simple, yet practically difficult task. In construction management it is known as work study or time study and there are typical methods and procedures which can be followed. Generally, the following data acquisition methods are possible:

- Video / audio recordings
- Jobsite personnel interviews
- Automatic sensor recordings
- Manual stopwatch recordings
- Activity duration databases
- Specification sheets

Which of these sources can be used depends on the amount of available time, jobsite conditions and data quality as well as on the available equipment and sensors. TBMs are typically equipped with hundreds of sensors for temperatures, pressures, motor speeds and other operational states. However, the logistic components such as cranes and vehicles are not monitored automatically in today’s TBMs. Therefore, other sources such as datasheets, estimations or direct measurements have to be conducted. As the following sections explain, each data source bears different advantages and disadvantages.

5.1.1 Historical Records

Many TBM jobsites share a similar structure. Therefore, it is likely that in a planning organization some form of historical records on productivity exist. Because they are already available and do not require additional data collection, using them may be attractive to practitioners and organizations. However, using historical information bears the risk of ignoring relevant differences between the historical system and the one to be planned. This can create false implications for the planning process. Therefore, it is always necessary to thoroughly analyze the source of such records. As typically data is stored in a condensed format due to reasons connected to volume and understandability, the processes of data condensation and interpretation must be clear to understand possible biases. With regards to mechanized tunneling, these historical records are mainly the daily and weekly performances of past projects as well as the corresponding equipment which has been used. Furthermore, all data generated by the possible sources listed in the following sections can be counted as historical records if originating in past projects.

5.1.2 TBM Machine Data

TBMs are usually equipped with data acquisition systems. These generate valuable data for the analysis of their operation. However most of the data is related to pressures, temperatures, motor speeds and similar parameters. These reveal relatively little about the logistical performance of a TBM. However, the key data which is usually recorded is the state of the TBM which can be separated into advancing, ring building or stop. One has to keep in mind that the transition from one operating state to another is not clearly defined and therefore different operators have different ways of switching between them. Nonetheless these values can be used as a basis for planning. They define the performance requirement for the complete logistic system.

5.1.3 Shift Reports

Almost all construction managers have their shift engineers prepare shift reports. These keep track of the main events during the shift. For TBM tunneling a number of similar standard report formats have evolved, capturing more or less detailed information. On most jobsites the shift reports are filled on paper by the TBM operator or tunnel manager to be then filed and forgotten. However, the emergence of online data management systems for TBM tunneling has led to a number of standardized electronic systems. They allow the user to choose predefined events and mark their duration in a timeline. Typically, possible errors are classified by numbers. These error-codes allow classifying downtime faster than manually writing them. Downtime evaluation is easier as well when standardized error classes are applied. The result is an electronic Gantt chart which allows the analysis of downtime and productivity. An example for such a data management system is shown in Figure 5-1. Each line corresponds to a specific error code. This data is still subjective as it is created manually. However, generally the data quality and integrity is much better than with paper based reporting. The data is questionable though as input data for planning processes or simulation studies because it shows the processes only from the TBM operator's point of view. Therefore, in many cases it does not allow identifying the cause for delays. The reports would just state the type of delay, for example "Segments Missing". This information can be used to validate simulation studies though.

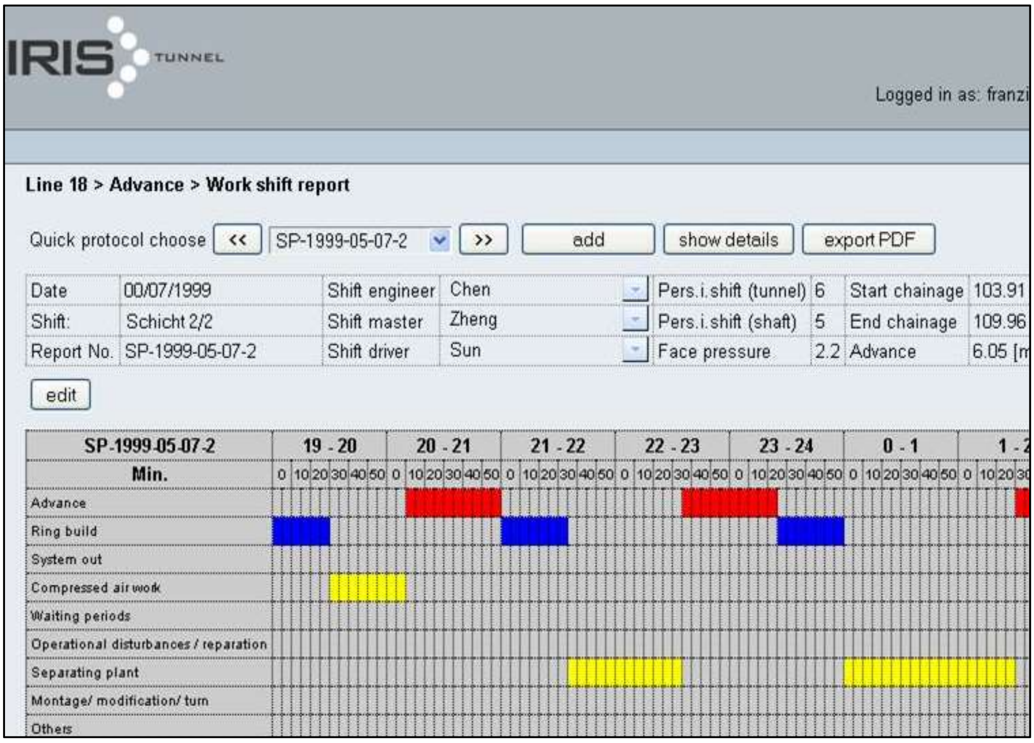


Figure 5-1: Excerpt of TBM shift report from the IRIS data management system (ITC Company Brochure, 2015)

5.1.4 Personnel Interviews

Staff on site has a broad knowledge on construction processes. Tunnel managers, equipment operators and supervisors can be a valuable source when time or data collection resources are not available. For process durations, operators could be questioned for example about the shortest, typical and longest duration of a process. These values could be used later to form triangular distributions or different scenarios. When conducting interviews, it is necessary to focus on retrieving unbiased answers. Also not every interviewee might have the whole picture in mind and will therefore answer only from his personal point of view.

5.1.5 Technical Datasheets

Manufacturer specifications offer the opportunity to use data which has been compiled by someone else. Most manufacturers provide theoretical performance data based on idealized operating conditions. Whether or not these claims can actually be achieved in a realistic operating environment is in many cases rather unsure. Therefore, technical datasheets can be used as a first reference, but should be seen rather critically. When comparing relative performance instead of absolute values, they rather give a useful guideline.

5.1.6 Manual Time Recordings

The most resource intensive form of data collection is direct observation. It requires spending considerable time on site and using a stopwatch, pen and paper to gather timings. Preparing dedicated forms can greatly increase practicability. As TBM tunneling sites are geographically too large to oversee them from one position, it is necessary to perform measurements from many different locations to be able to gain complete insights into the inner workings of its logistic network. This reduces the practical efficiency of manual time recordings. It also makes it impossible in many cases to measure two ends of the same process as both cannot be kept in sight from the same observation point. Therefore, individual datasets may be incomplete and could only reveal a picture when analyzed as a larger group of datasets. Nonetheless they are the only option to gather realistic data on most tunnel jobsites as no automatic systems for logistic process data acquisition are available.

5.1.7 Time-lapse Cameras

Camera observations are a form of manual time recordings. Especially time lapse cameras allow long term observations beyond human possibilities. They can be placed in strategic locations which allow viewing several processes in one angle. Since the resulting video can be viewed an infinite number of times, all captured processes can be observed and evaluated. Although capturing data on camera is a seemingly easy and straight forward process, the actual evaluation of the footage and determination of process durations requires significant manpower. Therefore, developments have been made to automate the analysis of video footage by programming recognition algorithms which can for example detect when a crane is handling segments.

5.2 Compilation of Reference Data

Over the course of the SFB-C3 research project, high importance was placed on the acquisition of a solid foundation of reference data. Observations, measurements and interviews have been conducted on a large number of tunneling jobsites. The jobsites include many metro projects, but also large diameter traffic tunnels. They lie in Europe, East Asia and the Middle East. As the data acquisition campaigns have been conducted by different people over the course of several years, correct normalization and structuring of the data plays an important role. The following sections introduce the available data material and discuss its properties as well as its shortcomings.

5.2.1 Available Datasets

Reference data has been collected on site, in literature and from interviewing construction managers to support viable performance estimates for the logistic systems on TBM jobsites. Manual and automated measurements have been performed on a total of 16 TBMs and the related jobsites in Germany, Netherlands, China, Singapore, Qatar and Spain over the course of 6 years. The measurements have used different data acquisition methods and covered different levels of detail and different focuses. While some measurement campaigns focused mainly on the internal processes in TBM and backup system, others have covered the processes on the jobsite surface and shaft. Table 5-1 presents an overview of the collected data. The actual data contains more detailed structure as will be discussed in the following sections. In total, the data structure corresponds with the identified processes in chapter 4. Due to the observation methods used, stationary processes such as the operation of cranes and TBM equipment are characterized by a higher number of individual datasets whereas mobile processes such as the movement of trains and trucks have been measured less often since the technical effort to monitor those increases with the movement length. As can be seen, the total number of datasets reaches from a mere dozen for the coupling and decoupling of vehicles to many hundreds for crane operations.

Table 5-1: Overview of available reference data sets

Vehicles	Surface Crane	Backup Crane	Erector	(Semi-)manual
driving 76	lift/lower 665	lift/lower 878	lift/lower 234	Unloading 26
maneuver 39	move 830	move 977	move 548	Installation 30
couple 14	hook/unhook 608	positioning and hook/unhook 689	hook/unhook 518	Loading 24
	positioning 142		positioning 566	

The observed projects cover different TBM types, diameters and logistic setups. They had to be anonymized by assigning letters to their project names. Table 5-2 gives an overview of the observed projects. The majority of TBMs which have been analyzed are used to construct metro lines and therefore lie in a diameter range between 6 and 7 meters. Few of the observed projects are excavated with large diameter machines. The number of similar project conditions allows drawing parallels between the projects and grouping comparable processes together for analysis. This is an important prerequisite to compare data of individual projects with each other and perform stochastic analysis across several projects. A detailed analysis of the technical differences between the logistic systems as well as inclusion of the surface processes will be performed in the following sections. On top of the data presented in Table 5-2, there are interview results as well as evaluated data from a large number of TBMs which has been made available by Herrenknecht AG.

Table 5-2: Comparison of data source TBMs

Project	Type	Dia.	Ring	Country	TBM Logistics	Quick Unloading	Segment Crane
A	Slurry	6.8	6+1	Germany	MSV	No	Direct
B	EPB	11.2	6+1	Germany	MSV/Belt	No	3 stage
C	EPB	9.2	6+1	Spain	2xTrain	Yes	3 stage
D	Slurry	6.8	7+1	Netherlands	Train	Yes	Direct
E	EPB	9.4	6+1	Spain	2xTrain/Belt	No	Direct
F	EPB	9.4	6+1	Spain	2xTrain	Yes	2 stage
G	EPB	6.6	7+1	China	MSV/Slurry	No	3 stage
H	3xEPB	6.6	5+1	Singapore	Train	No	Direct
I	4xEPB	6.6	5+1	Singapore	Train	No	Direct
J	EPB	7.1	5+1	Qatar	MSV/Belt	Yes	Direct
K	EPB	7.1	5+1	Qatar	Train	Yes	Direct

5.2.2 Data Consolidation

As the analyzed data originates from a multitude of different sources it is necessary to standardize data structure and format as well as the level of process atomization. The main goal of this step is creating comparability between different data sources. Processes have been atomized into their individual steps and each one’s duration has been measured separately. This allows using the individual durations as building blocks to estimate the theoretical durations of virtually any process chain which can be made up by combining them. Due to the different origin of the available data, this differentiation of sub processes has been done in different ways. Therefore, the measurements of durations from different projects are not directly comparable. A spreadsheet database has been created containing all available datasets from different TBMs and their jobsites. In a first step the process duration data has been distributed into four distinct sections representing different areas of the jobsite. These sections are surface cranes, cranes inside the backup gantries, segment transfer and vehicles. For each of these types, the data of all processes has been plotted for each data source individually. This allowed analyzing if the data from different processes can be grouped together. An example for such a process is connecting and disconnecting rail cars or MSV trailers. While originating from separate processes, both behave in a similar way as can be seen in Figure 5-2. In such cases, datasets have been grouped together to widen their base in further analysis.

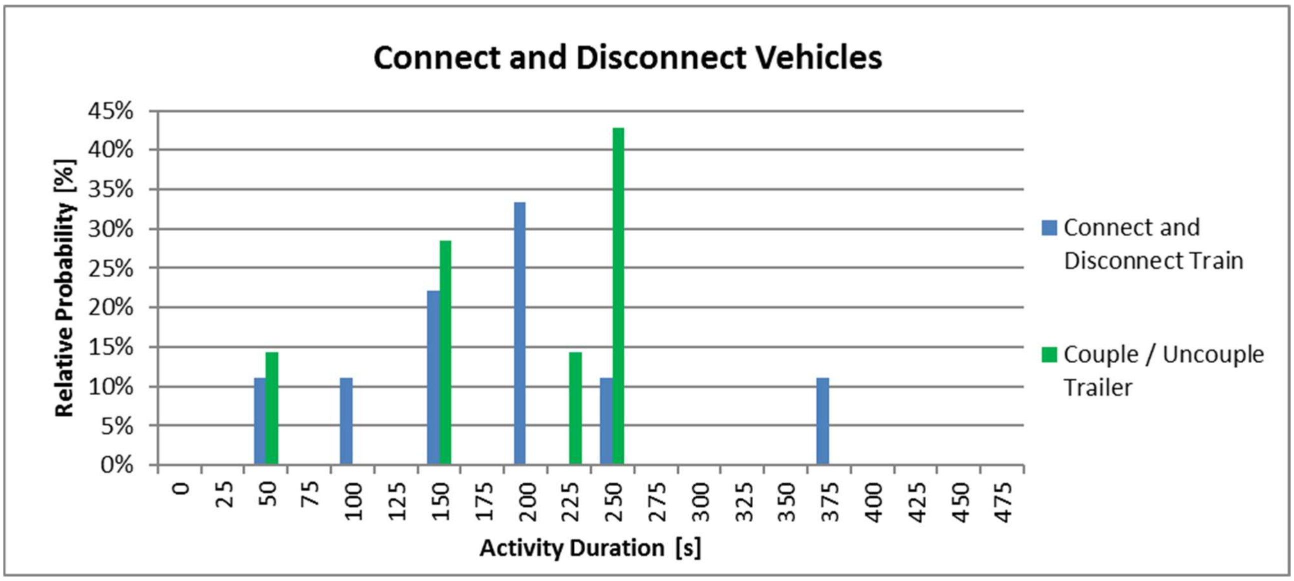


Figure 5-2: Duration of connecting and disconnecting different vehicle types.

For vehicles, driving durations, coupling and decoupling durations and maneuvering in the shaft have been singled out as the relevant process types. The surface cranes movement cycle has been separated into lifting, lowering and moving. As later analysis will show, geometry related durations are defining the cranes total operation cycle times to a much lesser extent than positioning and hooking or unhooking cargo. Nonetheless, transfer distances and angles are an important factor which is included in the measurements. In addition to these atomized process durations, measurements have been made for the whole cycle time of a mucking cycle using gantry cranes. The cranes within backup gantries have been grouped together and their process durations separated into horizontal movement, vertical movement as well as positioning and mounting / unmounting. The erector's processes can be categorized in a similar way. The process types moving, grabbing as well as positioning can be distinguished. On top of these structured datasets there are a number of datasets which do not fulfil the necessary criteria to be pooled with data from other projects. Either they comprise singular measurements or they consist of data comprising a whole chain of processes together which have not been separated into their individual components upon measuring. Examples for such is the duration for unloading a complete set of six segments from a train to the segment feeder or the duration for emptying a muck container which has been measured on only one jobsite individually. Datasets like these are not directly included into the analysis of durations but still support understanding the full picture of what happens on site.

The available collection of data contains incomplete datasets as well as data where measurement has been interrupted or stopped prematurely. This data has not been removed from the initial set of raw data as the reasons for such are not contained in parts of the available data. Therefore, data imperfections have been tolerated at this stage. That means that the data already contains some disruptions. A field which has not been covered in the available data is equipment availability. Literature, such as (Köppl, Thuro, & Thewes, 2015), (Köppl, 2014) and (Rostami J. , 1993) show data for wear processes such as cutter tool wear but no statistically reliable data on the failure rates of individual TBM components and jobsite equipment. Therefore, component availability is omitted from this study.

5.2.3 Statistical Analysis of Measurement Values

Individual activity durations follow stochastic distributions. This leads to a visible loss in overall performance with its severity depending on how much the durations vary (Weigl, 1993). Figure 5-5 provides a guideline that can be used to estimate this effect.

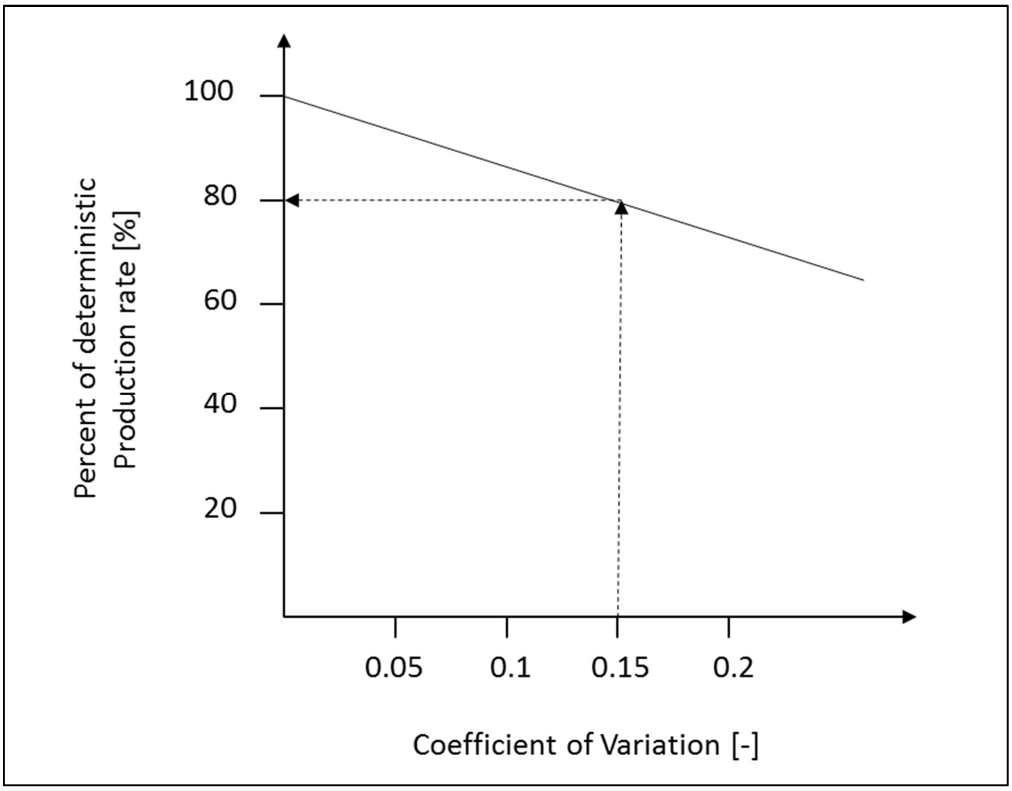
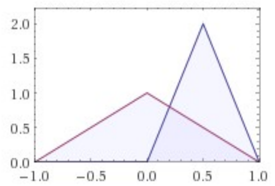
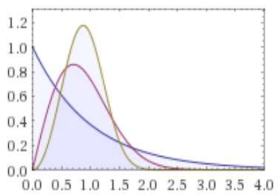
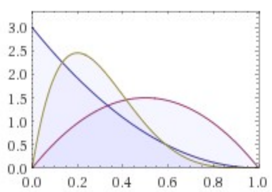
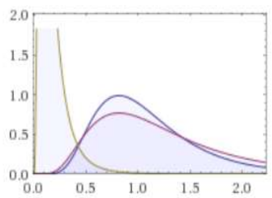
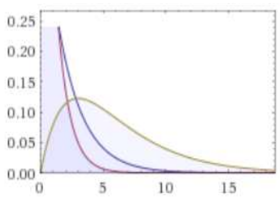


Figure 5-3: Overall performance loss caused by statistically distributed individual processes (Halpin & Woodhead, 1976)

If individual working steps vary by 15% in duration, the overall resulting performance may be lowered by a fifth. Therefore, it is not sufficient to determine the average durations of activities but it is necessary to also learn about their probability distributions and include them in the planning process. Table 5-3 presents the main probability distributions which are used in this work. Each of them is described by a number of characteristic parameters. The types of distribution and their parameters are determined in the data analysis.

Table 5-3: Properties of common probability distributions for TBM processes

	Distribution	Probability Density Function
Triangular		$f(x) = \begin{cases} \dfrac{2(x-min)}{(max-min)\left(\frac{max+min}{2}-min\right)} ; min \leq x \leq \dfrac{max+min}{2} \\ \dfrac{2(max+min)}{\left(\frac{1}{2}(-max-min)+max\right)(max-min)} ; \dfrac{max+min}{2} < x \leq max \end{cases}$
Weibull		$f(x) = \begin{cases} \dfrac{\alpha e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \left(\frac{x}{\beta}\right)^{\alpha-1}}{\beta} ; x > 0 \\ 0 \end{cases}$
Beta		$f(x) = \begin{cases} \dfrac{x^{\alpha-1} - (1-x)^{\beta-1} ; 0 < x < 1}{\int_0^1 t^{\alpha-1}(1-t)^{\beta-1}dt} \\ 0 \end{cases}$
Lognormal		$f(x) = \begin{cases} \dfrac{e^{-\frac{(\log(x)-\mu)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma x} ; x > 0 \\ 0 \end{cases}$
Gamma		$f(x) = \begin{cases} \dfrac{\beta^{-\alpha} x^{\alpha-1} e^{-\frac{x}{\beta}}}{\Gamma(\alpha)} ; x > 0 \\ 0 \end{cases}$

5.2.4 Constructing Artificial Distributions

If large data samples are available for the exact process to be simulated, the probability distribution parameters should be directly derived from the sample data. Not in all cases the underlying dataset is large or clear enough to draw conclusions from it with a high degree of certainty. The measure for this degree is the confidence interval. If a certain conclusion is drawn from a dataset, the confidence interval states, how certain this conclusion is for a specific margin of error (Adrian, 2004). The higher the desired confidence and the higher the samples variance, the more samples are necessary to reach a low confidence interval (Kreyszig, 1968). Since planning inherently projects past experiences onto future activities, it is necessary to learn about typical patterns and how to apply them to a new situation. Considerable research has been performed on the distribution of activity durations in construction (AbouRizk & Halpin, 1992), (AbouRizk, Halpin, & Wislon, 1994) (Xie, Fernando, & AbouRizk, 2001). After calculating skewness β_1 and kurtosis β_2 for a large number of data series from construction sites, the values can be displayed in a θ_1-θ_2 graph with:

$$\Theta_1 = \frac{\beta_1}{\beta_1+1} \quad \text{and} \quad \Theta_2 = \frac{1}{\beta_1} \qquad (14), (15)$$

This graph shows the possible combinations of skewness and kurtosis in different probability distributions. Flexible distributions cover lines, regions or even the complete plane. Such are the Beta distribution, the Pearson System or the Johnson System. Medium flexible distributions such as the lognormal or the exponential distribution are represented as lines. Inflexible ones such as the uniform and normal distribution are points. Subsequently the properties of the distributions of the site samples have been added. This diagram is shown in Figure 5-4.

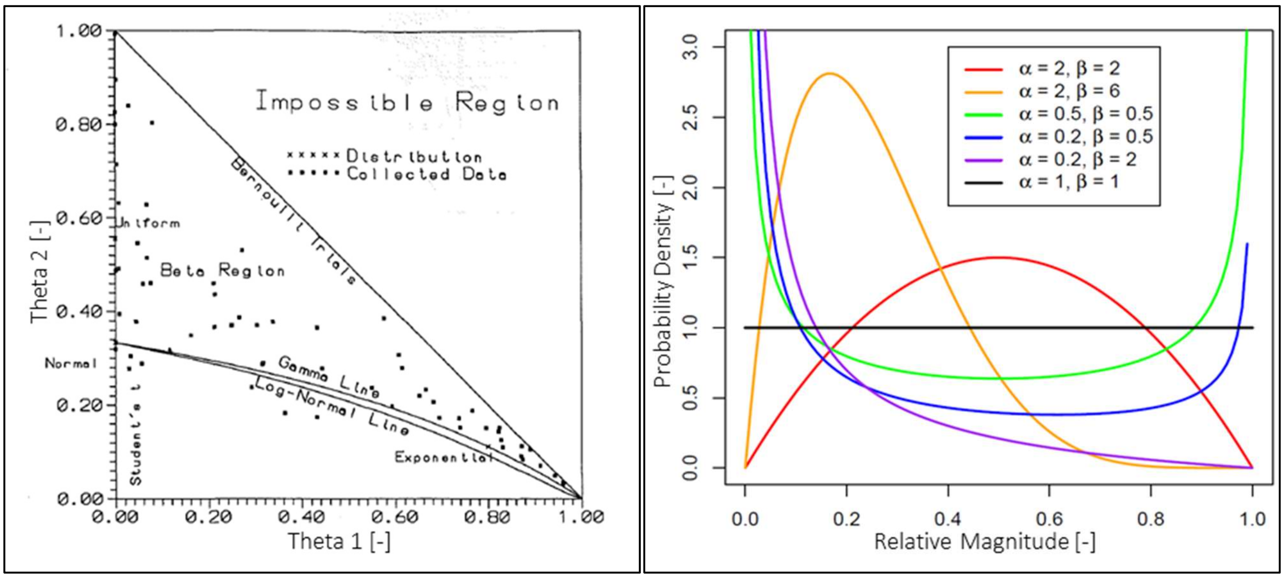


Figure 5-4: Skewness and kurtosis of different probability distributions and site activity data (AbouRizk & Halpin, 1992)(left) and various shapes of the beta distribution (right)

Figure 5-4 (left) allows a number of important conclusions. Most actual data points lie in the Beta-region. Few along the Log-Normal / Exponential line and very few are uniformly or normal distributed. Even those can be modeled by using the more flexible distributions such as the Beta, which can take many different shapes (Johnson & Beverlin, 2013), (Owen, 2008) as can be seen in Figure 5-4 (right). When comparing the most flexible distribution types discussed above, namely Beta Distribution, Johnson System and Pearson System, there is little practical advantage in using the latter two over the simpler Beta distribution in many applications. Many construction processes can be described by beta and gamma distributions with sufficient precision (AbouRizk & Halpin, 1992). This knowledge allows to construct artificial probability distributions if none are available for certain processes.

For this thesis, all planning has been based on actual measured distributions. The statistical evaluation software ExpertFit (Law, 2015) has been used to determine which functions describe the measured data best. The software produces a ranking of the most suitable distributions. The software's scoring function has been used to also determine how well the distribution fits and if it can be supported by a sufficiently large dataset. The applied distributions are tested for goodness of fit against the existing data and applied when fitting well enough. The oldest of these tests is the chi-square-test (Law, 2015). It is essentially a comparison of a histogram with the distribution curve. The Kolmogorov-Smirnov test compares an empirical distribution curve with the hypothesized distribution. In cases where the underlying data is not sufficient to justify the use of a complex probability distribution, using triangular distributions is a good way to estimate the behavior of a process (Law, 2015). Its properties can well be chosen based on expert interviews or a few available datasets.

5.3 Activity Durations on TBM Jobsites

This section presents the results of the analysis of all measured data, separated into the different areas and components of the jobsite. Each section gives an overview of the utilized data and its sources. The following sections have been separated:

1. Segment transfer
2. Activities throughout the backup system
3. Tunnel transport
4. Lifting processes in shaft and surface jobsite

The analysis results in practically usable information on activities the duration, its main performance factors and stochastic properties. Where available, the measured durations are shown in comparison to their design values. The data is anonymized and parametrized in the text of the thesis and completed with the actual measurement data in Appendix 5: Reference Data.

5.3.1 Segment Transfer Processes

Data on segment transfer has been acquired on projects with different logistic systems. Although the complete duration of the transfer process might not be comparable, its individual sub-processes are. All duration data has been manually measured by stop watch. The available raw data on these processes is therefore somewhat ambiguous in terms of assignment of sub-processes to groups. It may be discussed for example, if rotating the segment prior to placing it on the feeder counts as part of the movement or as part of the positioning process. While the original data contains 25 different sub-processes, such as dissipate vacuum, rotate segment or lower crane, it has been consolidated for analysis. In order to jointly evaluate the different available datasets, they have been grouped into the following three sub-processes which are solely depending on distance, design or operator skill:

- **Move crane** horizontally
- **Lower / Lift Crane** either with or without rotation
- **Position / Hook / unhook load** mechanically or by vacuum plate and positioning.

Each of the three processes is statistically evaluated based on the available data and compared to their design performance.

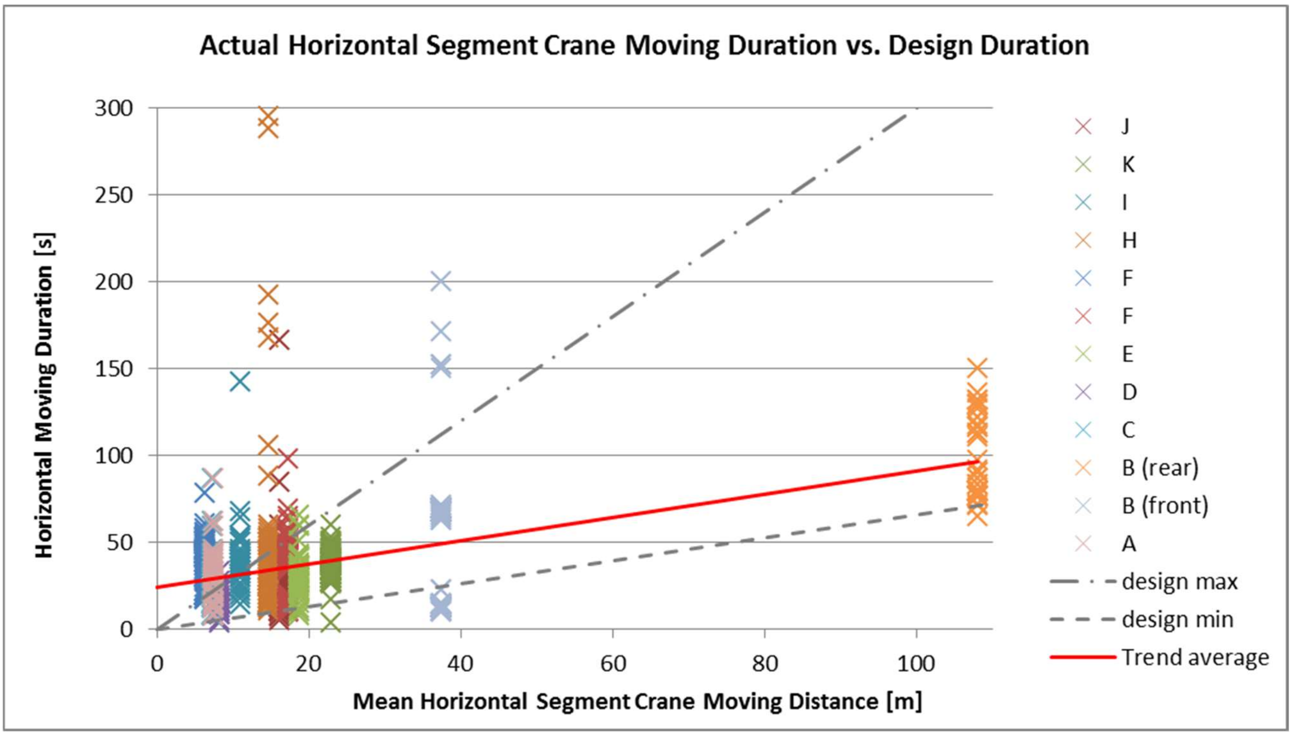


Figure 5-5: Actual crane horizontal moving duration compared to design values

The horizontal movement of segment cranes covers distances between 6m and over 100m. However, since the operator has to avoid collisions, watch out for the safety of other workers and communicate with the other workers to coordinate the logistics, it is highly questionable if the design speed of the crane is the defining performance feature for short distances. Over longer distances, the geometrical and design influences prevail.

Figure 5-5 plots the data from twelve different segment cranes named A to J against the design values. Segment cranes in TBMs are designed for movement speeds between 40m/min and 90m/min. However, this is only defining performance for very long distances as can be seen from the 110m long path on the right side in the graph. For the more common short transfer process from a vehicle in gantry 1 or gantry 2, the duration is mostly independent of the exact distance as the relative influence of coordination tasks increases. The vertical movement of the crane shows an even stronger effect of these coordination tasks as the absolute vertical distances are relatively small.

This global data evaluation can be used to determine rule of thumb values based on the average durations and dimensions of the TBM. However there is a large influence of the statistical variation of the movement duration as can be seen by observing the spread in Figure 5-5. The relatively high standard deviation of the movement duration indicates that it is necessary to discuss the statistical properties of this process. The data has been processed with the statistical evaluation software ExpertFit and scoring for different distributions has been determined for each dataset. Figure 5-6 shows a screenshot of the scoring for one distribution of the vertical segment crane movement. Based on how well different distribution types score; one is chosen to be used in further simulation studies.

Relative Evaluation of Candidate Models

Model	**Relative Score**	**Parameters**	
1-Log-Logistic (E)	100.00	Location Scale Shape	2.885 50.265 2.245
2-Log-Logistic	95.65	Location Scale Shape	0.000 53.488 2.404
3-Pearson Type VI	91.30	Location Scale Shape #1 Shape #2	0.000 23.789 6.189 2.940

Additional information about Model 1-Log-Logistic (E)
"Error" in the model mean relative to sample mean: 3.523 = 4.53%

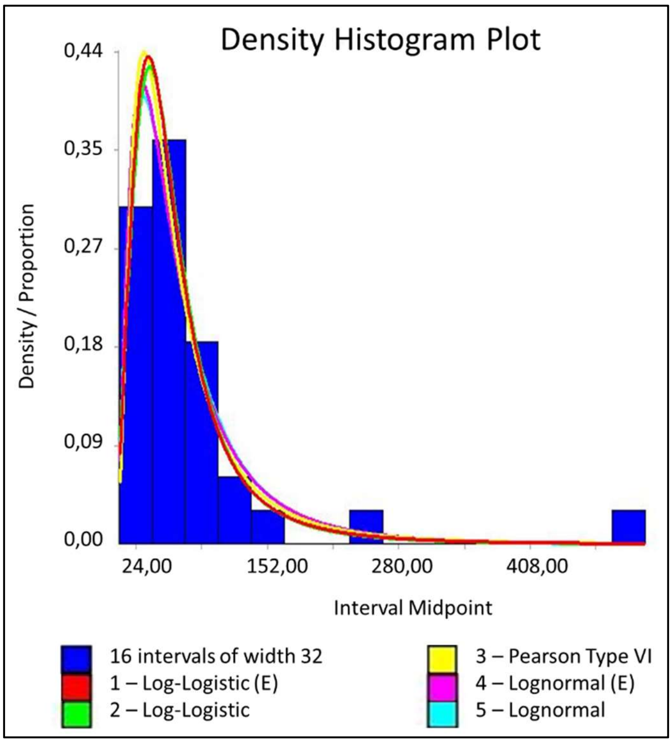


Figure 5-6: Screenshot of scoring results for different distributions for one dataset of vertical segment crane movement (left) and plot of ExpertFit comparison (right)

Figure 5-6 shows that in this case the vertical segment crane movement durations can well be described by a log logistic exponential distribution. The complete evaluation results can be found in Appendix 5: Reference Data. The vertical movement of the segment crane has been analyzed correspondingly to the horizontal movement. However, there are lowering operations where the crane must be rotated. This costs additional time which must be accounted for. Therefore, those two cases are evaluated separately. Figure 5-7 displays the durations for both against the vertical design speed of segment cranes. It is between 4m/min and 10m/min. Similar to the horizontal movement it is obvious, that the actual lifting or lowering distance only has a secondary influence. The main share of the duration lies in manual navigating and coordinating. The main Influence of the distance is on the minimum duration.

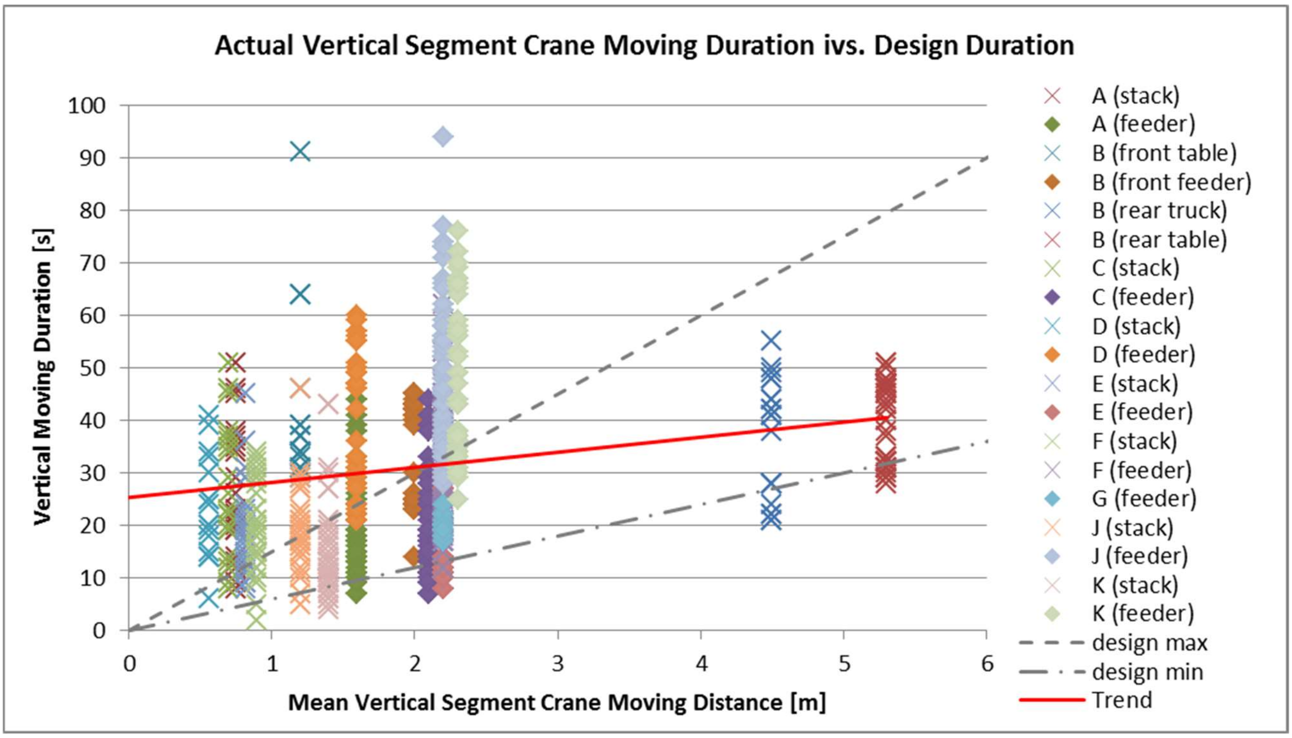


Figure 5-7: Actual crane vertical moving duration compared to design values (cross = without rotation; rhombus = with rotation)

As for the horizontal movement, the average vertical movement durations allow for a reasonable estimation in deterministic planning tasks. For a more detailed analysis, the measured probability distributions can be included into the analysis.

The last segment crane related process group consists of positioning as well as loading and unloading operations. They are shown in Figure 5-8. This is often overlooked in planning although operators spend a considerable cumulative amount of time on carefully positioning the crane. Whether mechanical gripping systems are used or vacuum plates to hold the segments, especially positioning and loading segments often costs considerable time. Due to the positioning of the crane, loading generally takes more time than unloading. While unloading typically just takes a few seconds, loading takes usually about half a minute.

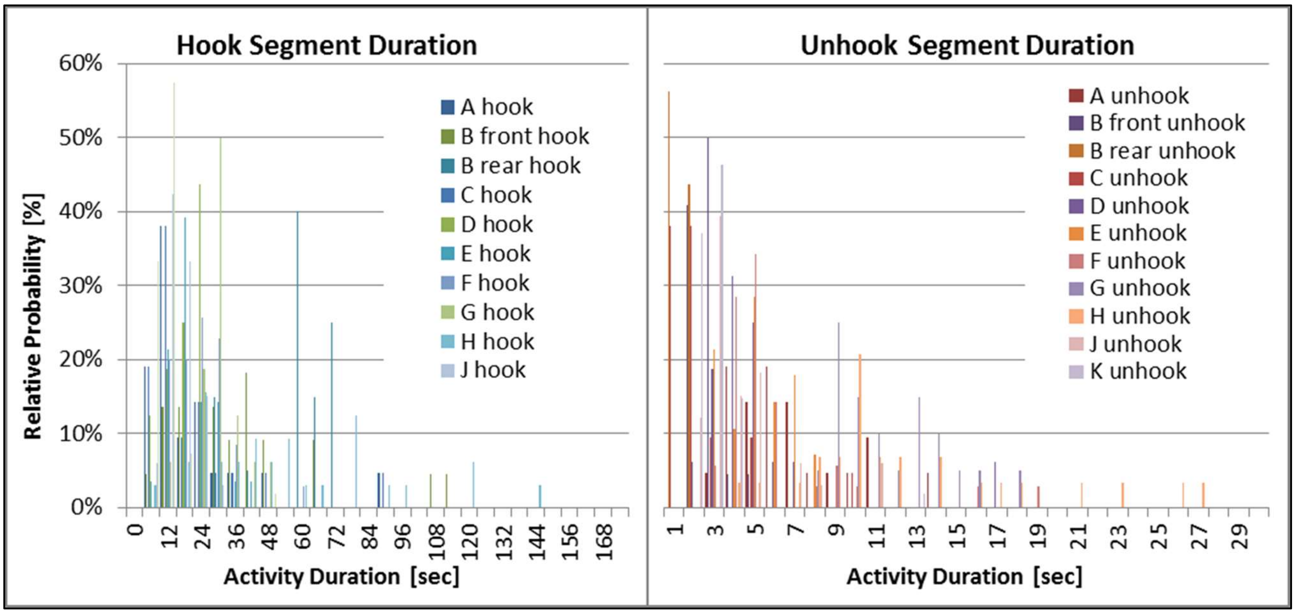


Figure 5-8: Duration of hooking and unhooking segments

5.3.2 Operational Processes within the Backup System

Many different material transfer and assembly operations take place in the TBM backup system as they have been identified in chapter 4.

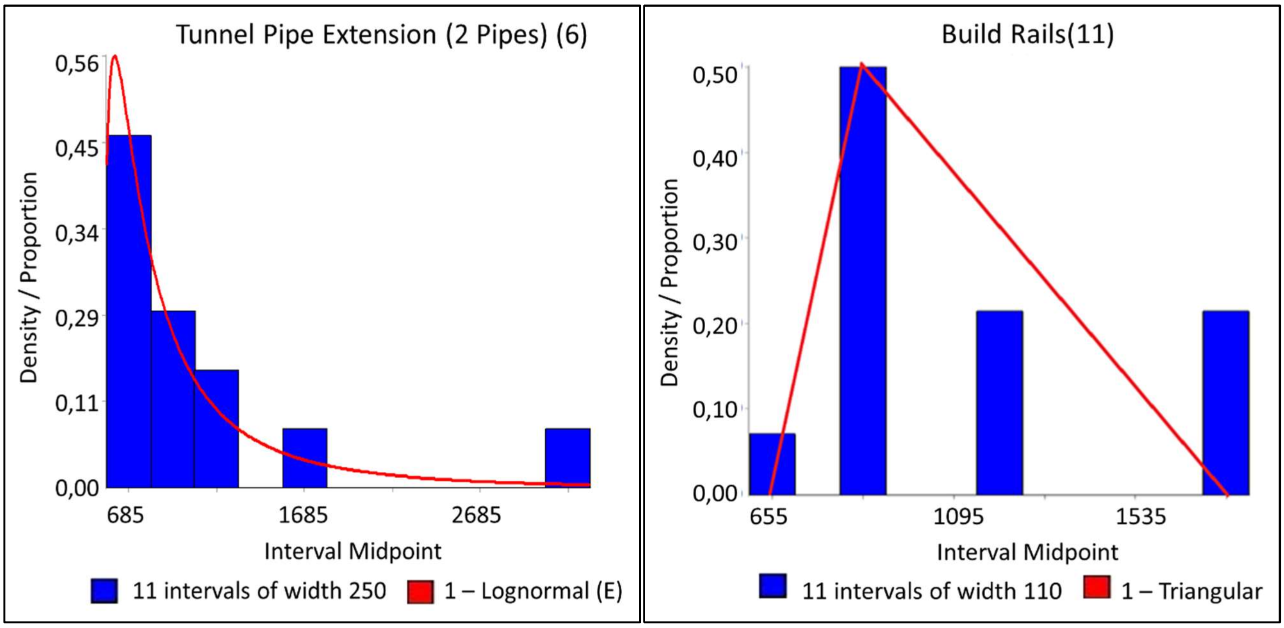


Figure 5-9: Probability distributions for activities in the backup system

For many of these, only limited duration measurements exist. Some involve a varying degree of manual labor as well. Therefore, they have been evaluated individually. Information on activity durations has been collected by manual measurements as well as by expert interviews. Most datasets are relatively small. Therefore, not for all of the the duration distributions can be determined with a high degree of confidence. Nonetheless it is necessary to develop an understanding of their behavior and to build criteria which are applicable for future planning processes. Therefore, they have been modeled with Beta and Triangular distributions within the range suggested by the available data and expert interviews. While the expert interviews hardly reveal the underlying distributions, they contain a fairly accurate estimation of the achievable minimum durations and encountered worst cases. Typically, they provide the range of durations which can be expected. Depending on the amount of available further measurements, this information has either been compressed into triangular distributions if very little data was available or into other distributions if more data is available. Figure 5-9 shows the results of this process for the tunnel pipe extension (left) and rail building (right), where only little data is available. The complete set of available data can be found in Appendix 5: Reference Data.

5.3.3 Tunnel Transport

Transports within the tunnel deliver people and material between the TBM and the shaft. There are two distinct aspects defining their performance. On one hand the actual driving and on the other hand maneuvering and coupling processes at both end of the transport process.

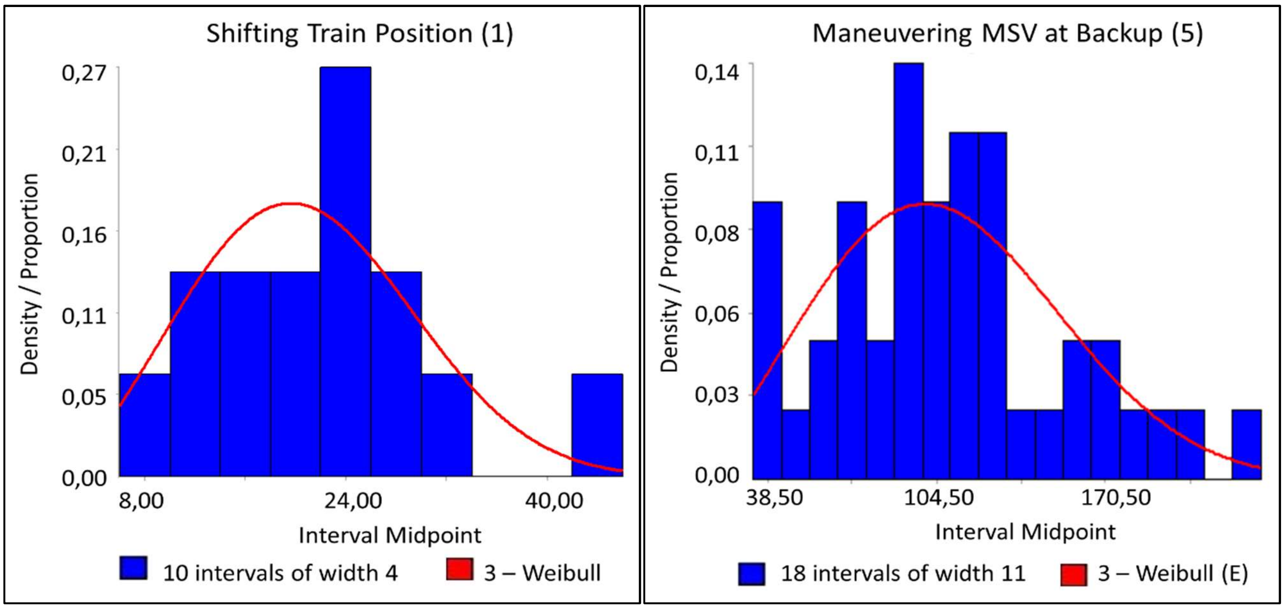


Figure 5-10: Activity durations of tunnel transport processes

Both follow different sets of rules. While driving in the tunnel is defined by speed limits, rail quality or the technical data of the vehicles, the coupling and maneuvering processes are relatively independent of the equipment's technical data and largely defined by structural and organizational aspects of the jobsite. Driving speeds are not subject to much variation if uninterrupted. Therefore, they are not further subject of the time study. They can be determined from handbooks, equipment datasheets or safety standards. The maneuvering and coupling processes however can have a strong impact on productivity. Especially in projects with small shafts where repeated shunting is necessary during loading and unloading processes, the effect can be severe.

There are three aspects that have been covered by measurements. The maneuvering of MSVs within a shaft between different loading positions and the coupling and shunting operations of trains in small shafts on the outside and the maneuvering of MSVs at the TBM on the inside. Figure 5-10 shows the distributions for maneuvering MSVs at the backup system of a large diameter TBM and the connecting and disconnecting durations of a train in a metro sized TBM. The complete set of distributions is contained in Appendix 5: Reference Data.

5.3.4 Lifting Processes in the Shaft and at the Surface

Lifting processes are one of the key aspects of jobsite design defining its overall performance. For many projects the lifting capacity in the shaft forms a bottleneck. Especially space constraints play an important role for the difficulties to increase capacity.

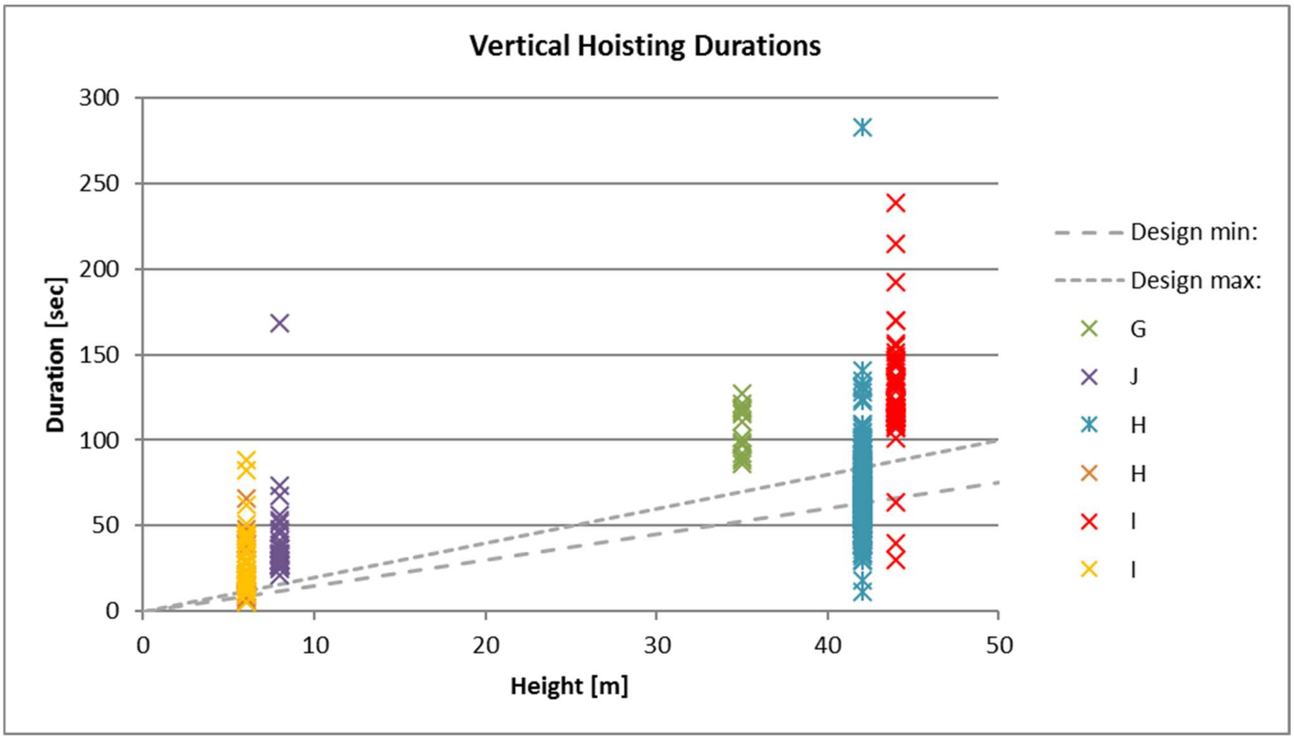


Figure 5-11: Hoisting durations of different projects compared to their design value.

There are two predominant types of processes relevant for lifting. On one hand, there are the actual movement durations of cranes, namely vertical movement, horizontal movement and rotation. These can be described by a minimum duration which is defined by the design parameters of the crane, its load and the physical distances or angles to cover. On the other hand, there are mounting, hooking, unhooking and positioning processes which depend on the available clearances and the design of the lifting tools. The movement durations of surface cranes show a similar pattern as for the segment cranes. For longer lifting distances they are clearly defined by the design hoisting speed. In the observed projects this value was between 30m/min and 40m/min. However, this just defines the minimum duration. Coordination tasks as well as slower overall movement speeds for shorter heights or distances lead to a strong performance loss for short distances when compared to the design figures.

Figure 5-11 shows this pattern for the vertical hoisting speed of different projects cranes. There is a series of measurements below the minimum speed. This is explained by the manual measurement process. This particular series had been measured with incorrect starting criteria. Due to its large sample size, it is nonetheless used to determine the underlying probability distributions. Additionally, to the mere movement of cranes, a large portion of time is taken up by positioning loads, hooking and unhooking.

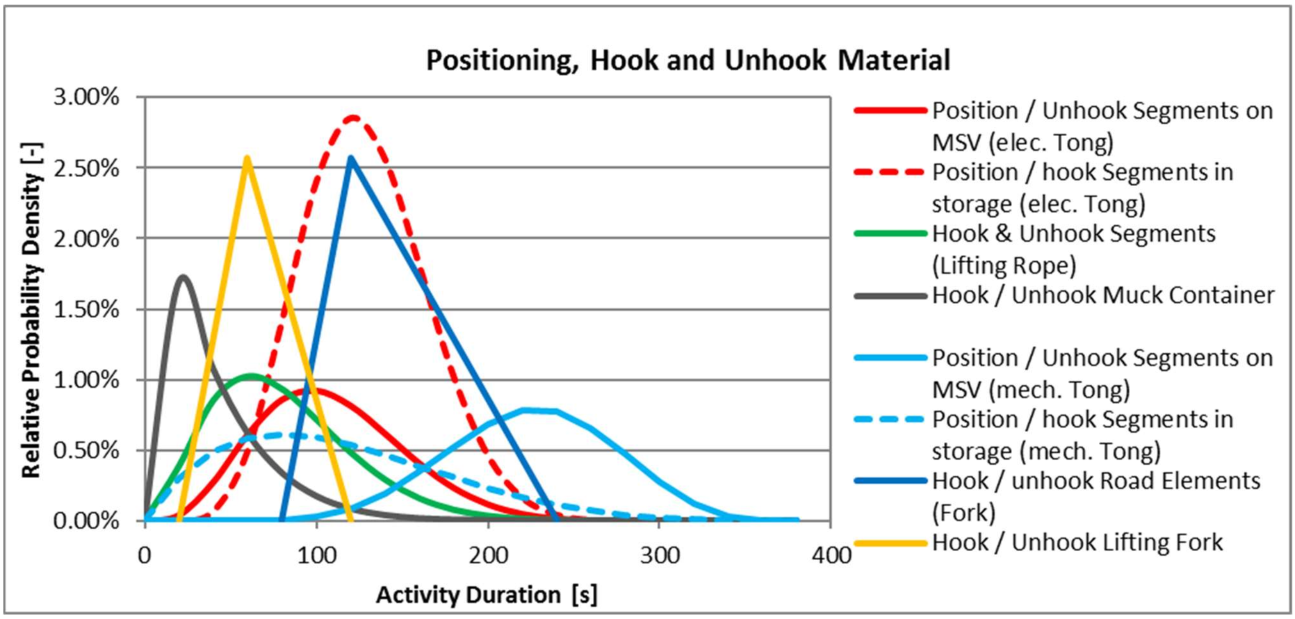


Figure 5-12: Positioning, hooking and unhooking durations.

This is shown in Figure 5-12. On one hand, it is obvious that different mechanisms for segment handling lead to different durations for hooking and unhooking cargo. It is for example faster to use lifting ropes for segment loading than mechanical or electrically operated segment tongs. Mechanical tongs are slower than electrically operated. The second big influence that can be observed is the time loss for precise positioning of cargo. Picking up segments in the storage yard is considerably faster than positioning them on an MSV or train. Especially where small tolerances must be kept, this costs significant time. The muck containers which are typically hoisted from trains to the muck pit are usually hooked and unhooked rather quickly. However, there are cases, where aligning procedures or mechanical issues cost extra time.

5.4 Remarks Regarding Activity Durations

The activity durations have been derived from the collected data for the purpose of using them for future planning of TBM logistics. The data reveals that most processes are influenced to a large degree by nontechnical factors. These factors are operator experience, coordination and communication, small scale management methods and detail planning. Due to their nature, they are not captured in the duration data and therefore it is not possible to derive them mathematically from the existing data. The also cannot easily be estimated or predicted for future jobsites. Thus one has to be careful when adapting the existing data to future projects with different technical boundary conditions. The sections 8.2.4 and 5.2.4 discuss possible strategies for dealing with insufficient data with regards to parametrizing a simulation model.

6 Model Development

Simulation studies require a detailed understanding and formalization of the structure and processes of the system to be simulated as well as clear and specific targets which questions should be answered by the study. Therefore, the development of suitable models is a key driver for successfully using simulation studies as well as for traditional analytic planning approaches. As practitioners would usually collect data in a less formal way than simulation experts, this chapter is divided into one section on system analysis focusing on the gathering of information and one on formal modeling which uses the gathered information to develop a formal model following the SysML standard. The example project which is used for all subsequent planning is introduced in this section as well.The modeling approach followed here can be applied universally to all tunneling projects.

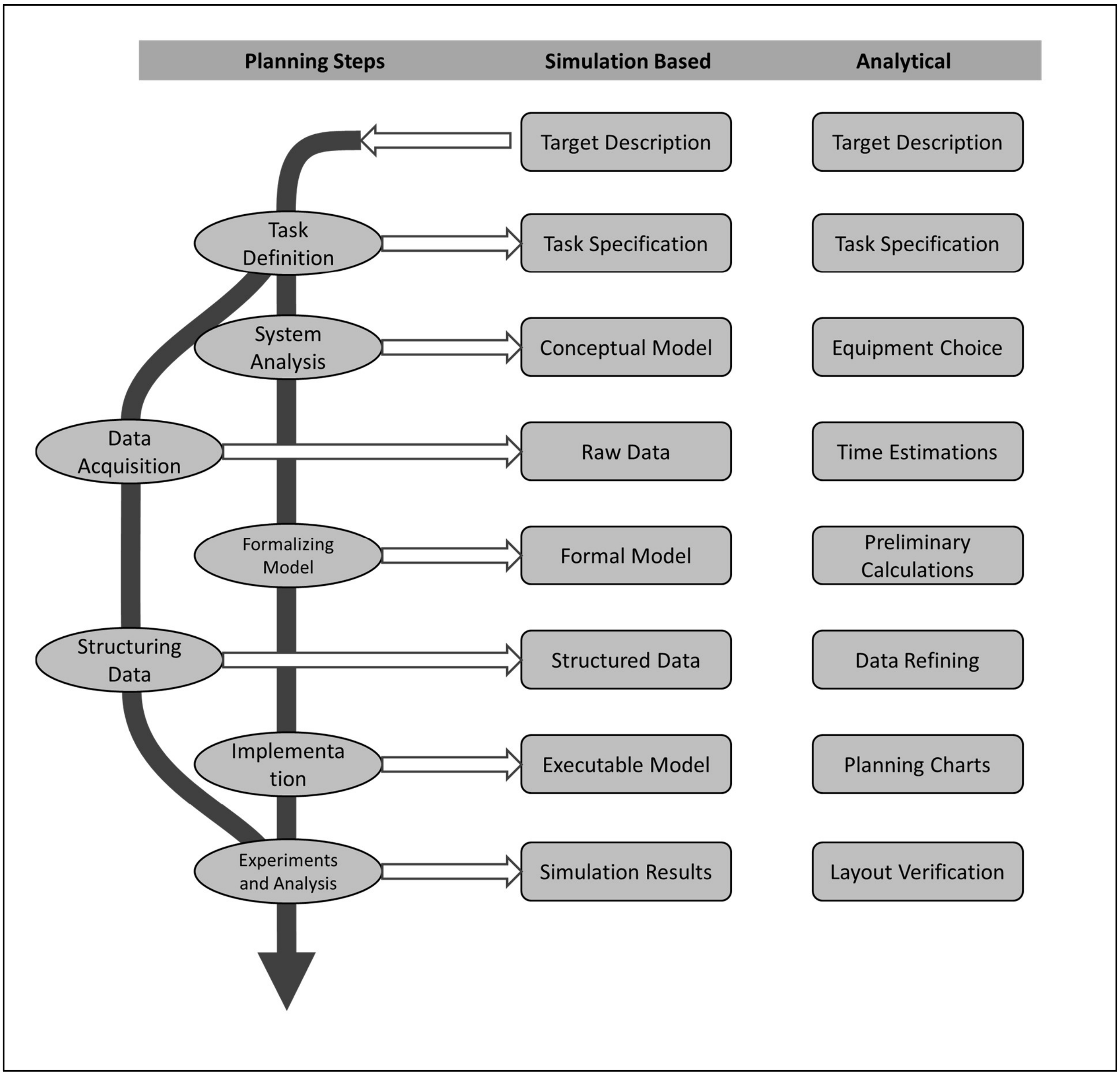


Figure 6-1: Procedure for verification and validation of simulation models (Rabe, Spieckermann, & Wenzel, 2008)

Details must be adjusted to the actual project though, as the logic relationships between processes changes in different project setups. In order to ensure a high standard of planning, a standard approach for verification and validation of simulation models is used and extended to the analytic planning procedures. The approach has been presented in (Rabe, Spieckermann, & Wenzel, 2008). Rabe et al. introduce the general procedure with the planning steps on the left and the related deliverables for simulation based and analytic planning methods on the right. Target description and specification mark the start. Then a conceptual model respectively the preliminary equipment plan is developed based on system analysis. After acquiring the necessary raw data, a conceptual model or the preliminary design calculations allow deriving the structure for refining the existing data. This is then used in the final design validations using either the finished simulation model or planning charts. A number of principles have to be followed to ensure planning quality. These verification and validation principles are outlined in section 8.4.4.

6.1 Example Project

For the purpose of providing a tangible example of the planning methods which are discussed in this dissertation, a fictional project is introduced which resembles a typical metro jobsite as it can be found in many cities around the world. Two parallel tunnels with an outer segment diameter of 6350mm are built from a western launching shaft to an eastern reception shaft which is 3050m away. The segments follow a 5+1 design with each ring 1.4m long which leads to little over two thousand rings to be built. This chapter gives an introduction into the main project features, the boundary conditions and a preliminary outline of the logistic structure that is planned in detail in chapters 7 and 8.

6.1.1 Alignment and Geology

The tunnel alignment represents a typical scenario found in many tunnel projects. While most of the alignment is located in full-face residual soil and marine clay, in some sections the interface to the base rock reaches the tunnel. Therefore, there are several areas with mixed face and full-face rock to excavate through which influences the choice of TBM and leads to varying parameters for excavation speed, tool wear and maintenance requirements. Figure 6-2 shows a longitudinal cross section of the geology. One can see the different sections featuring soils or rock conditions. Both tracks are similar but not identical in terms of the encountered geology. Details of the geology including each formation´s physical parameters are shown in Appendix 1 – Example Project Geology.

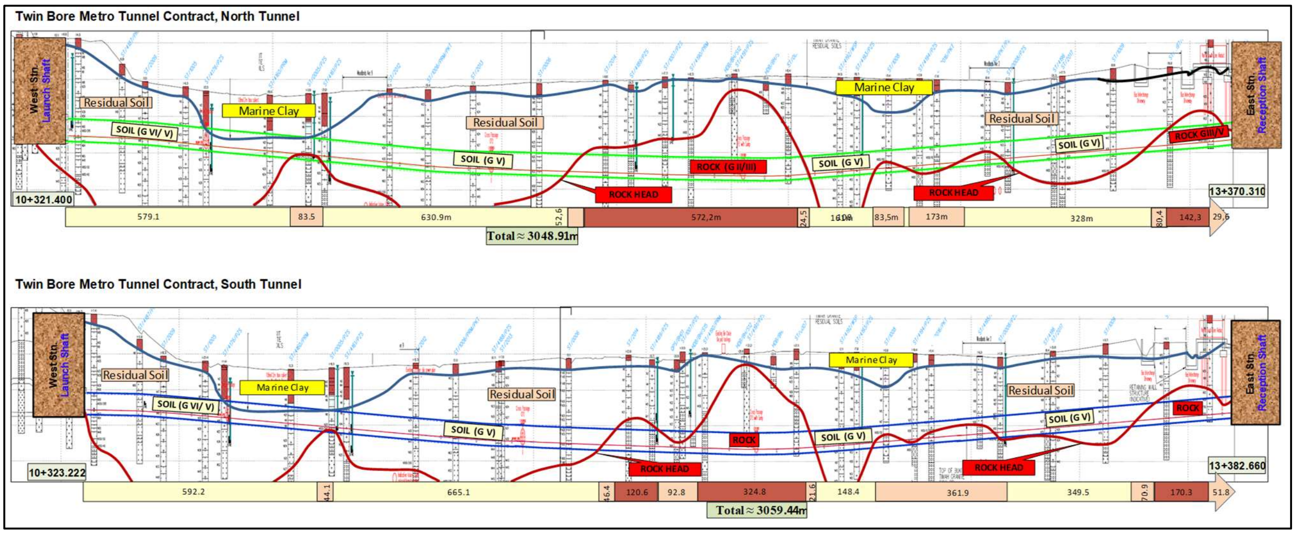


Figure 6-2: Longitudinal cross section of the fictional example project. (Top: North Tunnel, Bottom: South Tunnel)

6.1.2 TBM Technology

Two 6,6m EPB TBM´s are used to build the tunnels. They are simultaneously launched from the launching shaft in the east and disassembled in the western reception shaft upon completion of the drives. Figure 6-3 shows a schematic diagram of the TBM including the main technical data.

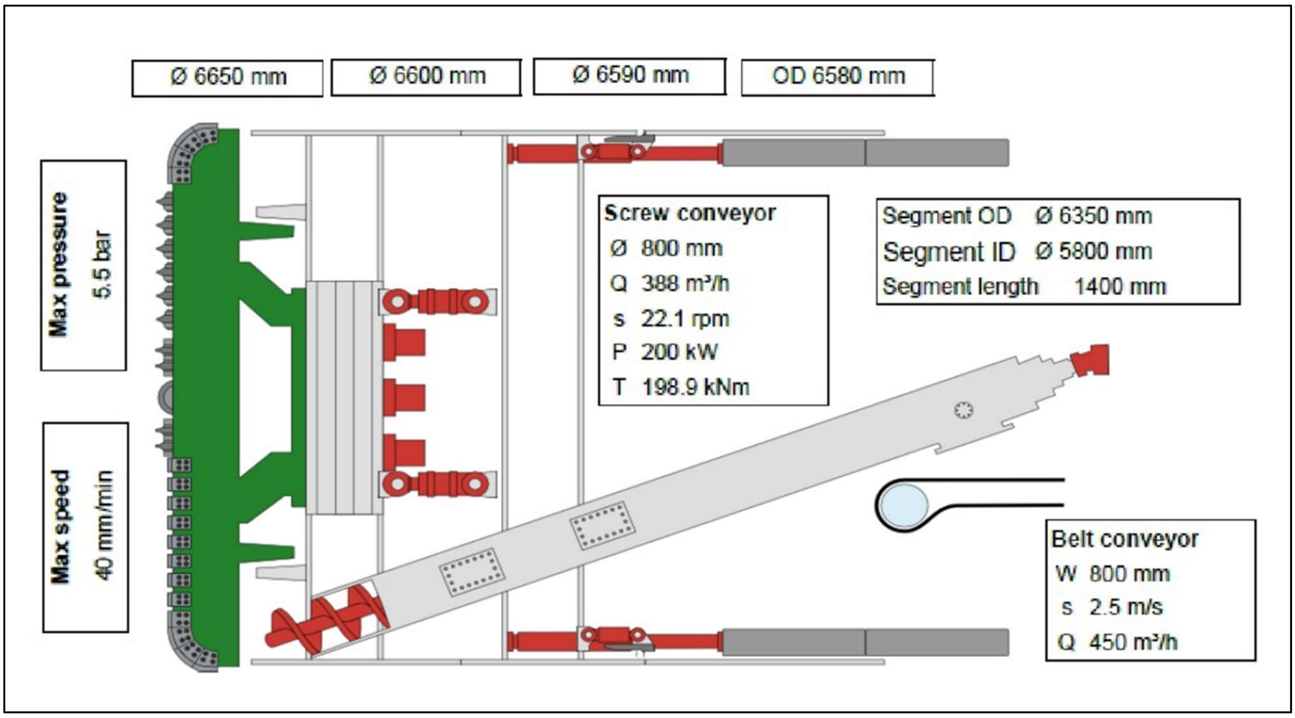


Figure 6-3: The EPB TBMs used to excavate the example project, (Herrenknecht AG, 2015)

The TBM's cutterheads are equipped with 17" disc cutters as well as scrapers to allow tunneling through mixed ground and short full-face rock sections. A displaceable maindrive is installed to adjust the cutting force of the discs precisely. The articulated tailskin houses an internal single component grouting system to fill the ring gap. Equipped with a segment feeder for a full ring, the machine allows for efficient and fast segment transfer. The backup system follows the layout shown in Figure 4-5 with an open type gantry and train rails between the two side sections that are housing equipment.

6.1.3 Preliminary Choice of Equipment / Planning Status

The planning process starts with a preliminary logistic layout that is subsequently analyzed regarding its performance. The preliminary choice of equipment is based on typical projects and contractor preferences. Mucking is assumed to be done by train and due to the space constraints in the shaft, two trains are used with each delivering half a rings material. A gantry crane and a crawler crane are used to lift and lower the material in the shaft. On the surface there are sufficient storage areas for all necessary goods available. The single component grout is filled via a pipe from the batching plant into the grout car and at the TBM a transfer pump is used to pump it into the storage tank on the gantry. It will be assumed that road traffic is permitted 24h per day so there are no restrictions regarding segment delivery and muck disposal at any time of the day. Based on these main characteristics of the planned jobsite, the jobsite logistics planning process will be shown in the next chapters. Figure 6-4 shows an overview of the preliminary jobsite layout.

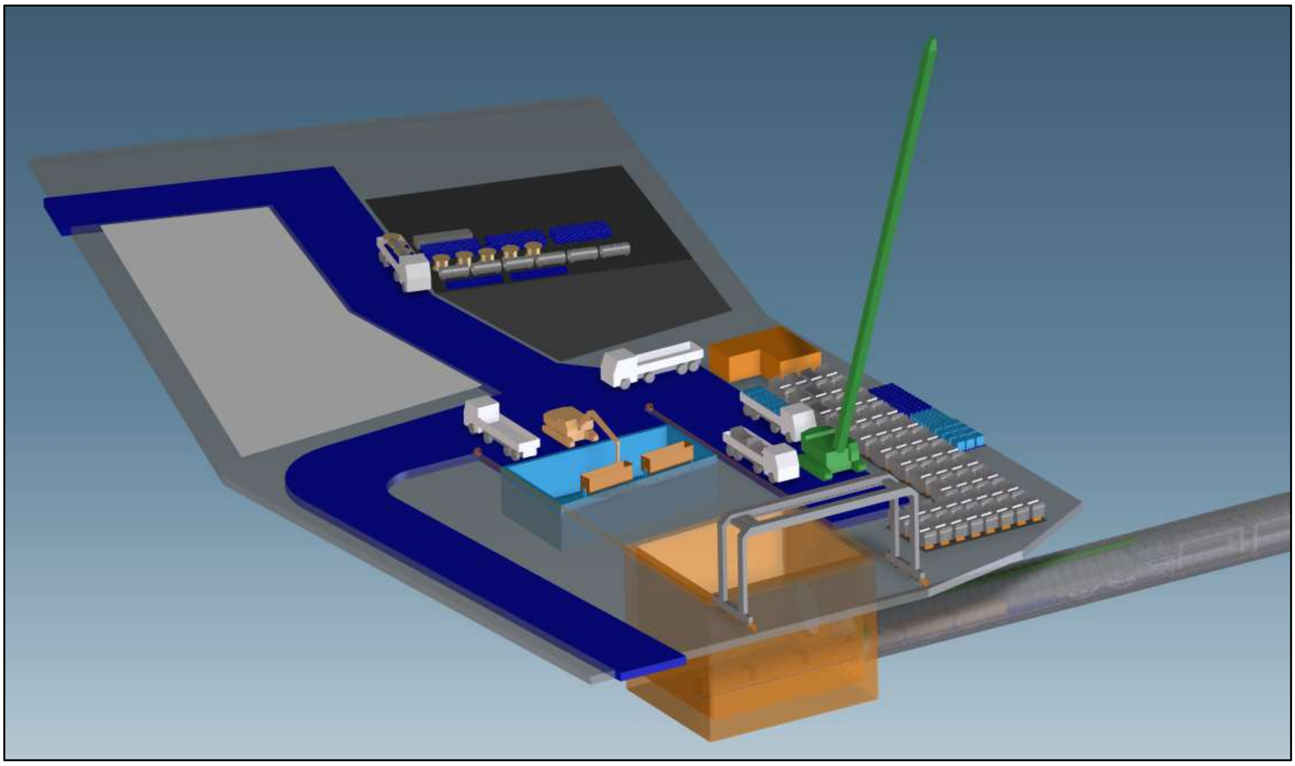


Figure 6-4: Schematic overview of the preliminary jobsite layout

6.2 System Analysis

System Analysis deals with information gathering and structuring including identifying the system boundaries and the suitable level of detail, the system elements and their relations with each other (Law, 2015). This information can be collected in field observations or by compiling and estimating theoretical information about possible new systems from existing data. The goal of the system analysis is finding all necessary information which allows the subsequent analyticanalytic planning or a formal modeling process. Which exact parts are necessary depends largely on the purpose of the simulation model. For management purposes other information is necessary than for engineering purposes. Also the information which is necessary for building analytic models is usually below the level of detail required for simulation modeling. This section explains the main methods of system analysis and how to gather and identify the required information effectively. Several principal sources for information on a system can be identified according to (Chung, 2004):

- Historical records
- Manufacturer specifications
- Vendor claims
- Operator estimates
- Management estimates
- Automatic data capture
- Direct observation

These sources allow gathering process duration data and structural information about any given system. The information gained from them can be condensed in lists and reports which contain all necessary information in a semiformal shape. Throughout the research behind this thesis a number of standard forms and reports have been developed which structure the information gathering process on jobsites. The forms can be found in Appendix 2 – Jobsite Logistics Survey Forms. They focus on the system elements as well as on the relations and interdependencies between them. Their usage is explained in detail in the following sections.

6.2.1 System Boundaries

The system boundaries are defined by the purpose and point of view of the model to be created. They dictate which elements are parts of the model. For logistics this includes all elements which are involved in time and resource consuming processes related to material handling on site. This leads to the definition of a boundary from the TBM / geology interface to the fence of the jobsite. By definition this includes the path of delivery trucks on site, their unloading and the further material handling until consumption in the TBM. The level of abstraction results from the level of detail which a simulation model should depict. For logistics planning, this means considering all regularly plannable material handling operations. Therefore, crane hoisting and transport of all regular consumables and construction material is included, while minor parts, spare parts transport and other unplanned events are excluded.

6.2.2 System Elements

Depending on the usage of the jobsite model there are two possible approaches. In case an existing jobsite shall be analyzed, the most suitable approach is a structured fact finding survey on site to collect the relevant information. In case a future project is to be planned, the gathering of information has to be done based on reference projects and checklists. The author has developed a standard form for this purpose which has been used on site to identify and list all logistic equipment in a systematic way. For each system element there is a certain range of typical information which should be collected.

Logistic Elements Overview
Example Project

Materials	Storage Facilities	Fixed Infrastructure	Resources
Muck	General Storage Area	Grout Batching Plant	Gantry Crane
Segments	Segment Storage Yard	Surface Access Roads	Mobile Crane
Rails, Sleepers, Assembly mat.	Liquids Storage	Tunnel Rails	Trucks
Ventilation Duct	Grout Silo	Shunting Platform	Trains
HV Cable	Bridge Area Storage		Rail Crane
Tunnel Pipe	TBM Gantry Storage		Segment Crane
Walkway Material	Muck Pit		Barrel Crane
Tenside			Tenside Crane
Grease			Grout Transfer Pump
Grout			Segment Feeder
			Excavator

Logistic Equipment Description
Example Project

Name	Gantry Crane
Description	• Gantry crane is covering the shaft and muck pit and does the mucking for both TBMs
Type	• DEMAG
Performance Data	• Round trip with muck bucket in 7-8 min
Main Processes	• Hook Bucket • Lift Full Muck Bucket • Horizontally move full bucket • Empty bucket • Horizontally move empty bucket • Lower Bucket • Place Bucket on train
Picture	

Figure 6-5: Jobsite inventory (left) and logistic equipment survey form with collected information on a gantry crane (right)

An example of this form is shown in Figure 6-5 on the right side. The whole document is separated into several sections to support gathering complete information on the available resources. The description of materials lists consumables, building materials and other parts which are moved around on site. The description of storage areas lists type of storage areas, their capacities, dimensions and positions. The description of resources covers all mobile machinery such as cranes, excavators, trains, trucks or similar equipment. It is completed by listing fixed infrastructure such as roads and railway track layouts. An inventory table is used to create an overview of all relevant system elements. This list is shown in Figure 6-5 on the right side. The example project has been structured based on references and a theoretical choice of equipment has been made for the planning process as shown in the compiled logistic elements forms in Appendix 3 - Logistic System of the Example Project.

6.2.3 System Structure

The identification of the correct system structure is just as crucial for manual planning as for the simulation modeling process. Only when the interactions and relations of the different model elements and processes are identified correctly, the model can represent reality. Therefore, this step defines the rules of all events within the model. The importance is identifying not only those processes and interactions which are visible at first glance but also those which seem hidden and might be caused due to indirect interaction. All of them must be broken down to direct action consequence relations which later can be programmed as the model elements properties.

The logical starting point for the definition of system behavior is listing all materials to be observed and step by step follow their path through the jobsite. This allows defining all planned handling processes. Nonetheless there are many unplanned minor processes taking place on a construction site which cannot be accounted for by this method. They can either be determined as additional “random” processes blocking certain resources or they can be expressed via the operational availability of the resources for planned processes. Over the course of this thesis long term camera observations have been used to determine type and extent of these processes. On all jobsites observed a much higher portion of random processes was detected than assumed initially by the jobsite managers. The main processes can be shown in process flowcharts which show the processes associated with each type of material such as shown in Figure 6-6. The processes listed here can be mirrored for each TBM in the example project. After identifying all processes, a matrix can be created, which shows the processes, associated resources as well as their starting and ending points. The matrix uses a color coding system to indicate possible interactions and conflicts. Grey marks no conflict, orange conflict for space, red conflict for resource. Conflicts can either be totally such as two processes need the same crane or partially such as when two trucks need to maneuver around each other and therefore operate slower than when undisturbed. The complete process conflict matrix for the example project is shown in Appendix 3 - Logistic System of the Example Project.

Materials Description Example Project	
Name	Rails
Description	• Tunnel Rails for Trains and Rails for Gantries incl. Assembly Material. Both are built in Bridge area and Gantry rails are disassembled after passing of TBM
Type	• 35kg/k rails
Estimated Consumptio n Pattern	• 1 pair of rails through whole tunnel • Circulating rails in gantry area
Weight / Dimensions	• L=6m • 35kg/m rail
Path through System	• Source/Delivery Truck – Mobile Crane – General Storage Area – Mobile Crane – Train – Segment Crane – Tunnel Floor Bridge – Rail/Sink • Source/Rail Crane – Train – Segment Crane – Tunnel Floor Bridge – Rail/Sink
Picture	

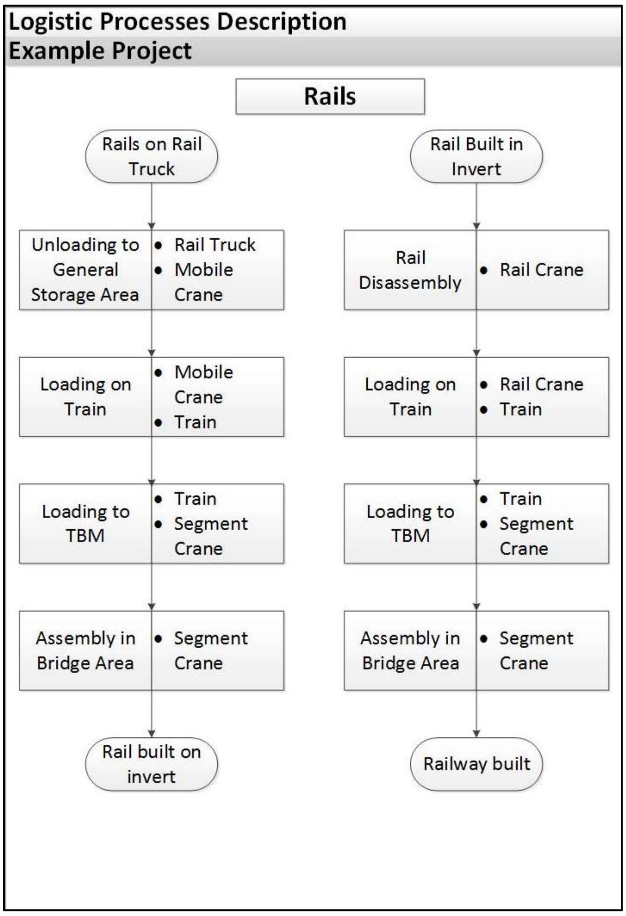


Figure 6-6: Materials form (left) and related process flowchart (right)

6.3 Formalizing the Model

Simulation based analysis requires precise formal models. Therefore, a formal syntax has been chosen to define the structure and behavior of the logistic systems in TBM tunneling. The chosen language is SysML as introduced in section 3.3.2. It consists of different diagram types which can describe all relevant aspects of the jobsite. A formal description as with SysML is an unusual tool in the construction industry and therefore not practical to use on site as a tool for analytic planning. But when translating the information gathered on site to the world of simulation modeling, formalizing the model in a specified syntax forms a valuable intermediate step to a simulation model as all relevant aspects of the jobsite are described without ambiguity. This allows programmers to implement a simulation study without being involved in the construction process.

6.3.1 Specification of the Model Structure

Internal block definition diagrams (ibd) describe the composition of a system. The highest hierarchical level of the system is shown in the context diagram in Figure 6-7. Based on a structure initially proposed by (Rahm, Sadri, Koch, Thewes, & König, 2012), the ibd has been extended with subsystems that can be replicated to contain several sets of identical equipment. In this case there are two parallel tunnels. The stereotype of the block diagram is chosen as <<*domain* >> indicating a less formal structure to allow reference to external influences which are not part of the formal model. The mechanized tunneling domain can be divided into four distinct types of sub elements which can be exchanged in a modular manner. The sub elements are of the stereotype <<*system* >> as they represent definite technical solutions. The systems *TBM* and *Backup* contain the elements and behavior of the tunnel boring machine such as consumption patterns and logistic systems which are essentially mechanical design variables of the tunneling technology. The systems *Tunnel* and *Jobsite* contain the logistic supply chain that is installed on site.

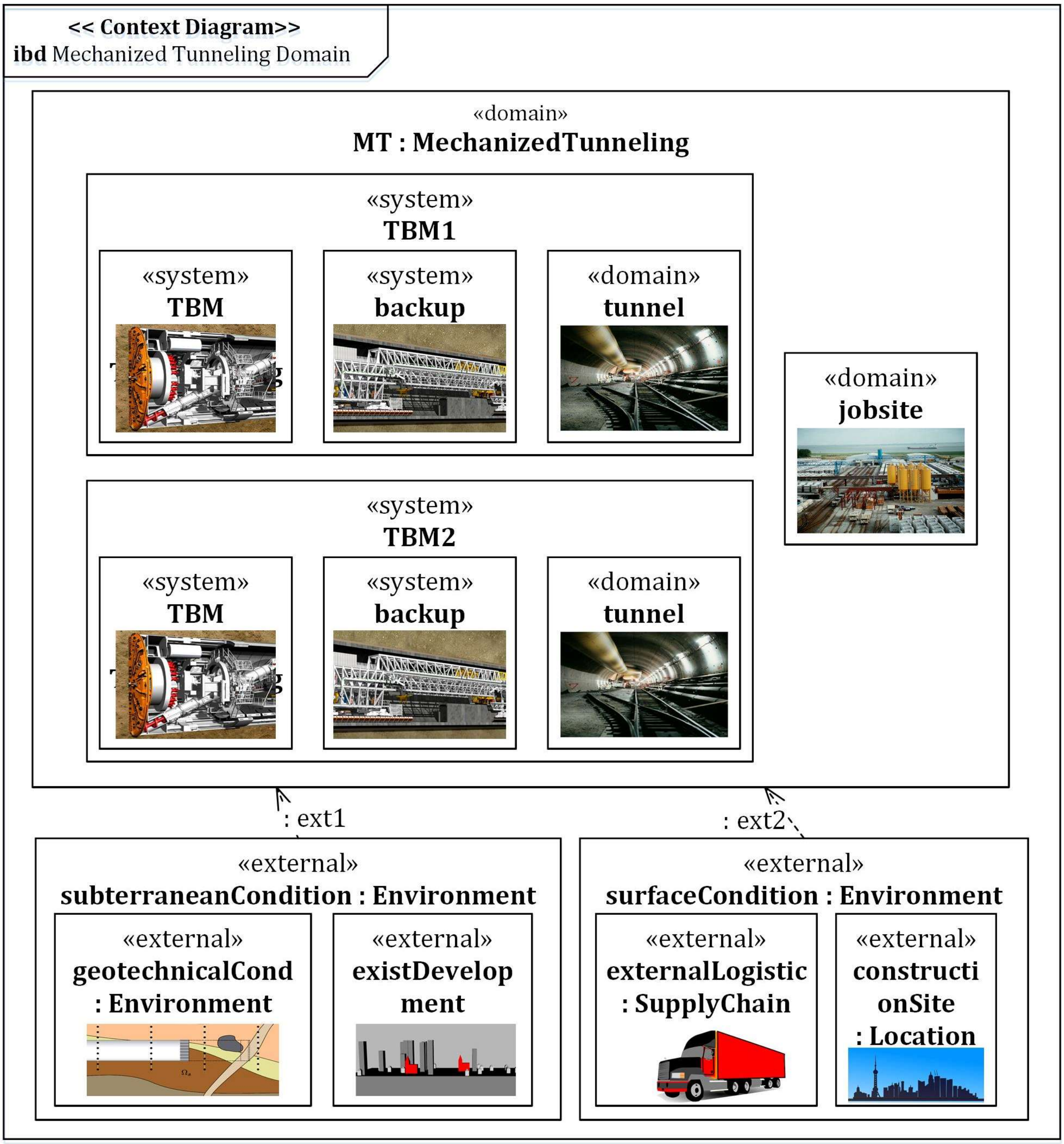


Figure 6-7 Context diagram of mechanized tunneling

The mechanized tunneling domain is extended by external boundary conditions influencing its behavior. They are modeled using block definition diagrams as well. These are the *<<external>>* blocks called *Environment*. They contain boundary conditions which are not explicitly part of the jobsite but must be considered. These are the geological conditions, geographical and urban surroundings of the jobsite, as well as the external supply chain and the legal and sociological boundary conditions to operate in.

6.3.2 Modelling System Elements

The system elements of the TBM are modeled using Block Definition Diagrams (bdd). They contain the hierarchical structure of the different technical systems on site as well as their operational parameters and properties. Figure 6-8 shows the detailed hierarchical block diagram containing the main elements of the jobsite. In essence they resemble the elements which have been identified in the system analysis phase in section 6.2. Few adaptions have been made with regards to formalizing the structure.

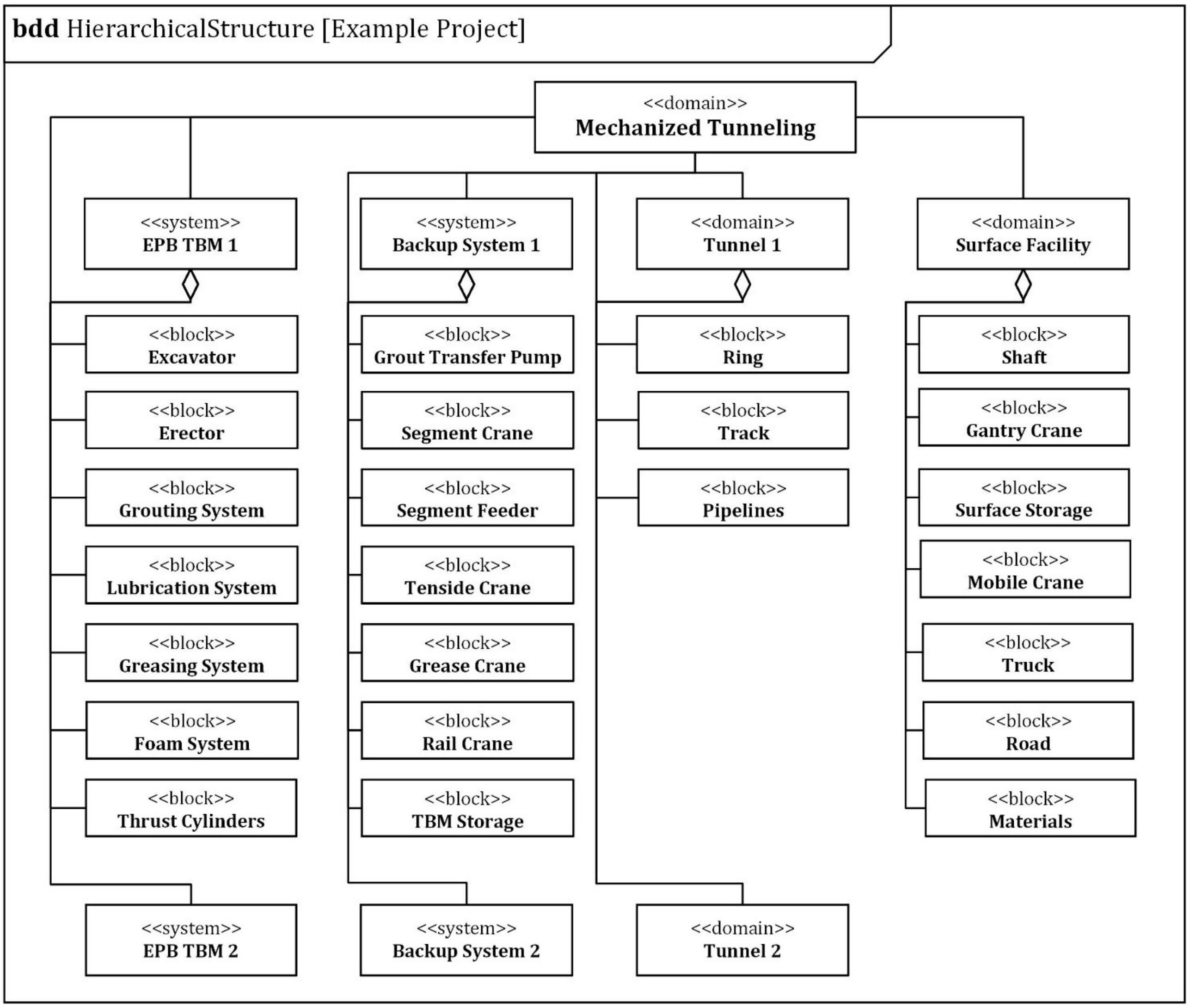


Figure 6-8: Hierarchical structure bdd of the example project

The four main systems, *TBM, Backup, Tunnel* and *Surface* contain numerous sub systems. Three of them, *TBM, Backup* and *Tunnel* are replicated to reflect the twin tunnels present in the example project. Each of the elements is described in its own block diagram containing its key technical properties and operation parameters. Depending on the technical solutions chosen in the specific tunneling project to be modeled, they might differ considerably. Other elements such as the *Excavator, Erector* or *Cranes* are present in almost all possible setups though. The block diagrams for each element contain the detailed information about its performance defining factors. Figure 6-9 shows the bdd of the TBM as an example. This example will be used to explain its content. The element *Excavato*r represents the TBMs excavation system.

As different types of machines such as road headers or EPB machines might use different methods for excavating, the general representation allows flexibility. The relevant property from a logistic point of view is the muck volume flow specified by the excavation rate. The flow specification contains *muck* and specifies its property as a liquid which defines the corresponding handling tools, namely containers or pipes. Not all elements require flow specifications.

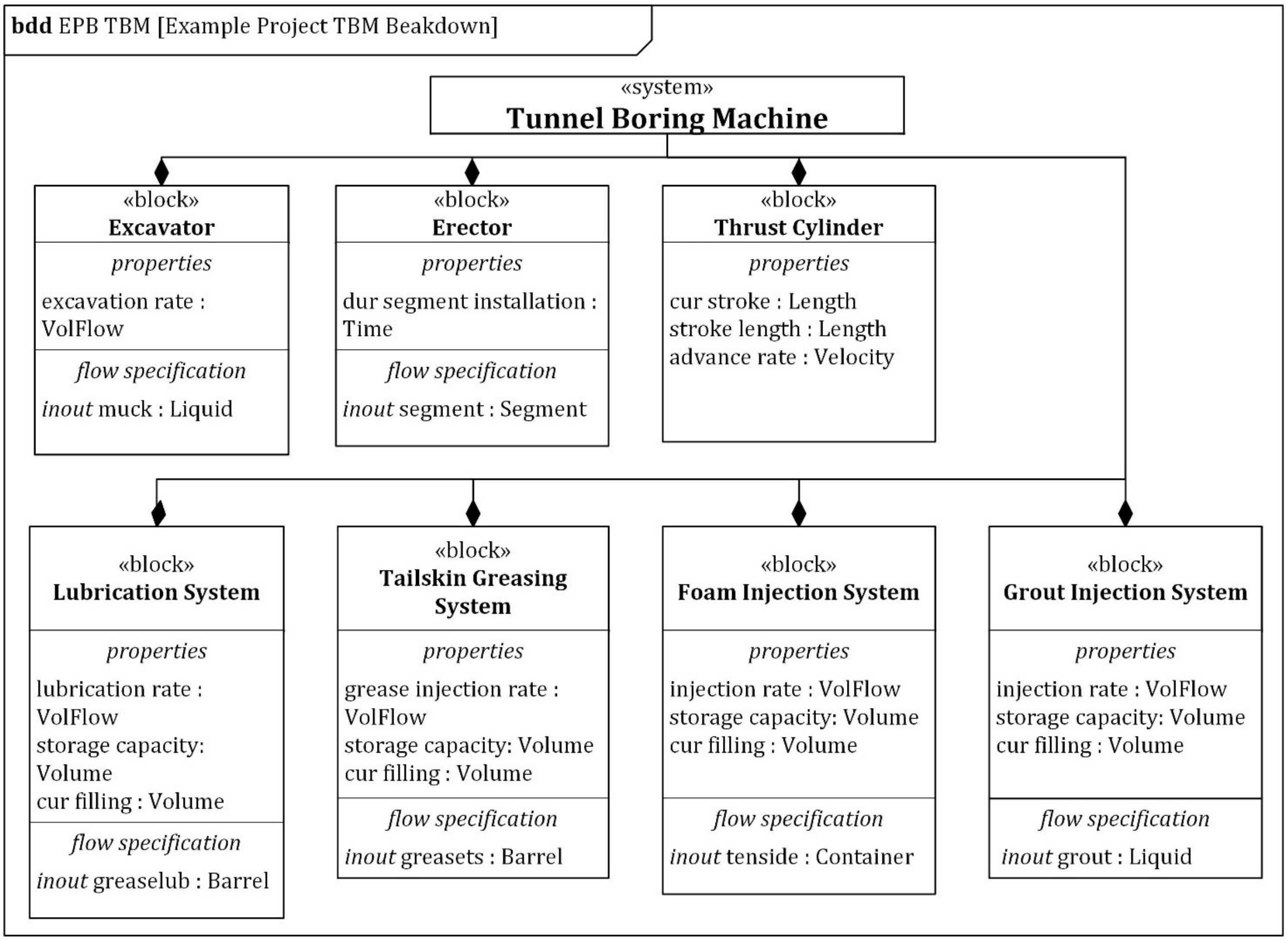


Figure 6-9: Block diagram of the TBM components for example project

The thrust cylinders can be defined by stating current and maximum stroke, as well as the advance rate. The remaining elements of the TBM, the *Foam Injection System*, *Grout Injection System*, *Erector*, *Lubrication* and *Greasing System* are described in the same way including their storage capacity, consumption rate and the current filling level with their respective consumable. Each system of the mechanized tunneling domain is modeled in this manner. The compete SysML model can be found in Appendix 4 – SysML Model of the Example Project.

6.3.3 Modeling Material Flow

The material flow through the jobsite can be modeled using internal block diagrams (ibd). All elements which move through the system, vehicles and material, are traced on their way from source to sink. The blocks they move through can either be other moving elements, resources or fixed installations. Figure 6-10 shows the ibd for the flow of segments through the system. After entering the system boundary in the surface domain, the segments appear first in the segment truck. Subsequently they are moved by different resources through the storage and transport network until they are built by the erector. After forming part of the tunnel, they disappear from the model in the subterranean domain.

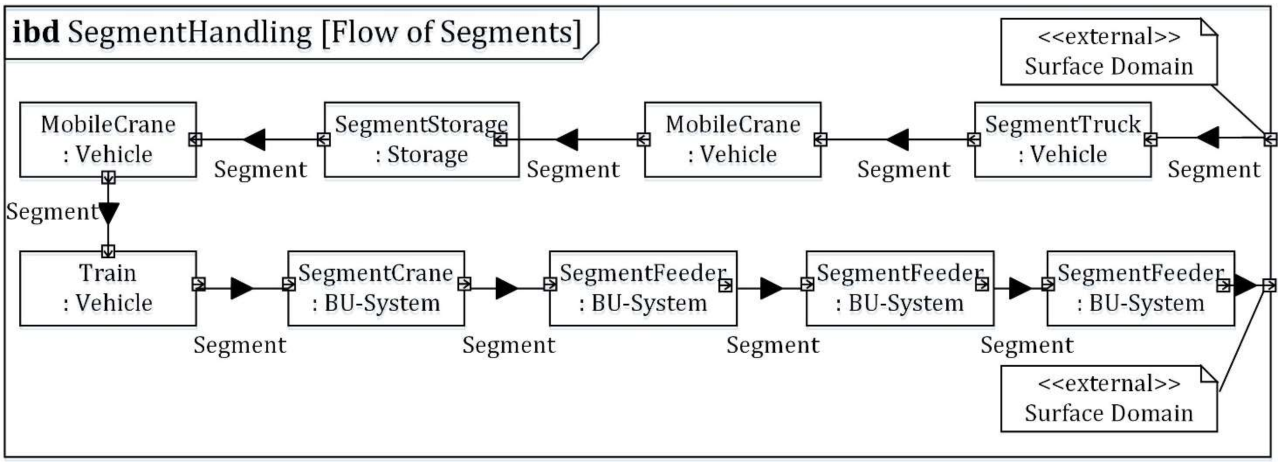


Figure 6-10: Internal block diagram for segment flow

6.3.4 Modeling Element Behavior

Statecharts, as introduced in section 3.4.2.2 provide a clear description method for the behavior of systems. SysML incorporates them in state machine diagrams (stm). After the initial start which is represented by a black dot, any element is in a certain state for a certain time. States are represented by rectangles with round corners. When certain requirements are fulfilled, they change the state to a different one. These requirements can be elapsed time or external triggers. Such external triggers are shown as requirements in the state transitions in the model. A simple example is the state machine diagram of the excavator shown in Figure 6-11. After initially being in an idle state, the fulfilment of the requirement *ringbuilding finished* triggers the next advance cycle. However, excavation can only be started if all required materials are available and all necessary subsystems are operable as well. Upon entering the state excavating, other system elements may trigger processes when observing this state transition. The excavator will keep excavating until the state *stroke finished* of the thrust jacks is active. When going back into idle state, the finished advance can be observed by other states. Statecharts do not reveal the addressee or origin of the requirements that trigger events. To model direct communication between elements, sequence diagrams are incorporated in SysML. They are introduced in section 6.3.5. Figure 6-11 shows the state machine diagram of the erector on the right side. The erector is a communication partner of the excavator. Both require the other on completing its tasks to operate. The ringbuilding state contains branches; another feature of state machine diagrams. After installing a segment, there is a check if the ring has been completed. Either the next segment is built or the ringbuilding is finished and the erector returns to idle state.

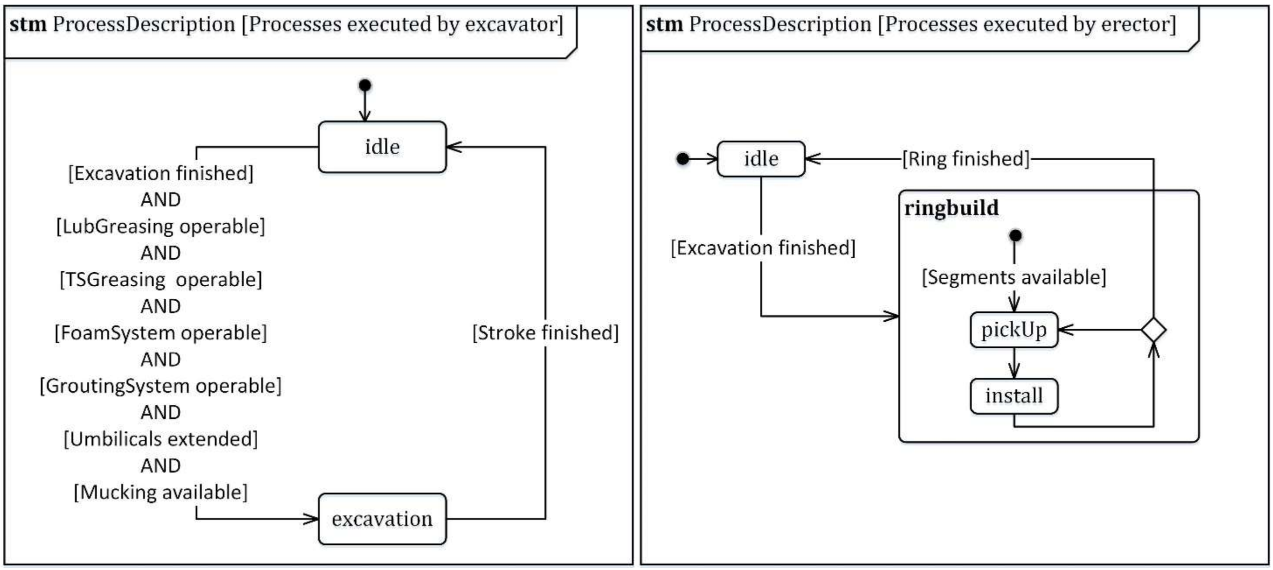


Figure 6-11: State machine diagrams of the *Excavator* (left) and *Erector* (right) elements

6.3.5 Communication throughout the Model

There are two possible ways to communicate throughout the model. One is the passive way by observing the state of other elements. If the state changes, the observer may trigger certain actions. An active communication method is sending messages between model elements. These messages can be shown in sequence diagrams. While state machine diagrams do not explicitly model the flow of communication between elements but the elements reactions to the received information, sequence diagrams focus on the information flow itself. Figure 6-12 shows the sequence diagram for the advance process. After triggered by the message from the environment that the ringbuilding is finished, the excavator starts the advance. Messages are sent to all relevant subsystems to trigger their start. Once the stroke has been completed, a message sent from the thrust cylinders is leading to the advance being finished and a message sent to the environment. A condition is to be fulfilled for all subsystems being operable. This is indicated by the substate *“opt”* in the diagram. With a few exceptions, this work avoids using active messaging but rather focuses on model communication by the mutual observance of states. In the executable simulation model which is presented in chapter 8, communication is facilitated by an event manager which informs different modules about their states.

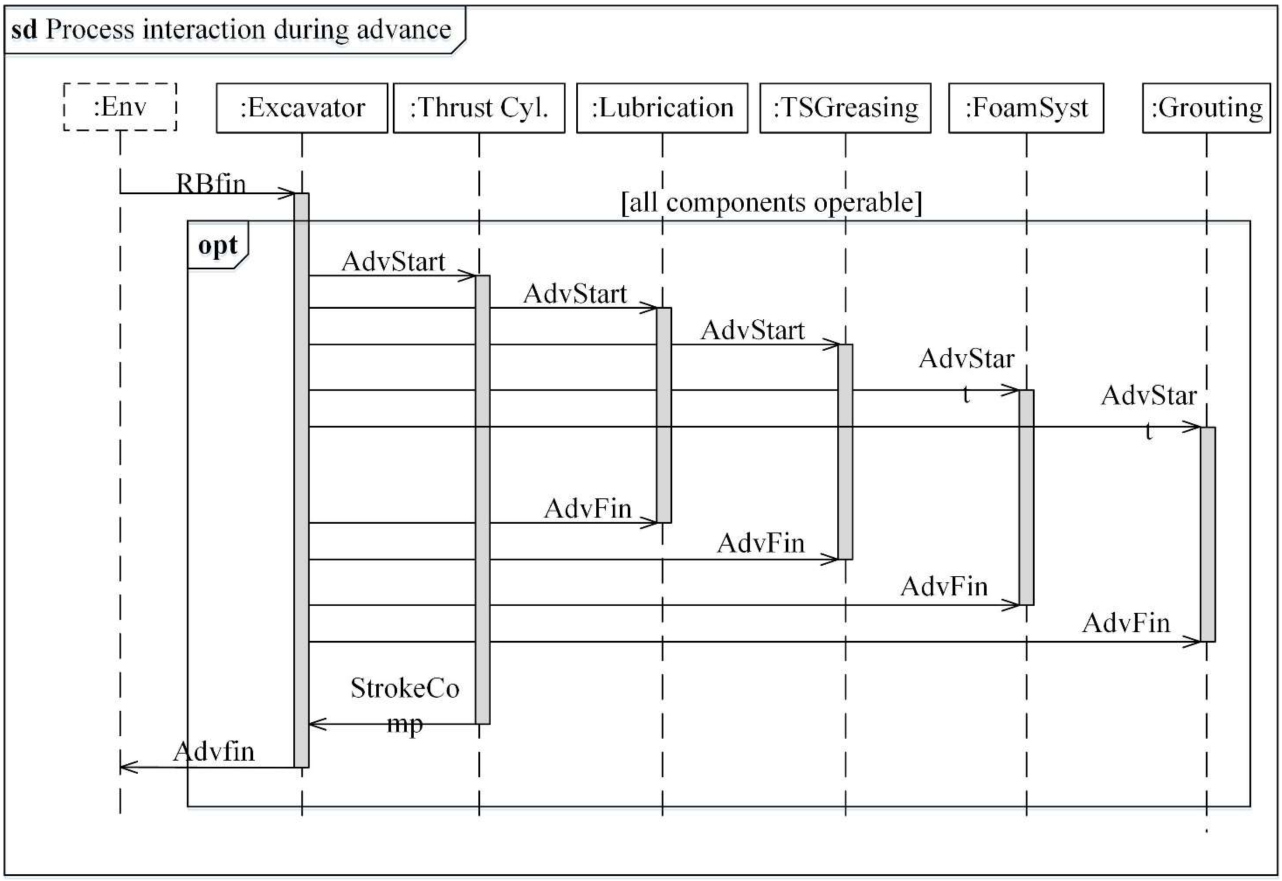


Figure 6-12: Sequence diagram of the advance process

6.4 Using formalized Models

Formalized models are very abstract compared to the usual workflow on a construction site. Most practitioners cannot relate to them and therefore they will not be regarded as useful initially to many. However, with the advent of simulation techniques, they represent a crucial link between the hands on world on a jobsite and dedicated simulation experts. As they contain the complete logical structure of the processes on a jobsite, simulation programmers are able to create models and run experiments without being directly involved with the constriction process itself. This allows a higher degree of specialization and thus creates better results. It is even possible to directly convert SysML diagrams into executable simulation models.

Another side effect of transforming mere flowcharts into a formal modeling language such as SysML is the enforcement of unambiguity. While non-formal process descriptions allow misinterpretation easily or might lead to certain mutual influences being overlooked, formal approaches force the modeler to analyze and classify the relations of model elements. This is a great advantage as many real difficulties on jobsites stem from mutual disruptions of processes which haven’t been known at the time of planning.

7 Analytic Methods for TBM Logistics Planning and Performance Prediction

As introduced in chapter 3, the tunneling industry uses a number of common tools to plan and validate the logistic systems which are operated on site. They are mostly not of academic origin but have been developed by site managers on the job and are seen in many different variations. A number of theoretical works on TBM tunneling include basic concepts of logistic planning but hardly in the level of detail which would be necessary in practice. They all have their place in planning but often although these tools are being used, still logistic problems arise later throughout many projects. This can in many cases be attributed to mistakes in the way of usage but also to using unsuitable methods for the questions to be answered. Another frequent issue is the use of improper input data. Knowing the abilities and limitations of these tools is therefore necessary to use them successfully. This chapter will outline a systematic planning approach developed on the base of these methods and underline their application with the theoretical principles that allow understanding their correct use. This is done by applying them to the example project which has been introduced in section 6.1. Generally, the planning process can be divided in a number of distinct steps:

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.

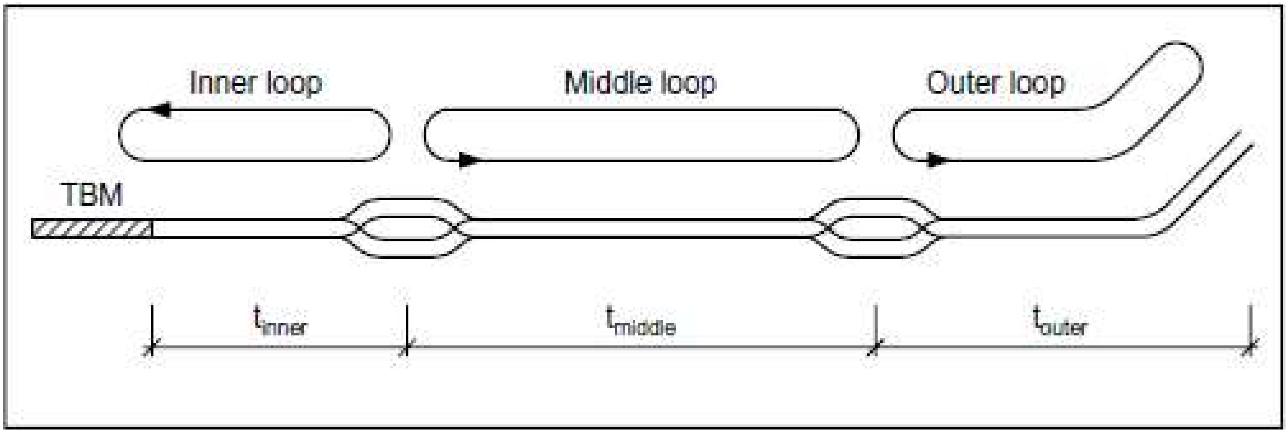


Figure 7-1: Transport cycles on a TBM jobsite (Bruland, 1998)

The main idea behind this procedure is compartmentalizing the different sections of the jobsite into individual sections or loops 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 step by step through the jobsite until knowing the whole system. This principle is shown in Figure 7-1 with loops between rails switches. 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.

Performance prediction for construction machinery defines different factors which determine the performance of certain equipment. These are foremost technical factors but also human, organizational and environmental factors (Girmscheid, 2004). While these factors may be derived for individual processes, with the exception of technical factors, they are not deterministic. This makes their prediction hard.

7.1 Performance Estimation

In order to estimate the performance of the TBMs, the tunnel alignment of the example project is separated into its different geological sections. For each section the estimated advance speeds are determined. While the Colorado School of Mines model which is introduced in section 3.2.1 is applied to the hardrock sections, the softground and estimated based on references in similar geology. In mixed ground sections the maximum penetration is estimated according to the CSM model as well, but capped at 10mm to protect cutters from damages. According to the longitudinal cross sections as shown in 6.1.1, the soil share distributions shown in Figure 7-2 can be extracted for the two tunnels. Subsequently for each type of geological formation, the penetration rate can be determined. These will be enhanced by estimated utilization rates and therefore an overall advance rate is determined. Further details of the encountered geology can be found in Appendix 1 – Example Project Geology.

Soil/ Rock	**North**		**South**	
	Length (m)	Distribution %	Length (m)	Distribution %
Full Face soil in G VI	1,569.15	51%	1,510.88	49%
Full face mixed soil (residual + Marine Clay)	213.39	7%	244.35	8%
Mixed face (G V + G III)	551.95	18%	688.51	23%
Full face Rock (Granite)	714.42	23%	615.69	20%
Total (m)	**3,048.91**		**3,059.44**	

Figure 7-2: Distribution of tunnel length in various lithologies for north tunnel (left) and south tunnel (right)

7.1.1 Advance in Hard Rock

In hard rock, the advance rates are determined using the Colorado School of Mines (CSM) Model. The model has been introduced in section 3.2.1. The described model has been implemented in an independent calculation software which is processing the values for TBM parameters and rock properties to derive estimated penetration rates. In an iterative process the parameters are adjusted until one of the limitations – thrust, torque or cutter geometry- for the performance of the TBM is reached. The alignment consists of several granite sections in different grades of weathering. While G VI and G V are already weathered completely and can be classified as soils, the GI to G IV sections show partly considerable hardness and abrasivity. Each of the four rock types is evaluated using the CSM model. A screenshot of the implementation of the software tool which is used for the calculations is shown in Figure 7-3.

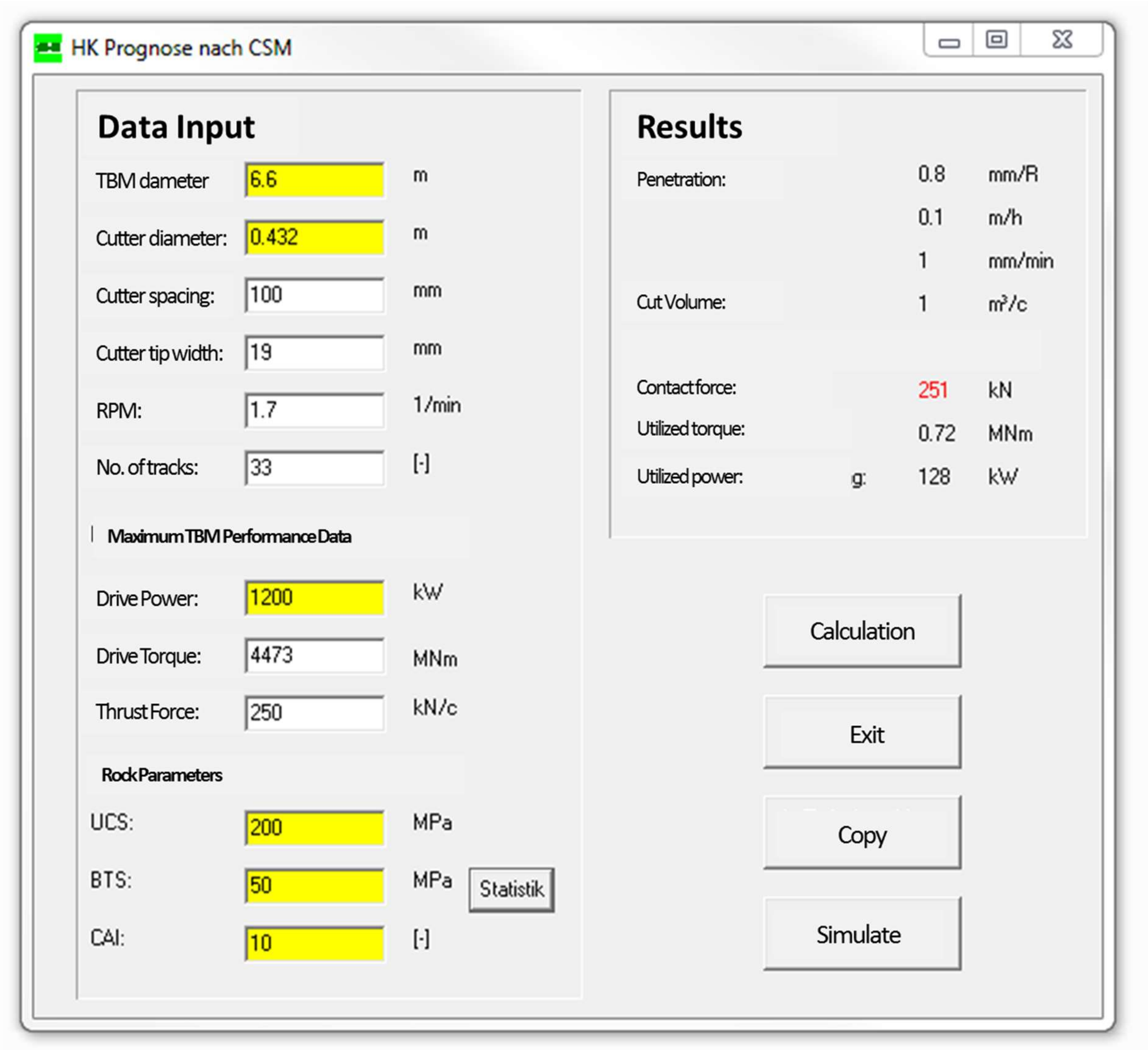


Figure 7-3: Software Implementation of the CSM model, (Herrenknecht AG, 2009)

One difficulty is usually the large spread of test result values. The calculation tool which has been used allows the input of ground parameters as normal distribution. This allows deriving probabilities for certain advance parameters. For simplicity the results shown here are calculated with average input values to derive average penetrations though. Based on the average values of hundreds of individual tests which are shown in Appendix 1 – Example Project Geology, the advance rates and wear parameters can be estimated as shown in Table 7-1. The full face rock sections are made up of GII and GIII grade rock, the mixed face sections mainly of G III and G V. As shown in Table 7-1, advance rates between 16 and 44 mm/min can be expected in the rock sections, depending on rock hardness and weathering grade.

Table 7-1: Penetration Rates and Cutter Wear in different Rock Sections

Parameter		**G IV**	**G III**	**G II**	**G I**
Unconfined Compressive Strength	UCS [MPa]	52	120	170	250
Brazilian Tensile Strength	BTS [MPa]	5.4	5.6	7.6	10.8
Cerchar Abrasivity Index	CAI [-]	3.23	3.58	3.77	3.5
Rock Quality Designation	RQD [-]	11	29	60	92
Penetration	mm / R	20	18	4,6	2,3
Advance Rate	mm / min	70	44	16	8
Cutter Lifetime	m³ / c	1318	1160	236	133
Cutter Changes / Ring	[-]	0,037	0,042	0,21	0,37

During tunneling in hardrock the influences on the advance rate are not only geological but also related to tool wear, damage risk and material transport. Especially due to the usage of an EPB Shield, the actual ground support while tunneling in the rock sections may be very difficult due to low fines content. This can further reduce the advance rates. The EPBs could be driven in open mode during the G II rock sections. This would allow high advance rates. When reaching the mixed face zones again, the machine must be driven closed mode again and subsequently the advance rates will drop until reaching the full face soil sections.

7.1.2 Tunneling in Mixed Face Ground

In mixed face conditions setting the advance rate for the machine is more difficult (Thewes, 2004). Theoretically, the model presented in (Thewes, 2004) would allow penetrations of up to 18mm with the rock parameters of G III. Therefore, advance rates close to 50mm/min would be possible. Tunneling in the soil sections of the face would allow even higher advance rates. However, the risk of impact and overload damages on the cutters is high. This risk can only be lowered by lowering the penetration rate and rotational speed of the cutterhead. Experiences on reference projects in mixed face geology and areas with many boulders have proven 10mm/min as a safe value to prevent damages. Although higher advance rates would be possible theoretically, the risk of shock impacts on cutters is high and therefore the penetration is artificially limited in such ground. In addition, the risk of face instabilities is high. Therefore, it is necessary to cross the mixed face section steadily and without stopping. This underlines the importance of adjusting machine parameters in such a way as to avoid damages instead of maximum drilling performance. Overall, although higher values may be calculated, depending on conditions, the advance rates should be limited to roughly 10mm/min in mixed ground.

7.1.3 Tunneling in Soft Ground

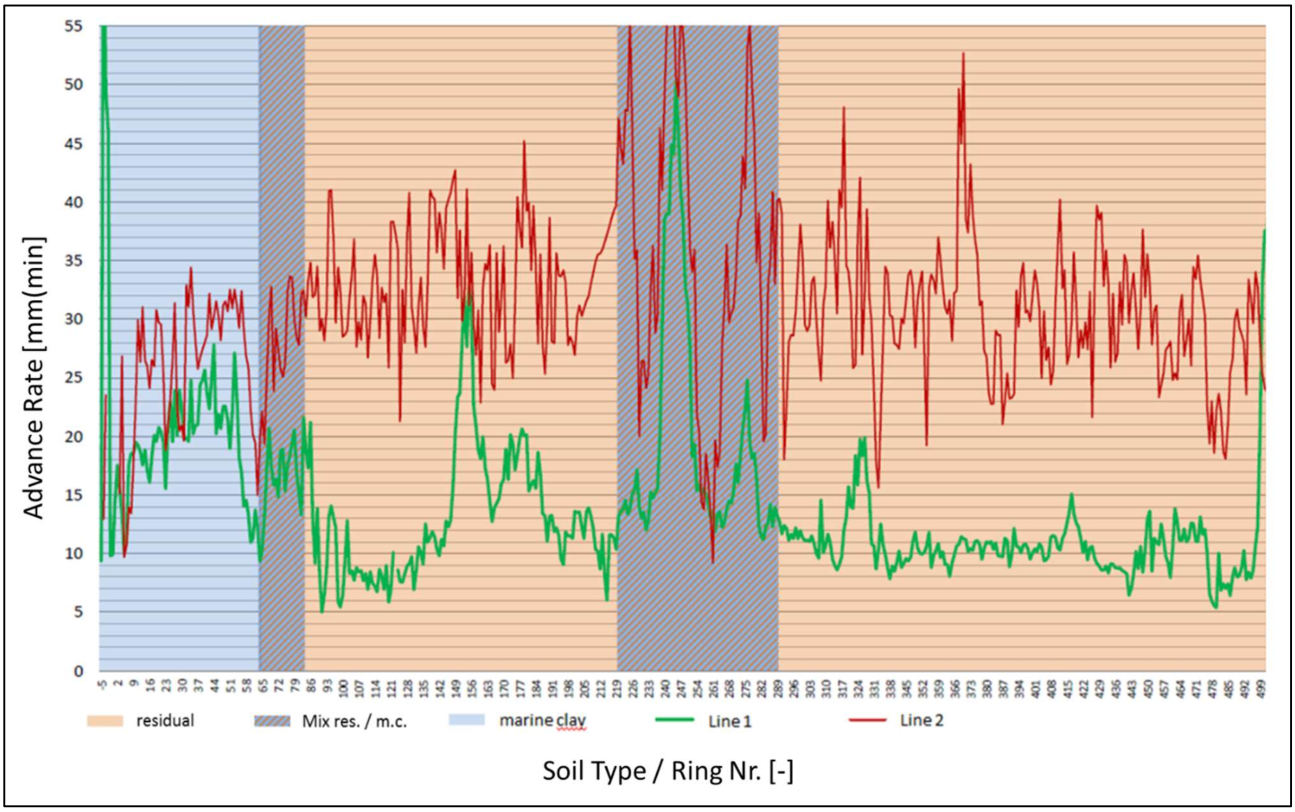


Figure 7-4: Advance rates of two reference projects in softground

There is no generally accepted analytic performance prediction model for softground tunneling. The variety and interactions between different soil particles and the countless number of different material properties have so far kept all attempts to develop analytic models from delivering realistic predictions. Therefore, the most reliable way to predict advance rates in softground is by comparison to reference projects which feature a similar geology and have been using a similar TBM layout and operation parameters.

The advance rates which are shown in Figure 7-4 have been achieved in the first and second lot (line1 and line2) of a reference project. Both have been tunneling through a comparable geology of residual soil and marine clay. Line 1 has been excavated before line 2 and the increased performance of line 2 can be attributed to learning effects regarding tool choice and conditioning. Based on this reference, it is to be expected to advance with 15-20mm/min in early soil sections of both drives, while learning effects lead to an increase to about 30-40mm/min towards the second half of the alignments. A learning curve model for mechanized tunneling in hard rock has been developed in (Wachter, 2001) and is adapted for the different soft ground tunnel sections using an inverse exponential decrease in performance losses.

7.1.4 Utilization Rate

A large influence onto the overall advance rate is the utilization rate. It is defined as productive time per overall time. Productive time for shield TBM tunneling includes advance and ringbuilding. In a number of publications focused on hard rock tunneling, lining erection is not included into productive time though (Rostami J. , 2015). Additional to the utilization rate of the TBM, its availability is often cited and usually a contractual element between TBM suppliers and contractors. The term availability refers to the technical availability of the TBM defined as the ratio of time during which the TBM is technically able to operate (i.e. not in the need for repair) to overall time. This value usually lies above 90%. The utilization rate mainly depends on the experience of the contractor and only to a minor degree on ground conditions and machine type. In Figure 7-5 (Maidl, Schmid, Ritz, & Herrenknecht, 2008) identify a number of typical working time distributions for different TBM types which have been measured in European jobsites. While the values for open TBMs vary significantly depending on geology, the values for shielded machines are strongly depending on operator experience and site management.

For shielded TBMs Maidl lists roughly 30% unproductive time, this is separated for maintenance, repair and downtime. Compared to international standards, such levels of utilization might be rather high. (Copur, et al., 2014) observed utilization rates around 50% on several projects in Istanbul. On the other hand, there are a few outstanding projects with utilization rates reach close to 90% after completing a learning curve. As the actual utilization rates will be hard to plan unless experiences with the actual jobsite management and operation crew exist, a conservative assumption should be made during planning stage. Later on possibilities for improvement should be actively researched and identified. This process is reflected by a growing utilization rate and shrinking ringbuilding time throughout the project. The learning curve model developed by Wachter (Wachter, 2001) is applied to expected utilization rates as well.

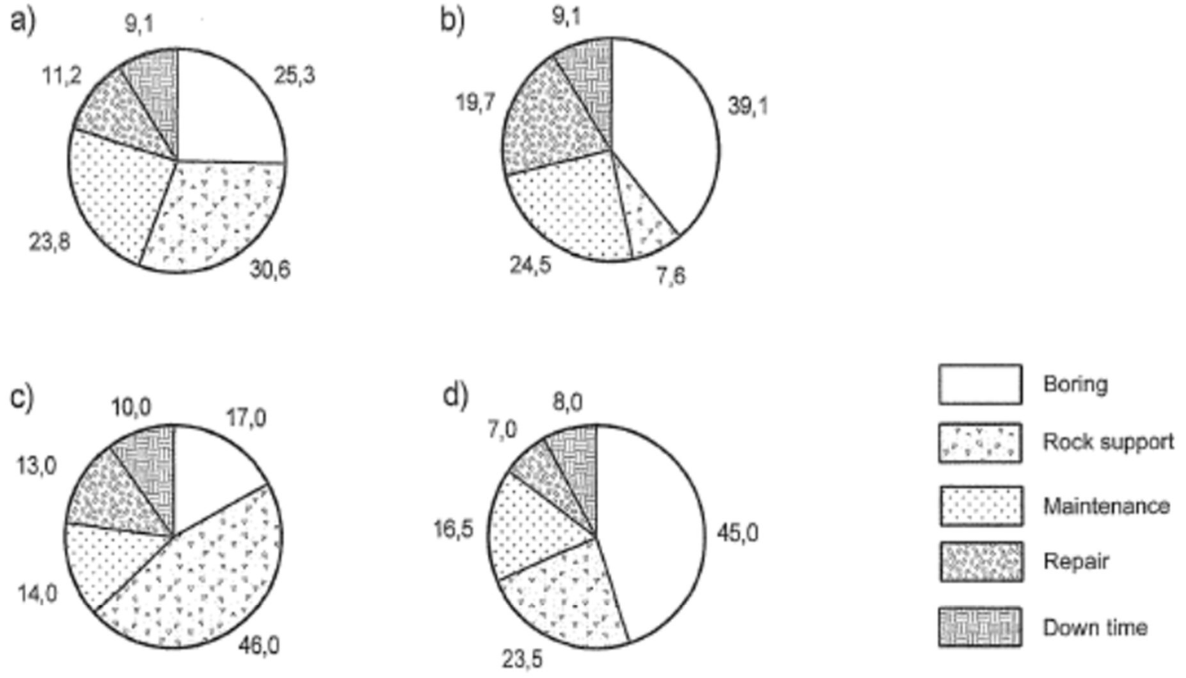


Figure 3-33
Distribution of activities during TBM excavation [%]
a) Gripper TBM ∅ 5 m with rock bursts
b) Gripper TBM ∅ 5 m with ruptures at face and around machine
c) Combination of a) and b)
d) Shield TBM ∅ 12 m

Figure 7-5: Working time distributions of different TBM types (Maidl, Schmid, Ritz, & Herrenknecht, 2008)

The ringbuilding durations also depend highly on skill and experience of the crew. Table 3-4 gives a guideline proposed by (Maidl & Wingmann, 2009). They propose a list of influential parameters on the ringbuilding duration as well, however without proposing their calculatory influence. The listed influences include foremost the number of segments per ring, segment size, connection method, lifting method, quality requirements, as well as the experience of the operators. Their proposed guideline is followed here.. Following operational parameter range will be assumed for the example project:

- 20 hours of daily operation
- 4 hours of daily maintenance period
- 40% - 75% utilization rate (considering maintenance as downtime)
- 45min – 90 min ringbuilding time

At a later stage, these performance ranges are broken down into an average performance scenario and a best performance scenario. While the average performance scenario reflects a moderate ringbuilding duration and advance rate, the best performance scenario assumes the best values which are realistically to be expected on the jobsite. Other jobsites might have higher or lower best performance values, as these are jobsite specific characteristics. The supply chain is calculated for both scenarios to ensure sufficient capacity. The availabilities are calculated based on a 24h work day in two 12h shifts. Time losses during shift change are included in the availability percentage.

7.1.5 Summary of Machine Performance Estimation

The individual advance rates, ring building durations and utilization rates lead to an individual daily advance rate for each geological section of the tunnel. An excerpt of this calculation is shown in Table 7-2. The detailed calculation is shown in Appendix 6: Analytic Planning Tools. Combining all sections leads to the expected total construction duration of 12.1 months for the north bound tunnel and 11.5 month for the south bound tunnel.

Table 7-2: Excerpt of the completion time estimation for the north tunnel

Track Chainage		Remarks	Advance Rate	Ringbuild	Cycle time	Util. Rate	Rings / day
From	To		[mm/min]	[min]	[min]	[%]	[-]
10,321.40	10,687.10	Full Face soil in G VI	15	90	183	40%	3.1
10,687.10	10,900.49	Full face mixed soil	20	72	142	50%	5.1
10,900.49	10,984.01	Mixed face (G V + G III)	10	63	203	50%	3.5
10,984.01	11,614.94	Full Face soil in G VI	20	54	124	55%	6.4
11,614.94	11,667.50	Mixed face (G V + G III)	10	54	194	50%	3.7
11,667.50	12,239.66	Full face Rock (G II / G III)	25	54	110	50%	6.5
12,239.66	12,264.20	Mixed face (G V + G III)	10	54	194	65%	4.8
12,264.20	12,425.24	Full Face soil in G VI	35	54	94	65%	10.0
12,425.24	12,533.48	Mixed face (G V + G III)	10	45	185	65%	5.1
12,533.48	12,616.97	Full Face soil in G VI	40	45	80	70%	12.6
12,616.97	12,790.01	Mixed face (G V + G III)	15	45	138	75%	7.8
12,790.01	13,118.00	Full Face soil in G VI	40	45	80	70%	12.6
13,118.00	13,198.43	Mixed face (G V + G III)	15	45	138	65%	6.8
13,198.43	13,340.69	Full face Rock (G II / G III)	25	45	101	70%	10.0
13,340.69	13,370.31	Mixed face (G V + G III)	15	45	138	70%	7.3

These durations do not include the assembly and disassembly of the machine or consider larger technical problems which often arise. They reflect a smooth though not overly fast completion which can be expected from a rather experienced contractor. The average performance of both machines is slightly above 8 rings per day. To further plan the logistic system, the maximum performance of 16 rings per day will be considered as well. Two scenarios can be identified as an “average performance” and a “maximum performance” scenario as shown in Table 7-3. These scenarios will be used subsequently for further planning.

Table 7-3: Average and maximum performance scenario for both TBMs

	Average Performance	**Best Performance**
Excavation Time	71 min	35 min
Ringbuilding Time	57 min	45 min
Cycle Time	129 min	80 min
Utilization Rate	57 %	75 %
Daily Advance	7 rings	13 rings

7.2 Determining Transport Volumes

The usual method to determine the transport volumes are simple transport volume tables which aggregate all information regarding consumables and materials from the TBM design data and tunnel infrastructure requirements. They provide a good overview of the requirements of the logistic system. They may be embedded into design sheets used for the TBM as well as individual calculations. The material consumption estimate is done based on different scenarios which have been outlined in Table 7-3 as average and maximum performance parameters. There are three different scenarios to be accounted for:

- Both TBMs in average performance
- One TBM in average performance, one in maximum
- Both TBMs in maximum performance

Often transport volume tables are separating the jobsite into several different areas and aggregate the transports for different goods in their batches between different locations on site. This has to be done detailed enough to picture all major transport operations. All processes must be atomized to prevent neglecting possible interferences between processes which have been grouped together at subsequent planning stages. As interferences between rather small processes can have a major impact on the overall durations, it is very important to fill the material transport tables on a detailed level. Practically this leads to two distinct sets of data. Firstly, there are the transport volumes for a single TBM for each scenario, secondly the joint volumes in the shaft and at the surface for both TBMs which have to be delivered to the site and stored and handled there.

7.2.1 Material Requirements per TBM

The material requirements for each TBM can be either derived from the TBMs design data or from experiences from past projects. Also special considerations regarding conditioning, greasing or other areas can influence the necessary amounts of consumables and should be considered. Table 7-4 summarizes the material requirements for each TBM and the necessary arrival frequencies for their supply.

Table 7-4: Material requirements per ring for each TBM

Material	Per Ring	Bring	Unit		Size	Frequency			Train
Muck	73 m³	4	Muck Car	of	10.2 m³	every	0.5 rings	on	Both
Segments	6 pcs	1	Stacks	of	3 pcs	every	0.5 rings	on	Both
Train Rail	0.47 pcs	1	Bundles	of	6 pcs	every	13 rings	on	Train A
Gantry Rail (circulated)	0.47 pcs	1	Bundles	of	2 pcs	every	4 rings	on	Both
Ventilation Duct	0.014 pcs	1	Cassettes	of	1 pcs	every	71 rings	on	Train A
HV Cable	0.01 pcs	1	Drums	of	1 pcs	every	107 rings	on	Train A
Tunnel Pipe	0.93 pcs	2	Bundles	of	6 pcs	every	13 rings	on	Train A
Walkway Material	0.35 pcs	2	Sets	of	1 pcs	every	6 rings	on	Train A
Tenside	0.11 cont.	1	Containers	of	1000 l	every	9 rings	on	Train A
Lub. Grease	0.02 barrels	1	Barrels	of	200 l	every	42 rings	on	Train A
Tailskin Grease	0.36 barrels	2	Barrels	of	200 l	every	6 rings	on	Train A
Tail Void Grout	5.1 m³	1	Tanks	of	6 m³	every	1 rings	on	Train B

After collecting the material transport requirements for each TBM based on average and maximum performance, these requirements need to be matched with a preliminary transport method. As introduced in section 6.1.3, the jobsite is planning to use two trains per machine which have four muck cars, one locomotive and one segment car each. Additionally, one of the two trains carries a grout car, the other one a flat car for other materials. Table 7-4 shows the delivery frequencies for all materials and on which train they are transported. While one train is delivering grout each ring, the other one commutes on many rings with an empty flat car and is used to deliver rails, foam, grease and other parts when necessary. The batch sizes which can be brought each time are matched with the storage capacity on the TBM backup gantries.

7.2.2 Material Supply Volumes to the Jobsite

These transport patterns apply for each TBM. For the whole jobsite the volumes shown in Table 7-5 result with the necessary adjustments made for the scenarios which have been identified. There is a considerable difference between a scenario where both TBMs advance with average speed and a scenario where both TBMs advance with or near maximum speed.

Table 7-5: Material volumes per scenario

Material	Per Ring	Daily Average/TBM	Daily Maximum/TBM	Daily Maximum/Site
Muck	73 m³	465 m³	985 m³	1969 m³
Segments	6 pcs	38 pcs	81 pcs	162 pcs
Train Rail	0.47 pcs	2.98 pcs	6.30 pcs	12.60 pcs
Gantry Rail (circulated)	0.47 pcs	-	-	-
Tenside	0.11 cont.	0.70 cont.	1.48 cont.	2.95 cont.
Lub. Grease	0.02 barrels	0.15 barrels	0.32 barrels	0.65 barrels
Tailskin Grease	0.36 barrels	2.32 barrels	4.90 barrels	9.81 barrels
Tail Void Grout	5.1 m³	32.8 m³	69.5 m³	138.9 m³
Ventilation Duct	0.014 pcs	0.1 m³	0.2 m³	0.4 pcs
HV Cable	0.01 pcs	0.1 m³	0.1 m³	0.3 pcs
Tunnel Pipe	0.93 pcs	6.0 m³	12.6 m³	25.2 pcs
Walkway Material	0.35 pcs	2.2 m³	4.7 m³	9.5 pcs

The supply of the jobsite and the storage capacities on site must be matched to maximum performance scenario as the jobsite storage capacities usually cannot be expanded at a later stage. The delivery batch sizes depend on the typical transport capacity of trucks, storage capacity and capital allocation as well as the delivery time of the related materials.

When looking at the number of trucks which have to commute, the amount of logistics which is even necessary to supply a jobsite with two metro sized TBMs running in one shaft it becomes obvious, that traffic volume and coordination are a great challenge. For larger machines the number of trucks which are necessary per day can easily surpass a thousand. In such cases, considering continuous transport methods becomes feasible. For the maximum performance scenario the delivery schedule of material to the jobsite is shown in Table 7-6. Taking the maximum storage volumes as well as truck loading capacities into account, a manageable delivery schedule is derived. Other considerations have to be bulk discounts, work for stock handling as well as permissible storage duration and lead times of the material. These material volume tables are the foundation for further planning. Drawbacks of these tables are the assumption of fixed durations and the reflectance of any types of interferences. Therefore, they should not be used as a standalone planning tool but rather as a step of collecting information for successive planning steps. The complete tables are listed in Appendix 6: Analytic Planning Tools.

Table 7-6: Jobsite transport and supply volume estimation

Material	Storage Capacity	Comments	Load per Truck	Trucks	Frequency
Muck	800 m³	Muckpit 20mx8mx5m	14 m³	every	1 day(s)
Segments	240 pcs	400m² storage area	6 pcs	every	1 day(s)
Train Rail	600 pcs	in general storage area	36 pcs	every	7 day(s)
Gantry Rail (circulated)	-	rotating in TBM Backup Area	-	every	-
Tenside	50.00 cont.	Barrel & Container storage area	12.00 cont.	every	8 day(s)
Lub. Grease	30 barrels	Barrel & Container storage area	20 barrels	every	30 day(s)
Tailskin Grease	60 barrels	Barrel & Container storage area	20 barrels	every	4 day(s)
Tail Void Grout	300 m³	Grout Silo in Batching Plant	10 m³	every	1 day(s)
Ventilation Duct	10 pcs	in general storage area	6 pcs	every	16 day(s)
HV Cable	10 pcs	in general storage area	4 pcs	every	16 day(s)
Tunnel Pipe	1000 pcs	in general storage area	500 pcs	every	40 day(s)
Walkway Material	400 pcs	in general storage area	200 pcs	every	21 day(s)

7.3 Designing the basic layout of the Jobsite

Layout plans are created for every jobsite usually at several stages throughout the project. They are used to visualize the usage of available space. Access routes, storage areas, assembly areas, offices, the structures which are to be built, traffic routes, location of fixed installations, cranes and all other facilities are shown on them. For the planning process, construction process, progress estimation and management purposes the layout plans of the site at different stages mark central planning documents. Therefore, they are regularly updated according to the progress of the construction. Figure 7-6 shows the basic layout of the jobsite with regards to the storage areas and logistic equipment which has been identified during the modeling stage as described in section 6.2.2. The development of the site plan is closely interlinked with the estimation of transport and storage volumes, as well as the general space requirements for all purposes. Therefore, an iterative development should be performed. Regarding logistics, the situation shown on the site layout defines the positions and reach of cranes, transport routes and possible conflicts. One such conflict might be for example between a transport route and the space requirements for ongoing construction operations. Even if just temporarily, blocking access for deliveries can interrupt the tunneling operation completely if it relates to critical goods. Furthermore, designing roads for one-way traffic flow is preferable to two-way traffic. In order to avoid such nuisances, the layout plan must be continuously updated to contain not only the assigned areas but also possible additional space requirement for temporary works. The layout proposed in Figure 7-6 will be used for further design of the logistic network.

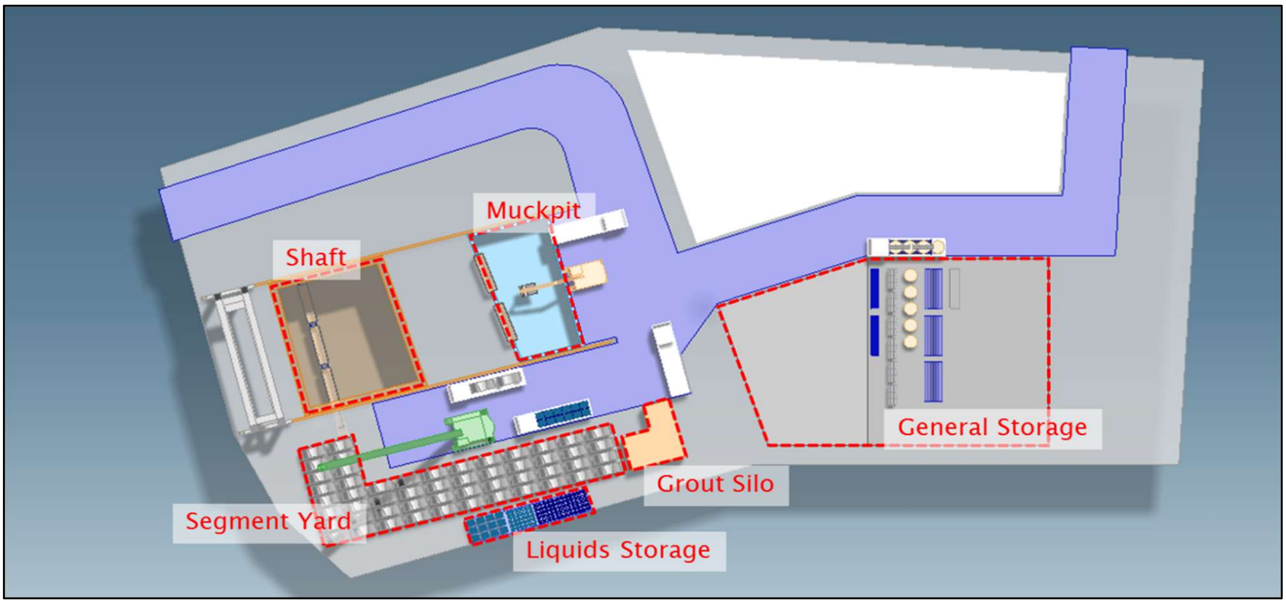


Figure 7-6: Layout of the example project jobsite

7.4 The Internal Working Cycle of the TBM

The basic approach for designing the TBM working cycle has been introduced in section 3.1.2. In order to define the machines working cycle, all processes have been identified throughout the modeling stage in section 6.2.3. To determine the TBMs working cycle, the processes must be brought into a Gantt chart. Figure 7-7 and Figure 7-8 show a 7-hour section of the TBM operation for average and maximum performance. The process durations have been assumed with average durations as determined in chapter 5. As analytic planning and simulation based planning are based on the same parameters, the complete set can be found in Appendix 7: Simulation Model Parameters. It becomes obvious that during most rings there are no issues and the cycle can be performed smoothly. For both scenarios there are several minutes lost every cycle due to changing trains during the advance. This forces the boring process to be interrupted for around 10 minutes to change the train. The actual duration during operation depends on the locations of california switches and the TBM. This directly increases the cycle time.

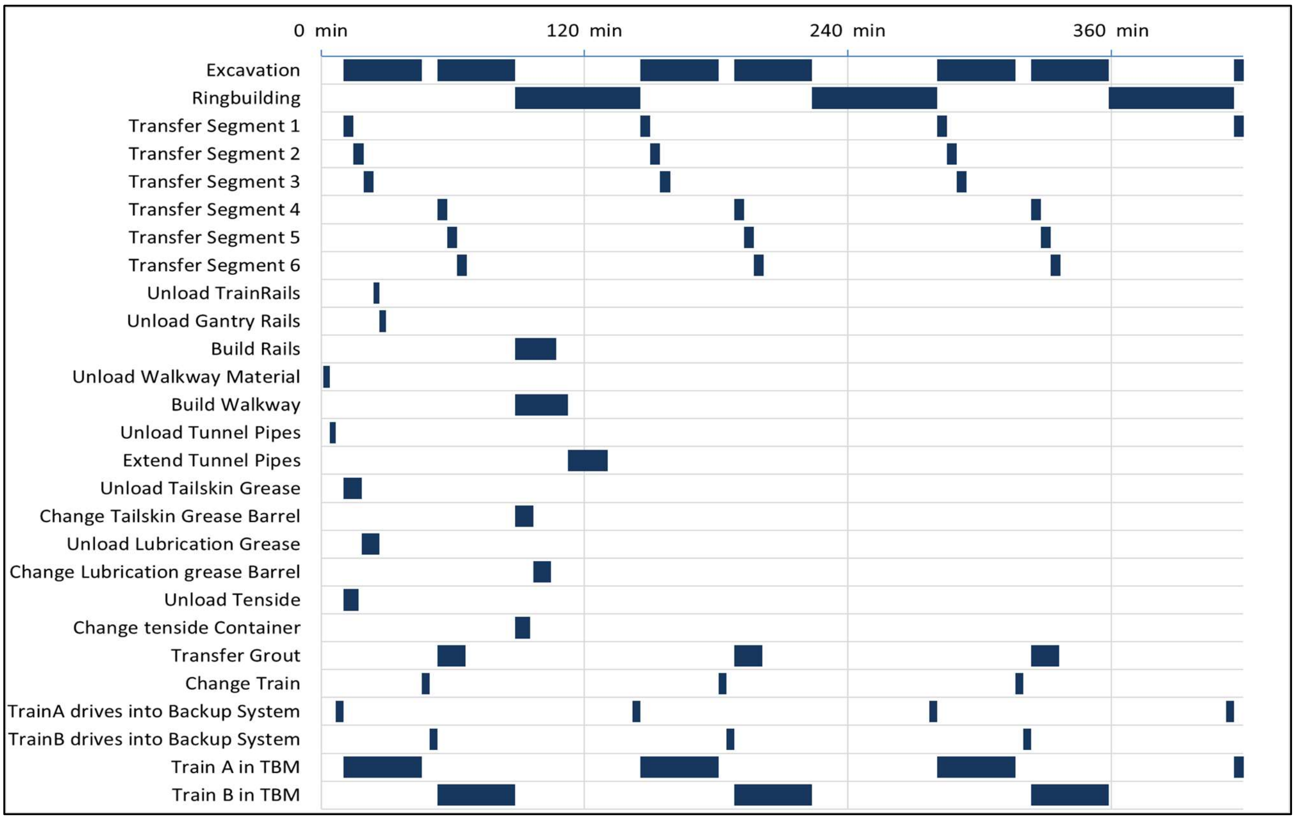


Figure 7-7: TBM cycle chart for the example project TBM in average performance (shown as table in Appendix 6: Analytic Planning Tools)

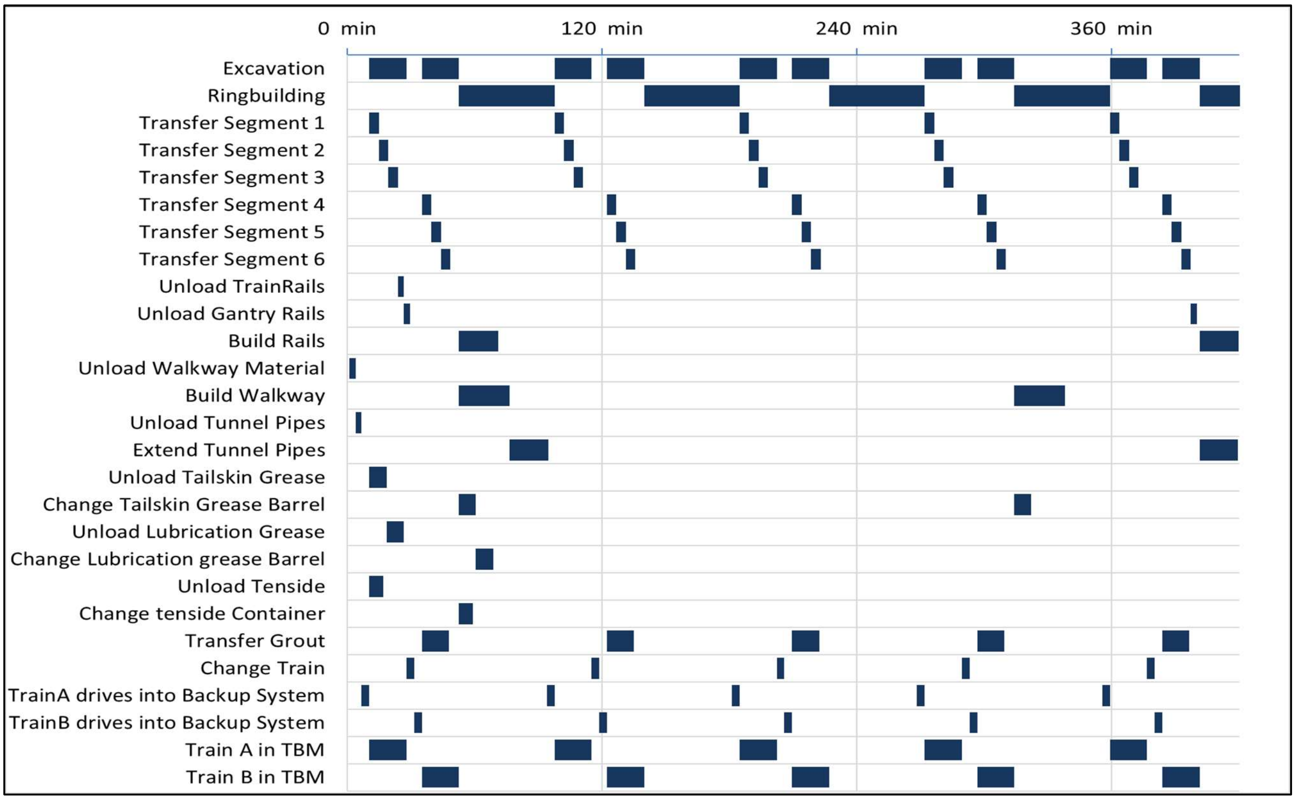


Figure 7-8: TBM cycle chart for the example project TBM in maximum performance (shown as table in Appendix 6: Analytic Planning Tools)

Additional to the processes shown there are several ones which take place in larger intervals such as the delivery of cutters, cable and ventilation duct. Depending on their duration they will interrupt the advance. Distributing them over several rings to avoid “process-congestion” further reduces standstills. Delivery and extension of the HV cables will interrupt the advance as well. However, designing the TBMs working cycle by using an isolated process chart ignores possible interferences inside the outer supply chain as it is assumed that the supply of the machine can always be timely following the TBMs demand. Therefore, the trains waiting time at the machine and the total cycle time for the maximum performance case form input values for the subsequent design of the transport cycle.

7.5 The Tunnel Transport Cycle

Vehicle timetables have been introduced in section 3.1.3 and will be designed for the example project throughout the following section. The tunnel transport cycle is using the above shown maximum performance scenario as its performance requirement. As both trains carry muck, the first one must arrive shortly before advance starts and the second one during advance. Therefore, the arrival interval is not constant. It is assumed that two trains can pass each other at the shaft and that a trailing california switch is placed behind the TBM to allow for quick exchange of the trains during excavation. Further californias may be placed along the length of the tunnel according to necessity. A shunting platform in the shaft allows splitting the train to make all cars accessible for the cranes. Figure 7-9 shows the proposed layout. With the proposed setup trains can pass each other in the shaft and directly behind the TBM. As excavation must be interrupted to change trains, this strategy minimizes the duration of this interruption. Table 7-7 shows the input parameters for the train cycle. The vehicle timetable shown in Figure 7-10 clearly shows that there is no need for further california switches along the tunnel if trains can pass each other at both endpoints. However, the mucking time in the shaft doesn’t leave much buffer time. Therefore, further increase of the TBM performance would not only require additional switches, but also create the need for a higher performance solution for mucking in the shaft. If mucking could be sped up, it may become possible as well to reduce the number of trains by one.

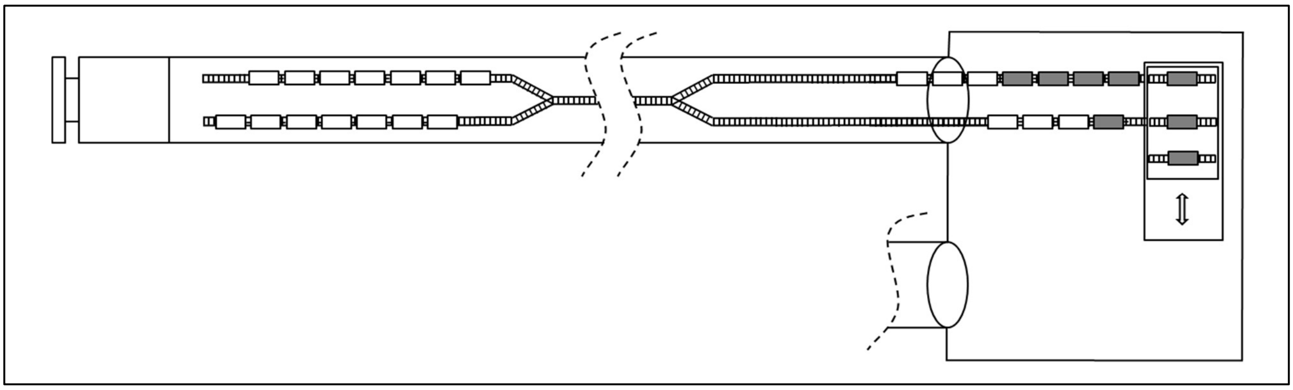
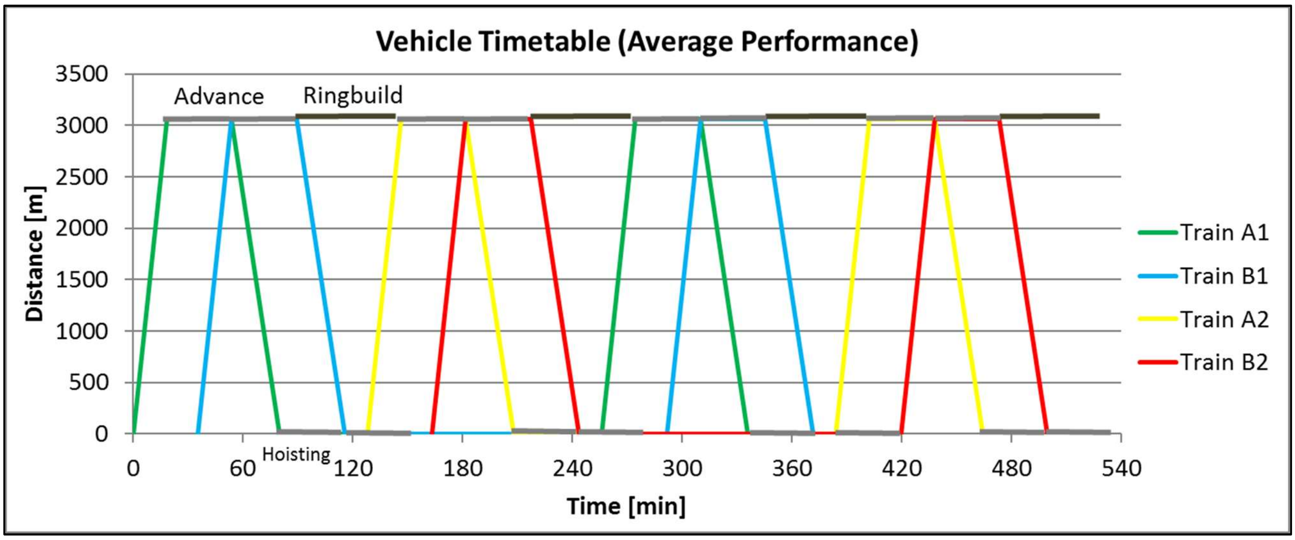


Figure 7-9: Proposed railway track layout for the example project

Table 7-7: Input parameters for the tunnel transport cycle

Parameter	**Value**
Train Speed	10km/h inwards; 7km/h outwards, 3km/h on switches
Standing Time at Endpoints	18min at TBM; 28min at Shaft
Ringbuilding Duration	45min
Tunnel Length	3060m

In this case the grout car and flat car would have to be switched between the two trains. As this would complicate coordination, the benefit is unclear. However, when indicating the mucking durations in the timetable, it already becomes obvious, that the single gantry crane is not sufficient to perform mucking for both TBMs running at maximum performance. This will be analyzed closer when determining the cranes working cycles.



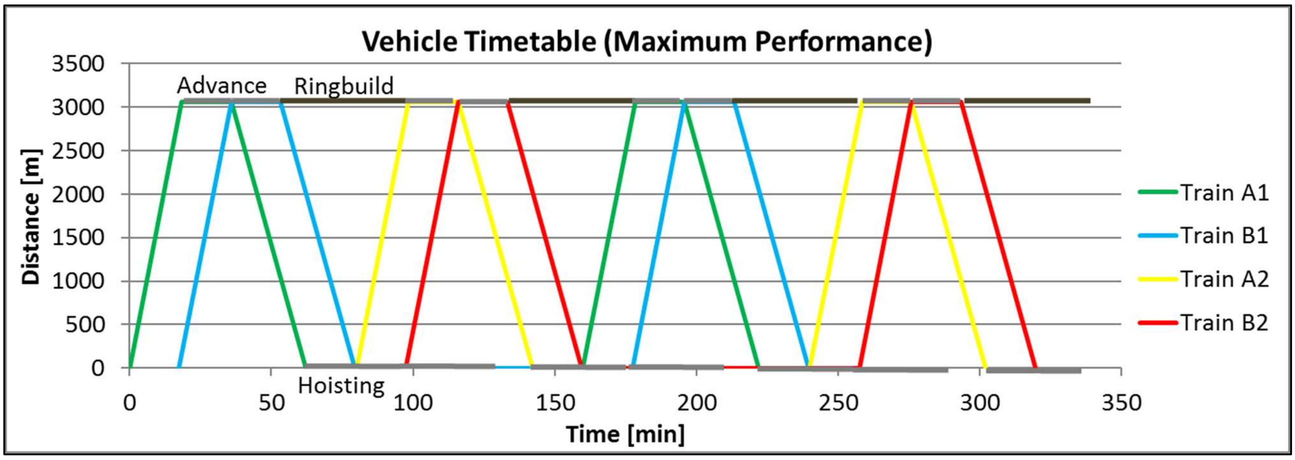


Figure 7-10: Vehicle timetable for average and maximum performance of the TBM

7.6 The Shaft Logistics

The small shaft leads to the necessity for trains to be shunted in the shaft floor to make them accessible for cranes. For this purpose a shunting platform is installed as shown in Figure 7-9. The platform fits three muck cars. After moving those three cars onto the platform, the rest of the train is accessible by crane. Loading and unloading operations can commence. Initially one gantry crane and one mobile crane are foreseen. All materials must be lowered and lifted by these two cranes. Additionally, they must have some free idle time reserved for additional surface operations such as unloading arriving trucks supplying the jobsite. Therefore, there are following key questions to be answered:

- Can the train shunting process be completed sufficiently quickly to keep the planned advance rates?
- Which effect do the crane cycles have on the TBMs performance?
- How much time is left for surface operations?

The shunting process is necessary to make all train cars accessible to the cranes. However, it costs additional time for the trains to spend in the shaft. The planned track layout is shown in Figure 7-9. Three muck cars must be placed onto the shunting platform. After loading and unloading the trains, the cars must be shunted back onto the track before the train may return towards the TBM.

Two cranes supply the TBMs. A gantry crane performs the mucking operation and a mobile crane all other loading and unloading tasks. Figure 7-10 has already indicated that the mucking cycle might not be able to sustain both TBMs operation at the planned advance rates. The following section will determine the possible performance losses. The crane operation is planned using crane cycle diagrams as introduced in section 3.1.5. They are based on tables which contain the durations of all individual working steps which the cranes perform. They are often prepared by crane suppliers to the tunneling contractors. The actual performance depends on the hook loads, operator abilities, jobsite communication and operation efficiency.

Movement paths should be known and the technical data of the cranes allows then to calculate the lifting and moving speeds. Taking each work step of the crane, the overall duration of a cycle can be determined. This process has to be determined for both cranes separately. Table 7-8 shows the input parameters for the shaft cycle calculation. Following the method introduced in Figure 3-5, the cycle is calculated. This includes on one hand the performance defining parameters of the loading and mucking processes and on the other hand the target cycle times for average and maximum advance speed.

Table 7-8: Input parameters for the crane cycle calculation (based on max. crane operation speed)

Parameter	Value	Parameter	Value
TBM min. cycle	80 min	Mucking horiz. Dist.	40 m
TBM avg. cycle	128 min	Shaft depth	40 m
Maneuvering Duration.	21 sec (x3)	Crane rotating angle	180°
Coupling Duration	201 sec (x3)	Hoisting Speed	40m/min
Muck Cars per Train	4	Lowering Speed	30m/min
Loading cycles per train	3(train A), 1(train B)	Traversing Speed	30m/min
No. of TBMs	2	Turning Speed	2°/sec
Muck Hook Duration	42 sec	Material Hook Duration	85 sec

Figure 7-11 shows the result. Fully emptying all four trains which are necessary to build one ring with each TBM takes 154 min. This is 26 min longer than the TBMs cycle in average performance and almost double the cycle time when assuming the TBMs best performance. Train shunting can be performed parallel which reduces the critical path cycle length to the duration of the muck hoisting cycle. In average it takes 132 minutes. Therefore, the mucking in the shaft is a bottleneck which limits the TBMs average cycle time to 132 min. This duration may be slightly reduced or increased depending on how the two TBMs advance is synchronized. It is obvious that plenty of free time exists for the mobile crane to perform unloading operations at the surface.

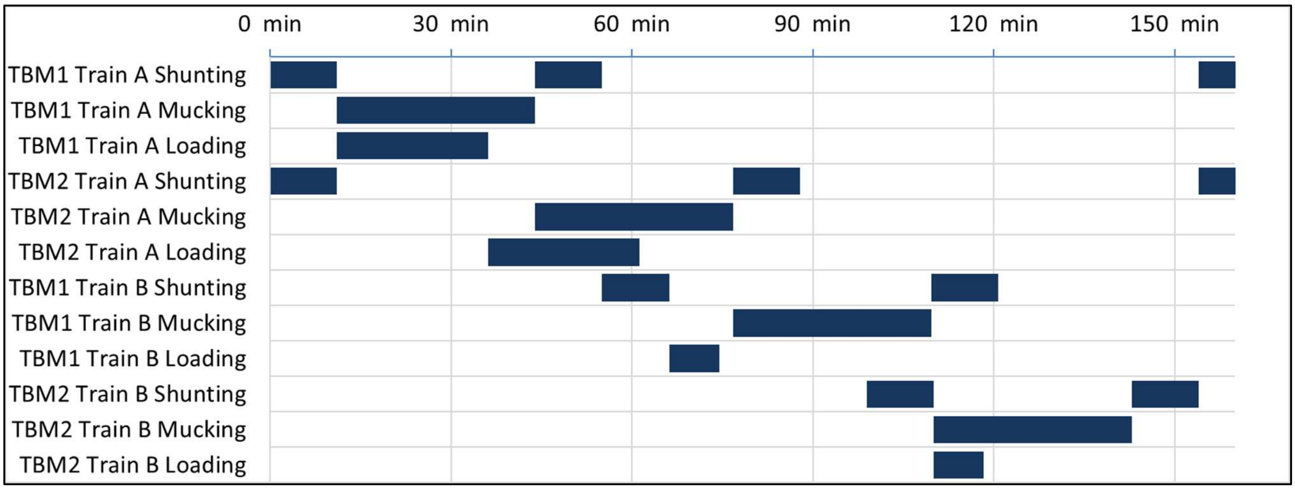


Figure 7-11: Working cycle of trains and cranes at their max. operation speed in the shaft for one ring of both TBMs (shown as table in Appendix 6: Analytic Planning Tools)

7.7 Surface and External Logistics

On the surface there are mainly delivery and material removal processes to plan. The main factors to consider are muck removal and delivery of segments, installation material and consumables. Table 7-6 summarizes the necessary amounts of material and the related number of trucks which are supplying the site. The major regular transports are segments and muck. Every day up to 27 trucks with segments must be unloaded. Using the method outlined in section 3.1.6, a cycle time of 5min can be determined. This task can easily be accommodated between the loading of trains. A daily total duration of little more than two hours would be required which cannot be used to service the shaft.

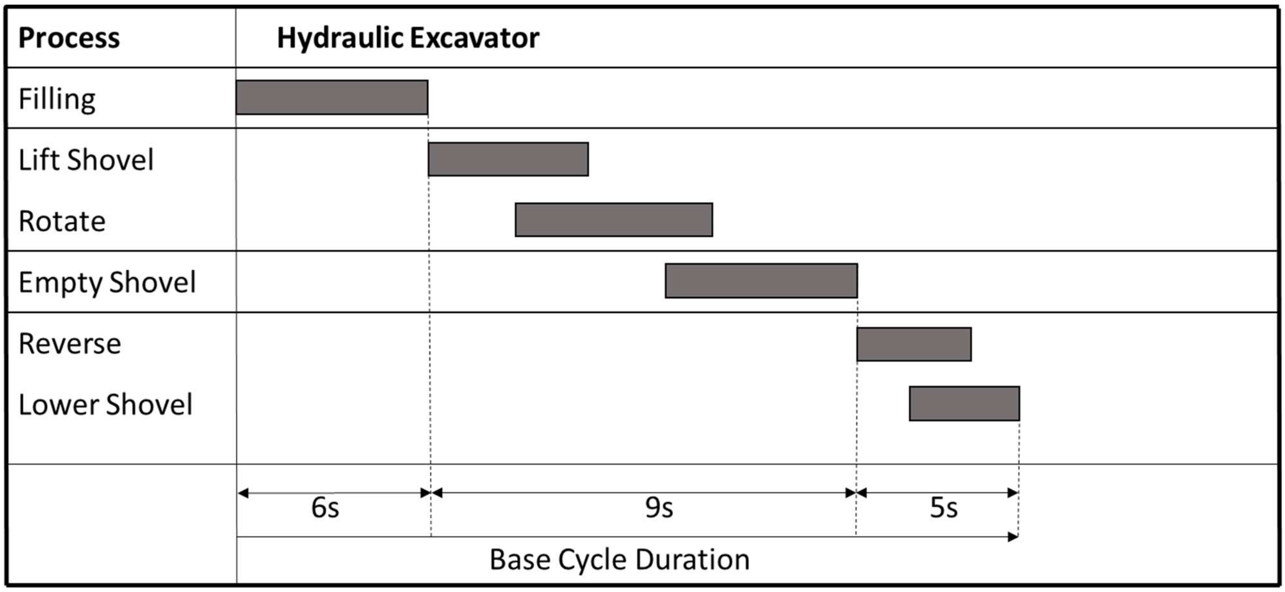


Figure 7-12: Determining the cycle time of the excavator loading muck (Girmscheid, Leistungsermittlungshandbuch für Baumaschinen und Bauprozesse, 2004).

As stated in Table 7-6, every day a maximum of 141 trucks must be loaded to dispose the 1969m³ of excavated muck. Each truck holds 14m³ of muck. With a shovel volume of 1,5m for the excavator this means 10 cycles for loading per truck. In total the excavator must perform 1410 cycles per day. Based on DIN18300 (Girmscheid, 2004) lists a cycle time between 18 and 20 seconds for a 1,5m³ shovel. The cycle time consists of the elements shown in Figure 7-12. They add up to 7:50h per day and can therefore be accommodated easily without developing into a bottleneck.

7.8 Summary and Review

The analytic planning methods form a step by step approach starting from the TBM and moving along the materials transport paths to determine each sections working cycle within the planned performance level. Direct feedback loops between the planning steps do not exist unless manual iterations are performed. In the present case the planning has revealed that the mucking process in the shaft poses a bottleneck for the proposed project design. The minimum cycle time that may be achieved for both TBMs is 132 min. Waiting periods frequently disrupt the advance cycle. The resulting operation cycle is shown in Figure 7-13.

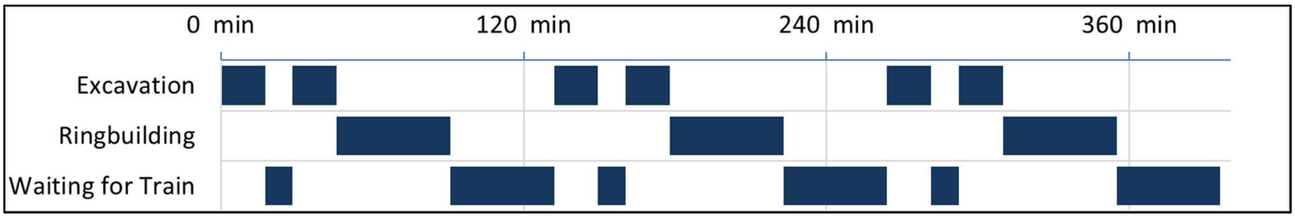


Figure 7-13: Actually achievable advance cycle, based on shaft logistics

A number of effects cannot be analyzed at all with analytic methods. Others can only be revealed with excessive manual iteration steps. These aspects and effects can be shown by introducing simulation software. Especially those which result from the interaction of probabilistic processes are difficult to understand based on purely analytic planning methods.

The different areas listed in Table 7-9 have considerable influence on a projects overall performance if the logistic network becomes more complex. In the presented example project where two TBMs share one shaft for supply, many of these effects are already difficult to grasp in an analytic planning approach. Some, such as the influence of geological uncertainty on the achievable advance rates can be captured by performing Monte Carlo simulation in spreadsheet based planning aids. However, the structural aspects of a logistic network are still not captured. To estimate their influence onto the TBMs expected performance, a simulation study is presented in chapter 8.

Table 7-9: Areas not covered satisfactory by analytic planning

Planning Aspect	**Examples**
Influence of parallel processes onto each other	• Repercussions from delays on one TBM to the other one • Effect of delays in surface operations onto the TBM cycle
Interaction of overlapping activities	• Effect of stochastic delays in segment transfer on the trains departure time at the TBM

Feedback loops throughout the system	• Effect of mucking cycle onto waiting durations at and positioning of switches in the tunnel
Holistic observation of the jobsite as a complete logistic system	• Visibility of the effects of individual events onto the whole jobsite as an interconnected system
Negative coupling of intercon-nected probabilistic processes	• Mutual influence of unloading duration of different goods which are unloaded after each other at the TBM in different locations.
Influences of disturbances	• Assessment of the effect of disturbances through-out the supply chain on the TBM. Such disturb-ances can be related to component downtime or caused by process interferences.

8 Simulation Based Logistics Planning

As outlined in section 7.8, a number of planning aspects cannot be investigated to a satisfactory level with analytic tools. Introducing simulation into TBM logistics planning solves several of these aspects. Section 3.4.3 introduced a number of applications for simulation in tunneling. When comparing their scope with the analytic jobsite planning process, a difference in level of detail becomes obvious. In order to support design decisions on the logistic system, a higher level of detail is necessary especially for material handling operations. However, it is very important to understand the abilities of both types of planning techniques to decide on which one to use for which types of problems. In areas where analytic solutions exist and are easy to find, introducing simulation might not benefit the planner enough to justify the additional effort. In other areas, sound planning can only be done using simulation techniques. This chapter follows the simulation study on the logistic system of the example project previously examined using analytic methods to clarify the implications and benefits of simulation based planning in TBM tunneling. The additional analysis capabilities that spreadsheet based Monte Carlo simulation delivers is examined as an intermediate case.

8.1 Monte Carlo Simulation of Process Chains

Most planners heavily rely on spreadsheets for most of their work. The obvious advantage is its wide availability and familiarity. With additional scripts and formulae, spreadsheets allow defining sophisticated logical operations. Input and output values are linked to each other by a defined set of formulas. There is however, a class of problems for which analytic solutions do not exist at all or are very difficult to find. This class is typically characterized by (Borshchev, 2013):

- Non-linear behavior
- Memory effects
- Non-intuitive correlations between elements
- Time and case by case dependencies
- Parallel probabilistic process chains
- Combinations of the above

TBM tunneling logistics is a typical representation of such a case. While many individual aspects of TBM logistics planning such as average performances of individual TBMs or the commuting duration of vehicles can well be captured in analytic models, there are many aspects that cannot. With increasing complexity of a jobsite –for example if several TBMs are supplied through the same shaft– problems arise which can only be captured by using executable simulation models. Foremost those are queuing models. If several parallel processes involve waiting entities and non-trivial probabilistic serving durations, analytic solutions for the overall waiting duration do not exist by definition. A typical example of this problem are the loading operations in the shaft shown in Figure 8-1.

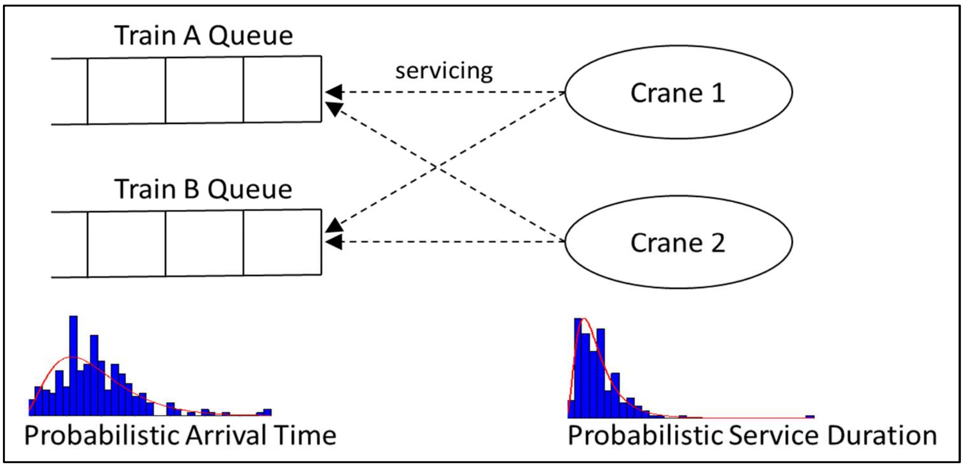


Figure 8-1: Queuing model of the loading processes in the shaft

While it is possible to calculate the cycle time of the muck hoisting and loading operations based on average process durations as shown in section 7.6, it is not possible to derive an analytic solution for the shaft logistics as a complete system. However, by using Monte Carlo simulation tools in spreadsheets, it is possible to calculate the influence of different probability functions on a connected sequence of events along a single critical path. Figure 8-2 shows how a sequence of individual processes – each of them of a probabilistic nature – can be combined in a Monte Carlo experiment to determine the overall behavior of the system in theory.

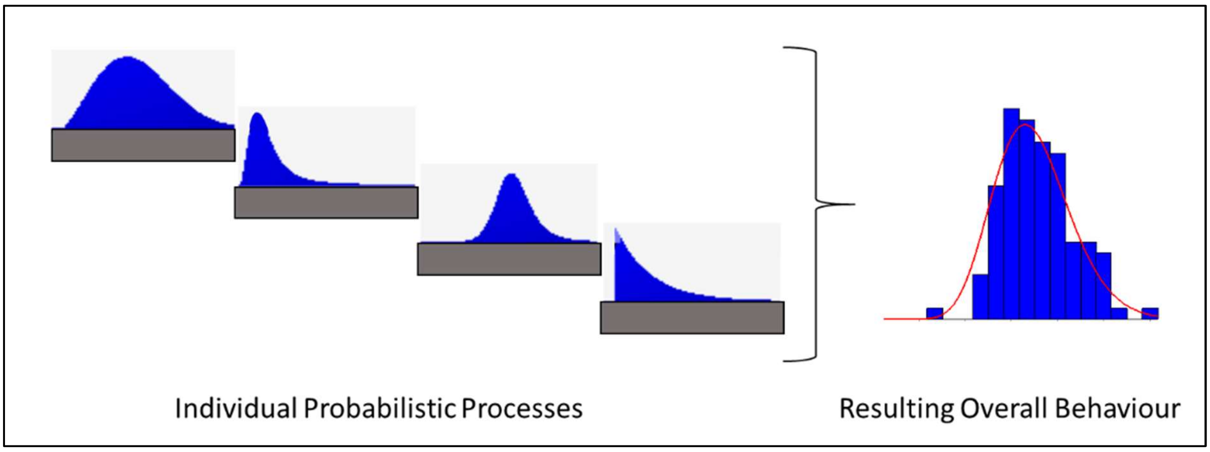


Figure 8-2: Principle of determining probabilistic overall system behavior

The waiting time of trains in the shaft is defined by such a chain of events. The trains must maneuver and shunt their cars to make them accessible to the gantry crane. Subsequently the crane must hook the muck containers, lift and move them to the muck pit, and after emptying them, return them to the train. This series of processes marks the critical path within the shaft and has been analyzed using the statistics add-on @Risk for Excel. The Monte Carlo simulation tool @Risk extends Excel models by adding the option of executing iterations of a calculation based on different samples from predefined probability distributions. When analyzing loading and muck hoisting durations in the shaft, the data in Figure 7-11 can be extended by replacing average durations with the underlying probability distributions. Subsequently the calculation of the trains waiting duration can be iterated *n* times and the resulting overall distribution for the total duration can be determined. This has been done based on the probability distributions given in Appendix 7: Simulation Model Parameters. The result is shown in Figure 8-3. The graph on the left shows the resulting overall distribution of the critical path in the shaft logistics. The graph on the right decodes the magnitude of influence of the individual processes on the overall chain. The larger the influence, the bigger the leverage to influence the overall result by improving this particular step. This marks an important advantage over the purely deterministic calculation based on average values as shown in section 7.6. However, this tool still focuses on only an excerpt of the complete logistic network. Another downside is that only predefined critical paths can be calculated. The effect of distributed arrival times of the elements, mutual process interactions or systemic changes over time still cannot be captured by such a model. In order to capture these effects, a more sophisticated simulation approach is necessary. This has been implemented in the commercial simulation framework Anylogic and is the topic of the subsequent sections.

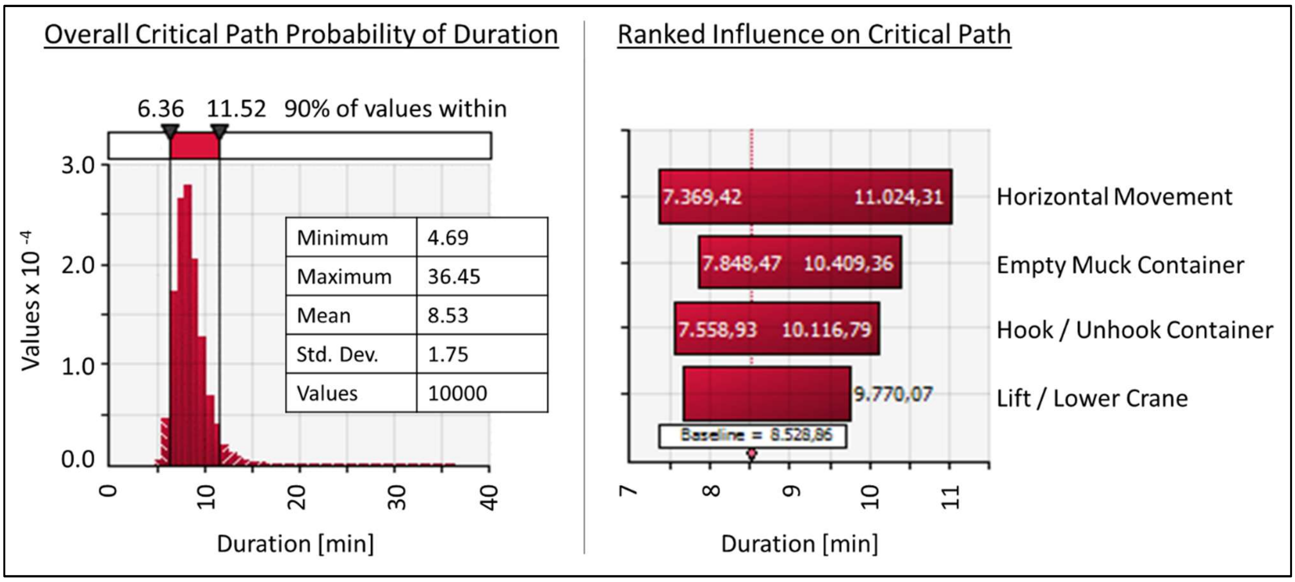


Figure 8-3: Duration distribution (in minutes) of the critical path in the muck hoisting cycle in the shaft from @Risk simulation

8.2 Implementation in a Simulation Framework

The formal model developed in section 6.3 has been implemented in the Anylogic simulation framework (XJ Technologies Company Ltd., 2008). Other than spreadsheet based simulation tools, this framework allows analyzing all processes on site and their interactions within a single model which leads to extended analysis capabilities. Especially the effects of uncertainty and mutual influences of different processes can be assessed in great detail. The Anylogic simulation software is a general purpose simulation software which supports different common simulation paradigms as introduced in section 3.4.1. Discrete event, agent based or system dynamic elements can be programmed and combined with each other. While containing many predefined elements, custom elements can be created using the Java programming language that forms the base for the Anylogic software. The TBM logistic model is built with its elements implemented as individual agents, which again have their behavior defined by state charts. Thus, each model element has its own defined behavior and is structurally independent from other model elements. The elements communicate with each other via an event manager that follows the observer-object design pattern.

8.2.1 Model Structure

The model contains all major logistics equipment elements on site. As in the theoretical SysML model, the executable model is structured into four main areas, the TBM, Backup System, Tunnel Transport and Jobsite Surface. TBM, Backup System and Tunnel Transport are grouped into an individual agent for each tunnel. Each element is implemented as its own modular java agent. This allows generating multiple instances of each agent in case several components of the same type are deployed on site. It also ensures modularity, which allows adapting the model to different projects. Additionally, the geological conditions and learning curve data have been added as an external reference on the models top level. On the structural level below the four main areas, all technical equipment that is relevant to performance has been modeled. Each component is again implemented as its own simulation module and instances are generated within the main areas they belong to.

Figure 8-4 shows a screenshot of the models top level in the Anylogic software. The purpose of the model is analyzing the logistic processes. Therefore, the main rationale behind developing its structure lies on the components for material handling and transport. Within the TBM, these components are the *Excavator*, grouping the excavation and muck handling functions within the TBM itself as well as the *Erector* for ringbuilding. The other components that are required for operating the machine are several support functions that use consumables and control their consumption. They are the *Grouting System*, *Tailskin Greasing, Lubrication* and *Foam System*. For these components to operate, continuous supply of consumables must be guaranteed. The logistics equipment within the backup system module perform unloading operations from the train.

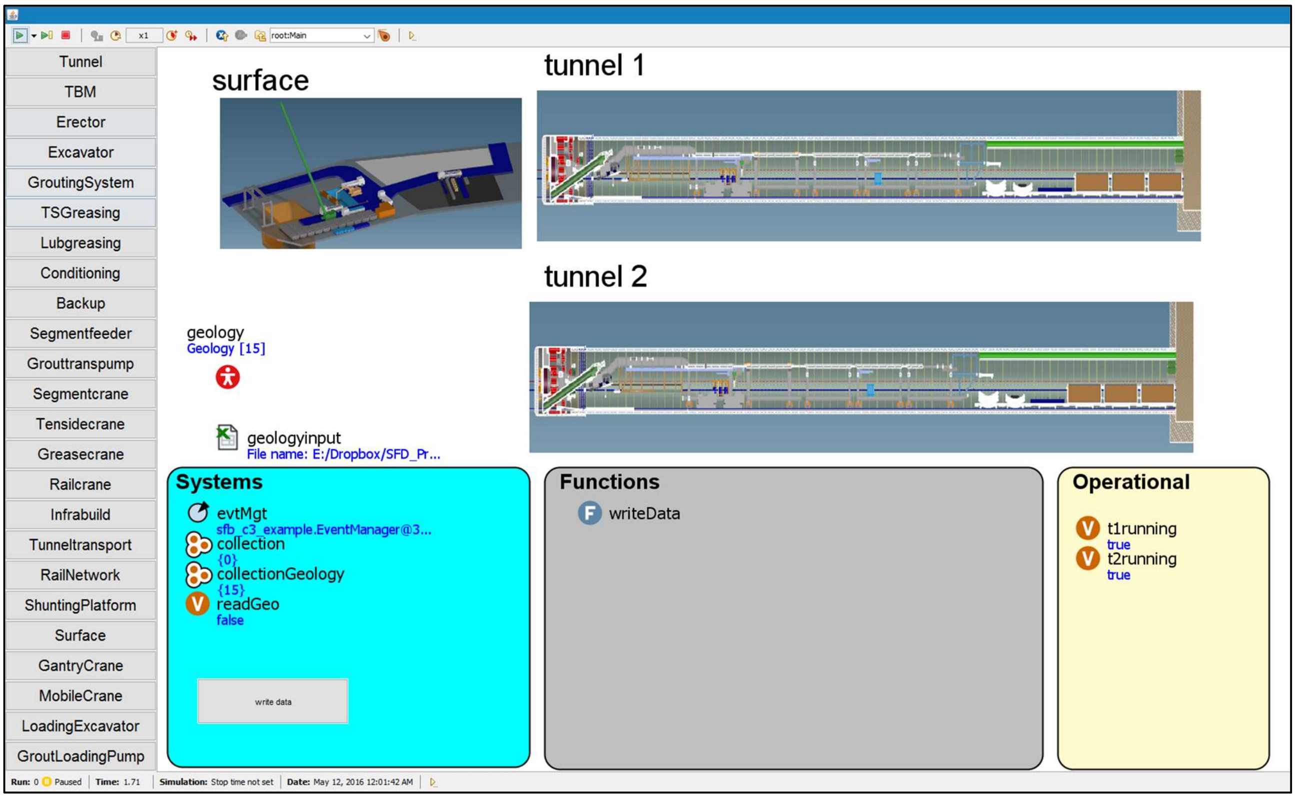


Figure 8-4: Screenshot of the models top level in the Anylogic software.

Within the *Backup System* module, the material handling related components are set. The *Segment Feeder* and *Segment Crane* deliver segments from the vehicles to the *Erector*. The *Grout Transfer Pump* transfers grout into the TBMs grout tank. Furthermore, there are the *Grease Crane*, *Tenside Crane* and *Rail Crane* to unload the related goods.

The *Tunnel Transport* module contains the *Rail Network* including *Switches* and *Trains*. The *Shunting Platform* in the shaft belongs to this module as well.

In the *Jobsite Surface* module are the *Gantry Crane*, the *Mobile Crane* as well as the *Storage Facilities*. *Trucks* arrive on site for material delivery and muck disposal. A *Loading Excavator* loads muck into the trucks for disposal.

8.2.2 Communication between Simulation Model Elements

The different model elements communicate with each other through a central event manager. This ensures a high degree of modularity as different elements do not need to know each other's internal structure to communicate with particular sub-elements. They only need to request or submit certain status information to the event manager. The event manager then forwards this information to other elements of the model. The event manager contains a list of predefined signals. Each element can register itself as an observer for certain messages. If any element within the system sends a particular message, the event manager forwards it to those other elements, which have registered as an observer for this particular message.

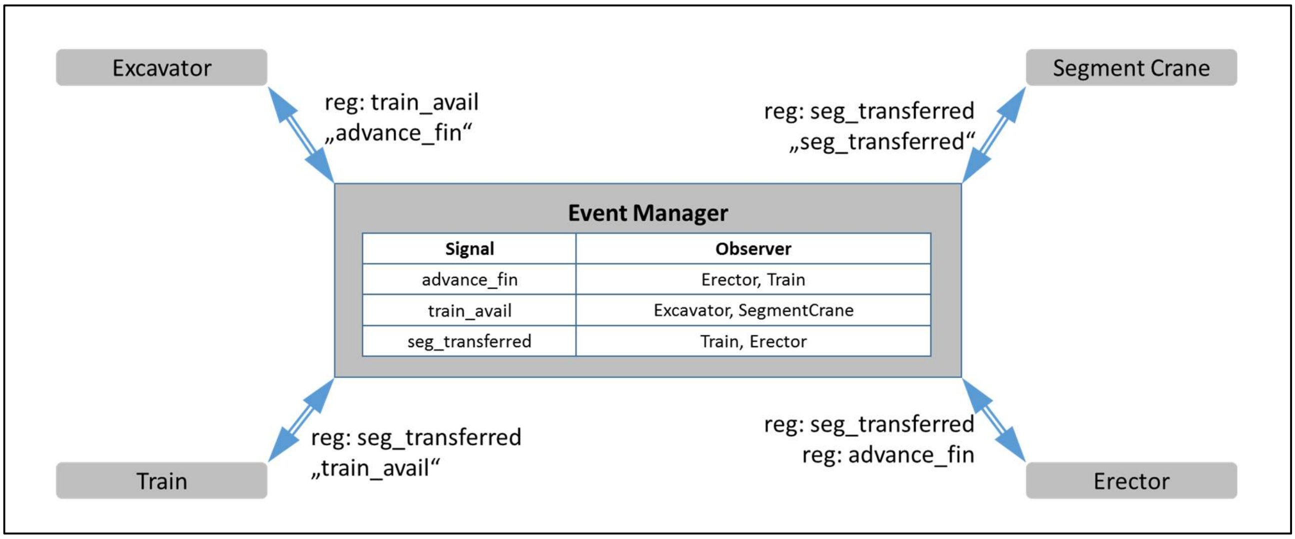


Figure 8-5: Communication principle through the event manager

Additional to the basic message, information on who is the sender element, as well as a boolean value are sent to transmit further information. All elements contain an update function that manages, which actions shall be performed locally within the element upon reception of a certain message. Figure 8-5 shows the communication principle of the event manager. The excavator registers for the message *"train_avail"* which signals the availability of mucking. Once finished with the advance stroke, the excavator sends the *message "advance_fin"* which is picked up by the erector which has registered for this message. This communication principle is implemented throughout all model elements. The model manager is of central importance to guarantee extendibility and adaptability of the model to different jobsites. Model elements can be replaced with other ones without the need to modify other parts of the model.

8.2.3 Modeling Components Activities

The components activities are modeled by statecharts as introduced in section 3.3.2. If certain requirements are fulfilled, the element can switch to another state. This could be logical conditions or time passing. Certain actions can be defined upon entry or exit of a state. Figure 8-6 shows the screenshot of the segment crane module as an example. The segment crane is in the state *idle* by default. When a train arrives with material to unload, the states *transfersegment* and *unloadrail* are entered. If *transfersegment* is entered, the different steps of the unloading process are cycled through until all segments have been unloaded. In case the train rails or gantry rails have to be extended, the segment crane will enter the state *buildtrails* or *buildgrails*. After all loading tasks are completed, the segment crane moves back into the *idle* state.

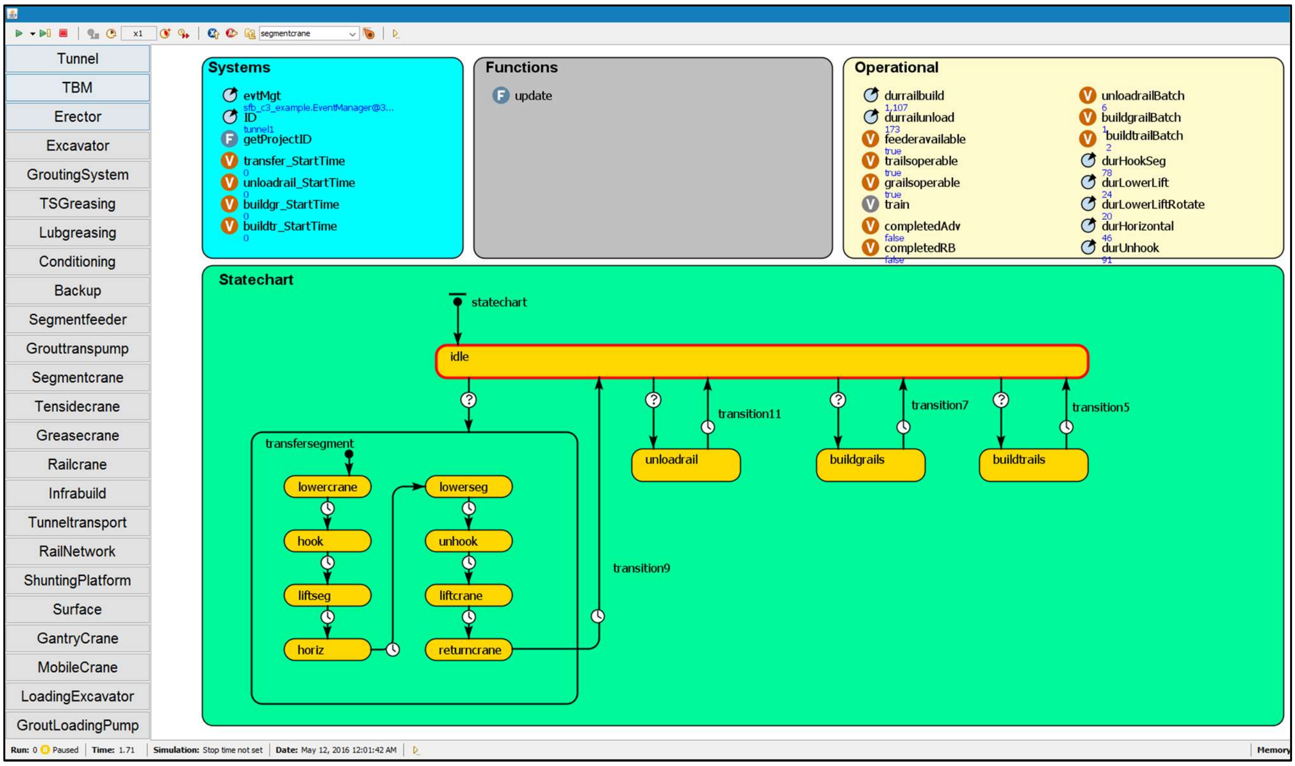


Figure 8-6: Screenshot of the segment crane module including its statechart

8.2.4 Defining Activity Durations

As a result of extensive field measurements, the activity durations of a large number of processes on tunneling jobsites have been determined. The measurement procedures and principles are explained in chapter 5 and the complete results of the data evaluation can be found in Appendix 5: Reference Data. AWhere available, the process duration parameters in the executable model should follow reference measurements. If exact references are not available, possible durations can be constructed. Several methods exist for this purpose. As explained in section 5.2.3, many construction operations have been found to be described well by beta distributions. Therefore, artificial beta distributions could be designed in cases where several series of measurements are available for the same type of process with different parameters. However, this must be approached carefully. If the available database is sufficiently broad, regression analysis or neuronal networks can be used to determine the influence of different technical parameters onto the distributions parameters. However, the main difficulty lies in the handling of unknown nontechnical parameters such as operator quality or communication patterns. As many important influences on the durations lie in the organizational quality and similar soft factors, estimating those correctly is difficult.

To avoid the additional uncertainty which artificial probability distributions add to a simulation study, for the study presented in this thesis, a direct transfer of existing data has been chosen. The complete set of all model parameters used in the presented simulation model is listed in Appendix 7: Simulation Model Parameters. The values originate from the measurement campaigns described in chapter 5. Datasets that match the technical parameters of the example project have been chosen from the available data to parametrize the simulation model.

8.3 Simulation Based Planning Support

In order to shed light on the implications and benefits of using simulation models as a tool for TBM logistics planning, the key points of the planning procedure as outlined in the analytic approach in chapter 7 are evaluated using the simulation model which has been implemented in the Anylogic framework. These include the TBMs internal operation cycle, the tunnel supply chain, shaft logistics, as well as the storage and loading operations on the jobsite surface.While executing the simulation model, runtime data is written and exported after a number of simulation runs. Table 7-9 summarized the drawbacks of analytic planning methods. Therefore, the following analysis will focus on these effects while following the step by step approach of analytic planning from the TBM to the jobsite surface.

8.3.1 Loading Operations within the Backup System

In order to analyze the loading processes within the TBM, the model utilizes realistically parametrized modules for all elements within the TBM, backup system and train interaction. All influences from the external jobsite sections are eliminated by reducing all process durations for surface handling as well as shaft and tunnel transport to neglectable levels. Therefore, they do not cause any possible delays within the TBM when executing the simulation model. This allows isolating all possible delays which originate from the loading operations within the backup system. The analytic planning outlined in section 7.4 already reveals that all loading operations except HV cable extension and ventilation extension can take place during the ringbuilding phase even in a maximum performance scenario. However, this may only be the case when considering average process durations. If probabilistic durations are assumed, longer durations may lead to a delay in tunneling in some cases. To establish a comparable base to the analytic planning methods, the process start and end times of each tunneling cycle are recorded. Based on these, a Gantt chart is created during runtime, which mirrors the structure of the result of analytic TBM cycle planning shown in Figure 7-8. Figure 8-7 shows the TBM operation cycle as recorded during the execution of the simulation model. When parametrized with fixed durations, the result is equal to the operation cycle as determined manually in chapter 7. As the simulation model is parametrized with probabilistic process durations though, the Gantt charts for each cycle as well as for each simulation run are unique and bear no indication for how representative they are for the overall performance. Only the subsequent analysis of aggregated stochastic data from many simulation runs shows interpretable results.

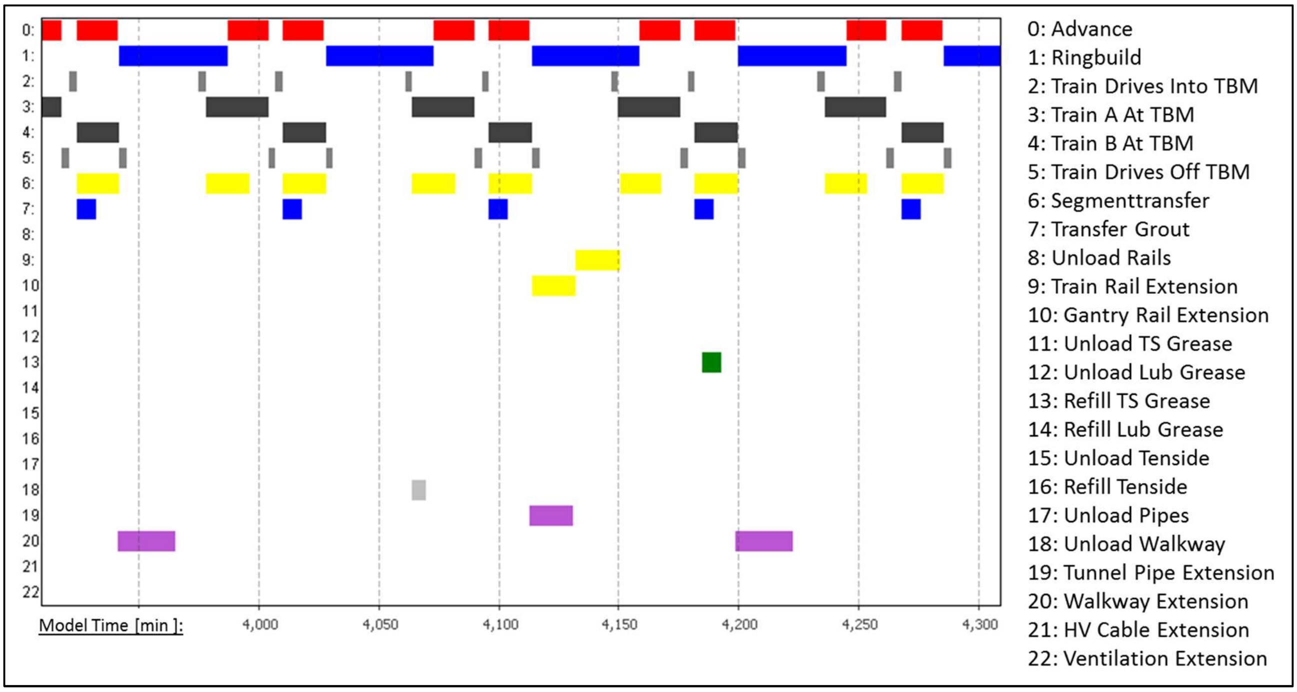


Figure 8-7: TBM operation cycle in a maximum performance scenario as determined by the simulation model

However, extracting Gantt charts during simulation runs allows observing the ongoing events and provide a valuable tool for validating the simulation model. Subsequently the simulation model is used to determine the characteristic downtime caused by the backup logistics in a Monte Carlo experiment of 1000 executions with probabilistic process durations. By comparing the results with the results of a simulation run with fixed process durations, the effect of deterministic process durations can be revealed. In order to ensure comparability and isolate the effect of logistics induced downtime, no other downtime is included into the model execution. Figure 8-8 shows this comparison. Downtime of 10.9% is caused by the necessity to change the train during the ring as each train only carries half a ring of muck. Downtime for HV cable extensions and ventilation duct extensions is included in this portion as well. In the case of the example project the additional downtime created by probabilistic process interactions effectively means that the critical path through the system changes when segment transfer takes longer than advance. As this is rather improbable, the associated additional downtime is shown in Figure 8-8 as a mere 1.2%. For the case of the example project, a robust design of the unloading processes within the backup system can be confirmed. Since the experiment only considers processes within the backup system, there are few parallel processes. In larger, more complex backup systems, probabilistic activity durations would drive up downtime to a larger degree as more parallel processes are executed.

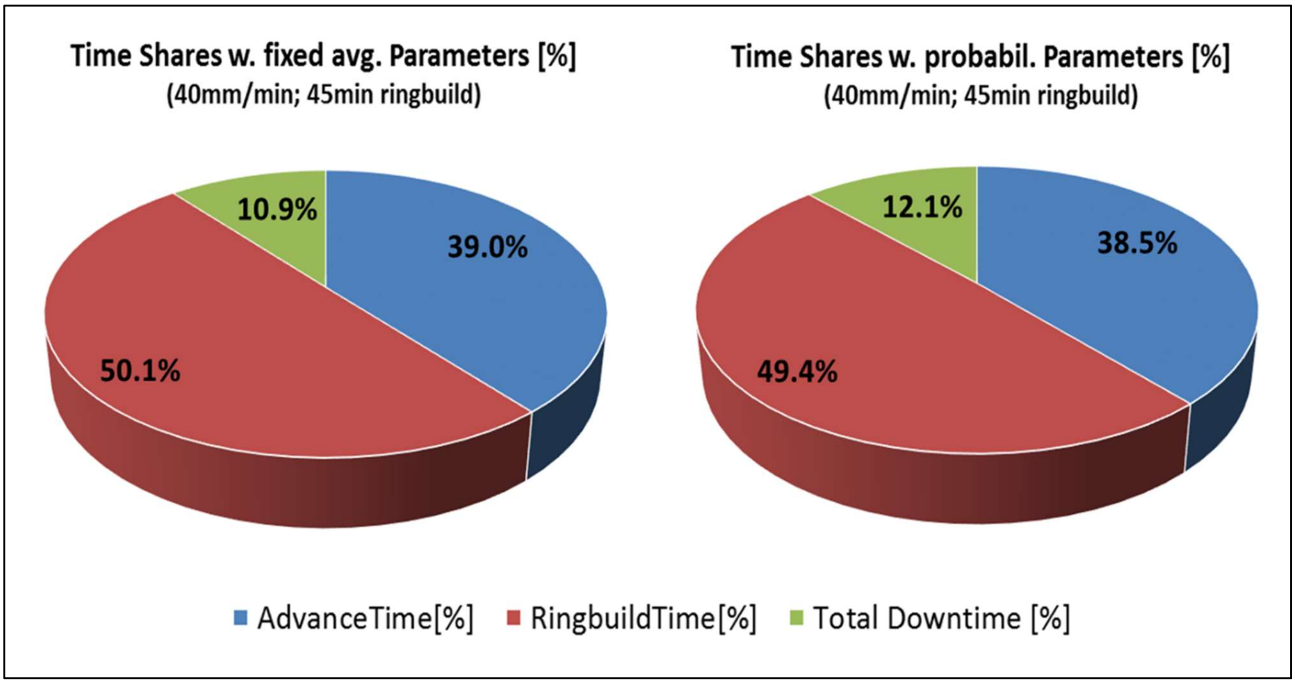


Figure 8-8: Additional delays caused by probabilistic process distributions within the isolated backup system. The results with probabilistic parameters show the average of a 1000 execution Monte Carlo experiment.

8.3.2 Tunnel Transport Cycle

In many projects the tunnel transport cycle is a major cause for downtime as either the number of trains and california switches is insufficient or their location incorrect. Therefore, the analysis of vehicle cycles forms one of the key elements of jobsite logistic planning. Figure 7-10 shows the vehicle timetable charts which analyze the transport situation in the tunnel. They depict a handful of vehicle cycles at a particular given tunnel length. According to Figure 7-10 the cycle is just not restricting the advance speed when operating both TBMs at maximum performance. The necessity of four trains was also determined for a maximum distance of 3km. One switch at the TBM and one switch at the shaft allow trains to pass each other. One effect that can hardly be estimated with analytic planning is the accumulated time loss due to a too little number of trains. If this amount of time can be determined, it becomes possible to perform a cost-benefit analysis for the purchase of additional vehicles. The exact tunnel length at which additional trains become necessary can only be determined after performing a large number of iterations using manual vehicle timetables. In a simulation experiment, the threshold where additional trains are necessary shall be determined, as well as the cumulated time loss when operating with only two trains per tunnel. In order to isolate the tunnels from possible disruptions caused by the crane hoisting processes, their durations have been fixed to low average durations in this experiment. Therefore, a bottleneck in the shaft is artificially avoided to determine only those time losses, which are caused by the tunnel transport cycle. To account for traffic disruptions within the tunnel, a triangular distribution has been assumed for the driving speed of the trains. One simulation run is performed with only two trains. Subsequently additional trains are added to the system at the point where downtime would increase otherwise. A Monte Carlo experiment is performed to determine the average downtime for each scenario. The experiment results are shown in Figure 8-9.

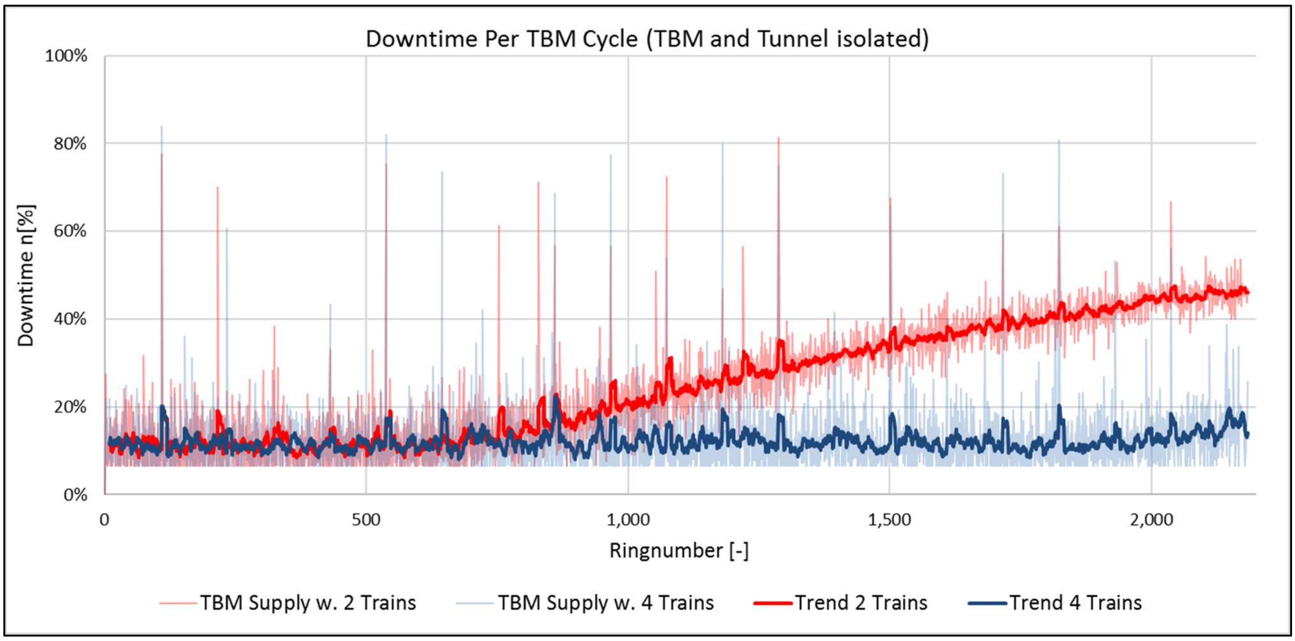


Figure 8-9: Trend line of time toss per ring for TBM supply with two trains and with four trains (single simulation run)

The comparison reveals that until ring 650 there is no difference. When the tunnel becomes longer, the driving durations require a second set of trains. When supplying each TBM with four trains, an increase in downtime starts to show around ring 2100, shortly before tunnel completion. If the tunnel was longer, additional trains and switches were necessary. High peaks are visible for rings where the HV cable or ventilation has been extended. They are independent of the transport scenario. Averaged over the whole tunnel construction period, the second set of two trains reduces the average downtime from 28% to 12.1% of the cycle time. This difference leads to a difference in tunnel completion time of 30 days. As in the previously discussed scenarios, the downtime cannot be lowered below this threshold due to the train change in the middle of the excavation cycle.

8.3.3 Loading and Unloading in the Shaft

The analytic planning process has revealed that in the example project the shaft is the bottleneck of the logistic supply chain. Figure 7-13 shows that the actually achievable performance is significantly reduced by the logistic system. The main reason is the gantry cranes cycle time for muck hoisting. The unloading of muck containers lies on the critical path and cannot be performed as fast as the TBMs can advance. While its performance can sustain a low advance rate for both TBMs, it is insufficient to allow both TBMs to advance at a high rate at the same time. Figure 8-10 shows the Gantt chart of a single simulation run for the shaft processes in this situation. The graph shows that the gantry crane is the bottleneck as it is permanently in use. Any slowdown directly impacts the availability of both TBMs. As the shown Gantt chart is the result of a single simulation run, the underlying data only becomes representative, when statistically analyzing a large number of runs as shown in Figure 8-11.

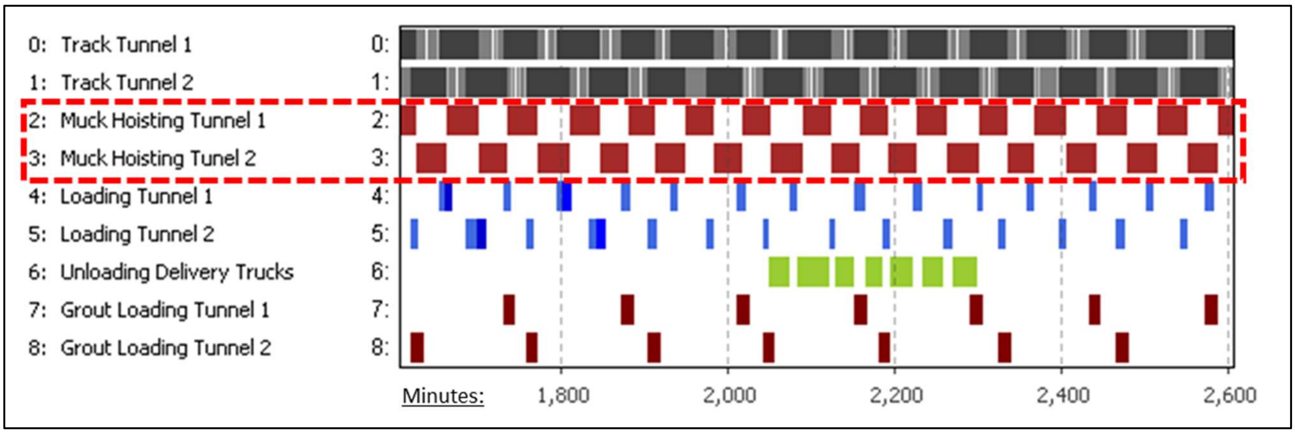
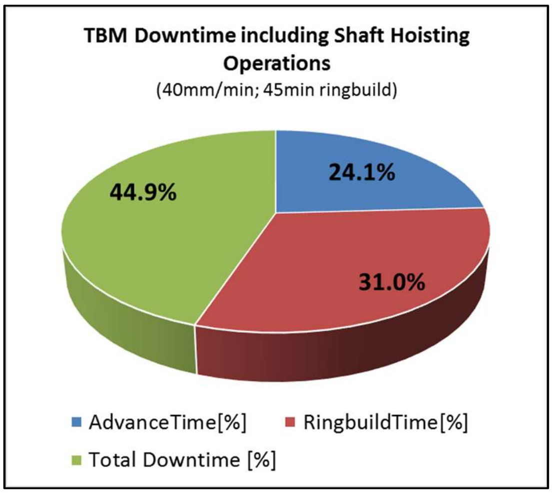


Figure 8-10: Activities in the shaft when advancing with both TBMs at maximum advance rate

The process interactions within the shaft and their influence on the TBM cycle durations are investigated further using simulation experiments. In the first experiment both TBMs are set to their maximum performance and the average resulting downtimes are determined in a Monte Carlo experiment. In a second experiment, the performance of one TBM is reduced to determine how this affects the performance of the other TBM. This procedure allows setting up possible scenarios and estimating the resulting performance losses. While the analytic planning just shows which average total advance rates can be reached, a simulation model reveals the effects of interaction between the logistic chains of the two tunnels. Figure 8-11 shows the downtime induced by the bottleneck in the shaft in the pie chart on the left side. The diagram on the left indicates that due to the cycle time of the gantry crane, 44.9% downtime arise when both TBMs are advancing at their planned maximum rate. Compared to the availability level can be sustained when isolating the tunnels from the shaft as described in the previous set of experiments, this marks a sharp incline. The gantry crane cannot perform the muck hoisting quick enough to sustain high advance rates on both machines. This leads to a mutual influence of the two TBMs advance rates as they are linked to each other through this bottleneck. This effect is shown in Figure 8-11 on the right side. When the TBM in tunnel 2 is forced to slow its advance rate and ringbuilding time at ring 500, the cycle duration of the other TBM decreases by about 20%. Especially for larger, more complex logistic networks effects like this are non- trivial and can only be solved using simulation techniques. The analysis in this experiment has been based on the maximum planned TBM advance rates. The subsequent section 8.3.4 extends this point of view with a holistic scenario involving learning curves and geological data.



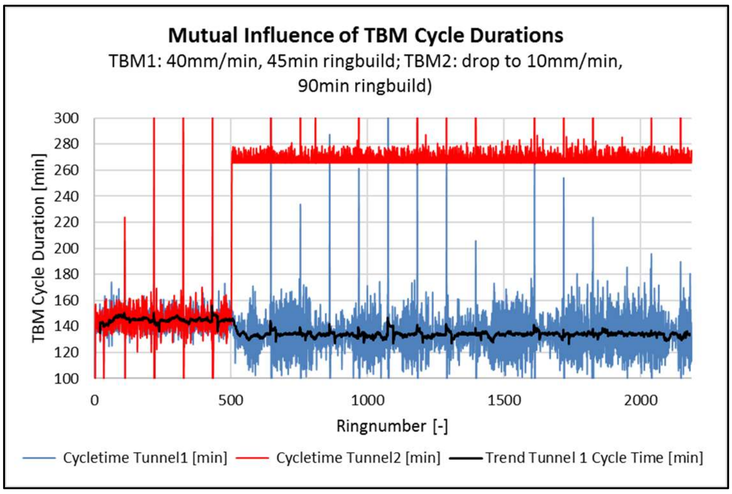


Figure 8-11: Performance losses due to interactions in the shaft between the two tunnels logistic chains

8.3.4 Holistic Simulation of all Influences

One major advantage of executable simulation models is the holistic view on the jobsite which they allow. All known effects on productivity can be combined with each other in order to determine the production rate of the jobsite. Additional to the previous experiments, this experiment includes different advance rates depending on the geology as well as learning curves leading to lowered ringbuilding durations over time. It does not consider probabilities for individual component failures, advance speed as well as ringbuilding time. Therefore, for determining probabilities for the overall completion time, this model would need to be extended on the base of individual component failure rate measurements. Including these would obscure and overlap the downtime caused by the design of the logistic system to determine which is the purpose of this experiment. These factors are considered in the downtime assumptions made in analytic planning. This simulation experiment only determines the downtime related to logistics. Figure 8-12 shows the resulting TBM cycle durations and downtime portion when executing a single run of the simulation model with geology based advance rates and learning curve based ringbuilding durations according to section 7.1.5. While the previous analysis has mainly focused on maximum advance rates and short ringbuilding durations, this experiment applies reduced values as estimated after geology analysis and past experiences. Unlike the maximum performance assumed before, this experiment is examining, how the logistic system can cater to the in reality often significantly lower performance demand of the TBMs. A number of interesting observations can be made which not only illustrate the practical limitations of the chosen logistic system but also lead the direction for possible measures for overall performance improvement. Table 7-2 shows the achievable advance rates and ringbuilding durations separated according to the different geological sections.

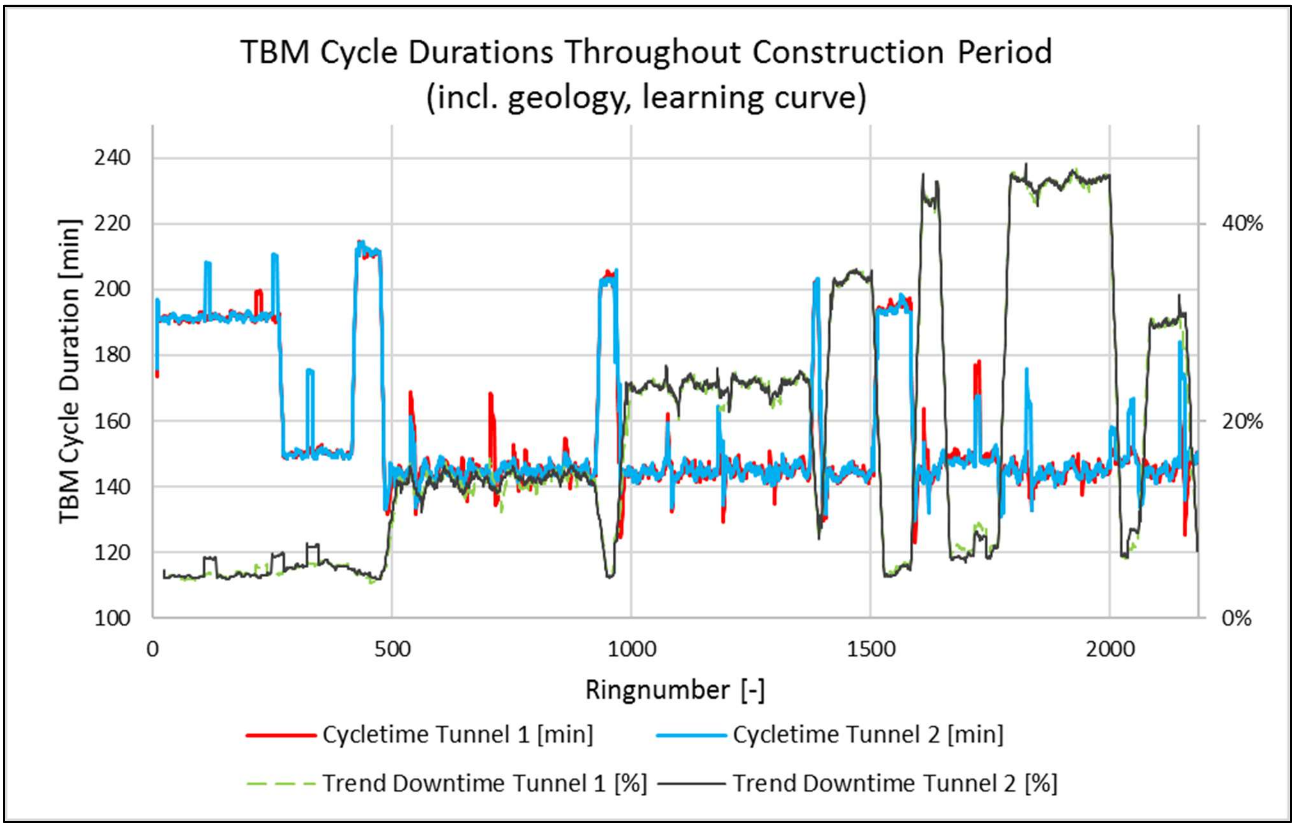


Figure 8-12: TBM cycle durations and downtime throughout the tunnel construction in a single simulation run

During the first 500 rings, the cycle durations are above 150min and therefore the downtime induced from insufficient logistics is very low. A comparison between the next section (ca. ring 500 to ring 900) and the section between ring 1000 and ring 1400 reveals the limitations which the logistic system imposes on the TBM advance rates. Although the advance speed has increased from 20mm/min to 25mm/min, the cycle durations cannot be reduced. The complete performance increase is consumed by additional downtime. This limitation persists as the construction continues with even higher advance rates and shorter ringbuilding durations. With a few interruptions by rock or mixed ground sections, the second half of the tunnel construction has been predicted to allow cycle durations between 80min and 100min as shown in Table 7-2. The periods with steep jumps in cycle duration such as they can be seen around ring 450, ring 900 or ring 1600 are caused by the encounter of mixed ground sections which significantly reduce the advance rates. An analysis of the actually achievable cycle durations as shown in Figure 8-13 reveals two peaks. The left one originates from the softground sections and the right one from mixed ground and granite sections with significantly lower advance rates. Although the advance rates of many rings would allow cycle durations below 100min, the majority lies between 130min and 160min. This marks the limitation imposed by the logistic system. In the analytical planning approach, the slowing influence of the logistic bottleneck seems to be underestimated as can be seen when marking the optimal cycle time of 80min and the determined average of 128 min. Also when considering the analytically determined logistical limitation to 132min cycle time, there is a gap to the simulation results. However, when comparing this with the advance rates which have been forecasted in the analytic planning, this level is sufficient for most of the project. The limitations are effectively limited to those few sections with relatively high advance rates and lower ringbuilding durations in the second half of the construction phase. However, what becomes clear is that the simulation based planning approach immediately takes into account the effects of the logistics on the advance rates. Compared with simulation based planning, the analytic planning approach would lead to an overly optimistic prognosis.

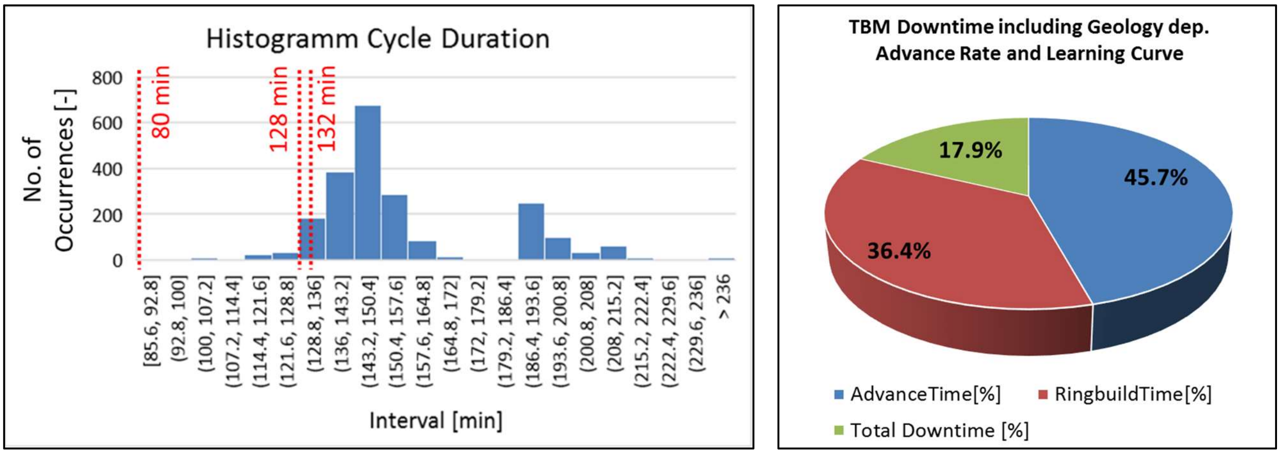
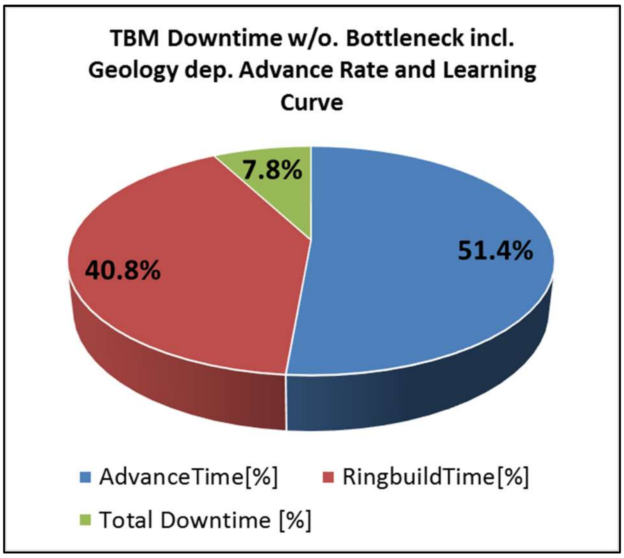


Figure 8-13: Overall performance and utilization shown by histogram of recorded cycle durations during a single simulation run with comparison to the respective analytic planning results in red dotted lines (left) and overall achievable utilization (right)

8.3.5 Removal of Logistic Bottleneck

The previous analysis revealed the gantry crane to be the systems bottleneck. Even if the TBMs could advance faster, they are held back by the removal of muck. While most jobsites use cranes to hoist muck in the shaft, some use vertical conveyors or sludge pumping systems. This leads to a great relieve of the pressure on the logistic system as hoisting operations can be restricted to the delivery of material to the machines. This scenario has been examined in a simulation experiment. In this experiment the muck hoisting has been replaced with a continuous transport system. The muck containers on the train can be emptied within a few seconds and are ready to return to the machine immediately afterwards. The operation of the mobile crane for loading of the trains remains unchanged from the previous experiments. The results of two Monte Carlo experiments with this configuration are compared. When assuming actual cycle durations as restricted by geology and learning curve, the logistics related downtime can be slashed to 7.8%. If assuming maximum performance for both TBMs over the whole project, it still reaches only 14.1% compared to the 44.9% which have been reached in a configuration using the gantry crane for muck hoisting.



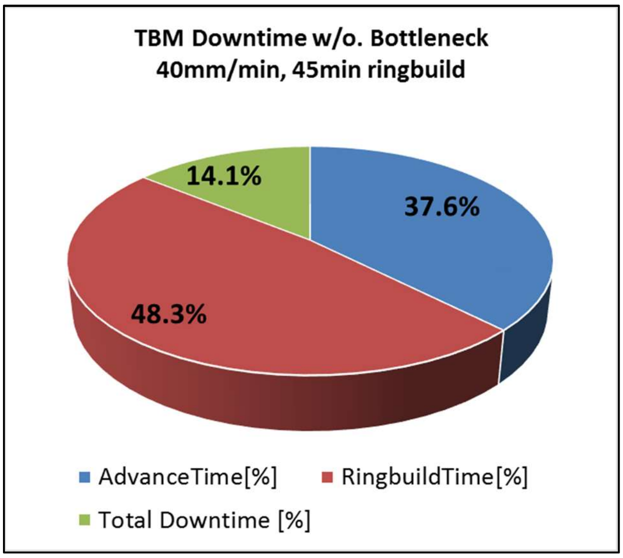


Figure 8-14: Downtime reduction after removal of bottleneck for actual predicted performance (left) and maximum performance (right)

8.4 Review of Simulation Study and Comparison to Analytic Planning

The presented simulation study of the example project has enclosed all major aspects of performance planning and downtime estimation for TBM tunneling. Based on a relatively simple example project, the advantages of using simulation studies to reveal more detailed information than in analytic planning processes have been demonstrated. The design of the model follows a modular approach, which allows it to be adaptable to many different jobsite layouts and technical setups. However, since a large portion of its benefits result from a precise reflection of the detailed logistic system on site, there are also a number of imperfections that stem from the tradeoff between a higher level of details on one hand and general applicability on the other side. The following sections discuss the results of the performed simulation study as well as the implications and limitations that have to be considered when using the results.

8.4.1 Discussion of Results

The simulation study has followed roughly the general procedure of analytic tunnel logistics planning. Starting from the TBM itself, the logistic system has been analyzed, gradually including an extended scope. During each experiment, the examined area has been increased while isolating it from outside influences. This allows pinpointing weak points as they are not overshadowed by possibly greater influences from other parts of the system. As in analytic planning processes, the study has been designed along the requirements for high advance rates, meaning short cycle durations. However, the requirements for the logistic system´s performance level are comparably low in the chosen example project. Although many TBMs are designed for advance speeds of 80mm/min, a large number of projects exist, where this level of performance is never reached. Therefore, the analysis has focused on such a scenario. The evaluation of the logistic system reveals very high levels of downtime when assuming low cycle durations. Below a threshold of 130min cycle duration, the logistic system reaches its limitations. Since the TBMs are assumed to exceed this performance only in few sections of the tunnels, the actual additional downtime to be expected is relatively moderate. The design of the logistic system increases the expected logistic induced downtime from around 12% when only evaluation the TBM and backup system to around 18% for the complete jobsite. As 12% of downtime are caused by switching trains within each ring, less could only be achieved by using a single train per ring. However, this would cause difficulties within the small shaft, as a single train would require more shunting operations while unloading. The simulation experiments reveal that process interactions between the two tunnels have a significant influence on the performance of the TBMs. In a more complex logistic system, these effects would be even more influential.

8.4.2 Comparison to Analytic Planning Results

The simulation study reveals information, which cannot be determined using analytic methods with the same level of confidence. The reasons lie in the different working procedures as well as each methods capabilities, which are summarized in Table 9-1. In analytic planning, the general working approach is making assumptions of the requirements for a certain isolated element of the logistic chain and the calculating its performance for a specific scenario. Simulation based planning on the other hand, includes all elements of a system and reveals its overall behavior. Due to the stochastic parametrization, many possible scenarios are evaluated in Monte Carlo experiments and the results are generated in form of probability distributions for certain possible results. Figure 8-13 shows a histogram of the cycle times as determined in a single simulation run and the results of analytic planning in dotted lines for comparison. The analytic planning process has been based primarily on an optimistic and an average cycle time of the TBM as shown in Figure 7-7 and Figure 7-8. Based on these cycle durations, the tunnel transport capacity has been determined and the lifting cycle for the supply of both TBMs in the shaft has been calculated. Figure 7-13 shows the resulting maximum performance of 132min per cycle. In contrast, the simulation based planning process shows a probability distribution of achievable results. As it considers additional effects such as interdependencies, its average results differ as well.

The simulation based approach paints a more detailed picture overall. Figure 8-13 shows the distribution of cycle times which is actually to be expected when considering all geological and operational boundary condition. The performance which has been estimated by the analytic planning process seems overly optimistic. When considering all known influences, the typical cycle time lies between 130min and 160min and can be attributed in detail to the different sections of the tunnel. In summary, simulation based planning allows for a better performance estimation and delivers exact information on bottlenecks in the supply chain with regards to the severity of their effect. Section 9.1presents a detailed comparison of the capabilities and operative aspects of simulation based and analytical planning methods.

8.4.3 Discussion of Limitations

Every simulation study is just as good as its methodology and input data. Since no model can be an exact replica of reality, it is important to understand the abstractions, assumptions and analysis steps, which lead from the initial data to the simulation results. The study presented here simplifies the logistic processes to some degree by eliminating many non-standard events from the system and only considering handling of plannable material consumption. In reality there are many activities which are unplanned or unstructured and which bind resources. An example is using the cranes for sorting material in stock. Such events have not been modeled and therefore the actual downtime on site will be higher than the present model predicts. However, there is significant potential to structure these processes and include them into simulation models. Another limitation in the presented simulation study lies in the lack of data on the reliability of individual components. A large portion of downtime on TBM jobsite stems from equipment failure and the related repairs. Currently planners use estimated global downtime to address this issue. Figure 8-15 shows the development of advance, ringbuilding and stop time in an actual project that is comparable to the example project in terms of geology and machine type. Also the overall time shares for the three components of the cycle are shown. Figure 8-16 shows the related penetration and advance rate over the course of the project. Together, both graphs reveal the learning effect as well as the geological dependency. Due to equipment downtime in all kinds of components, the actual cycle durations are higher than in the results of the presented simulation study.

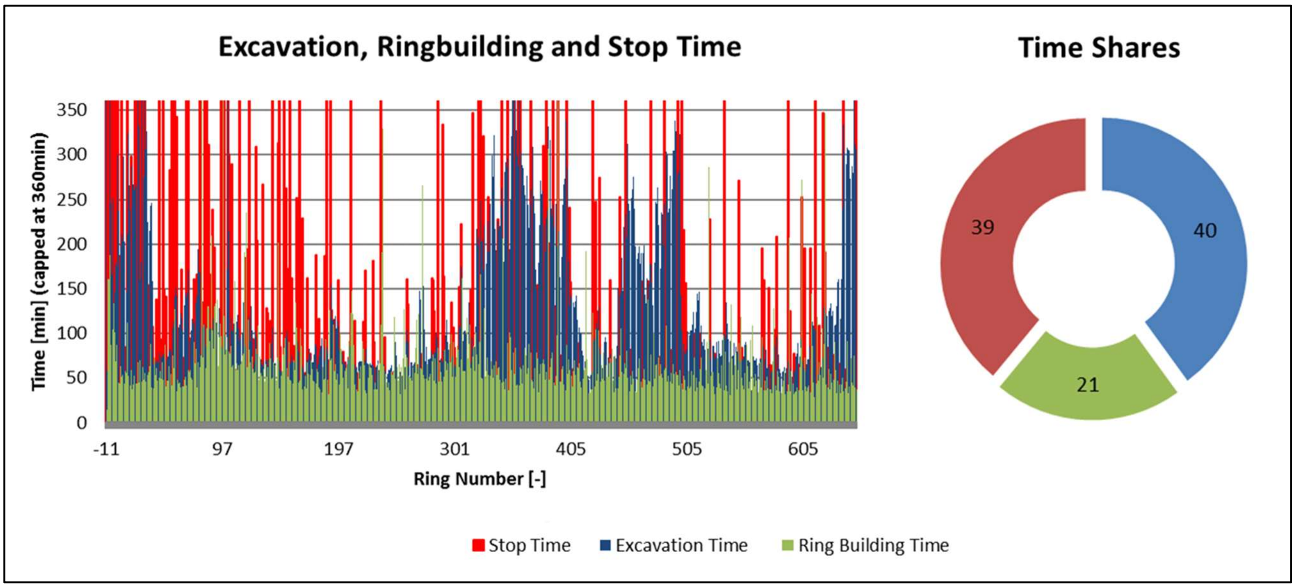


Figure 8-15: Advance, Ringbuilding and Stop durations (left) and time shares (right) in an actual reference project (Herrenknecht AG, 2015)

Another limitation of the simulation study lies in the transferability of results to other projects. The underlying data that has been used to parametrize the simulation model originates from jobsites that are directly comparable in their technical and organizational structure to the example project. If the simulation model shall be used to support planning other projects, additional input data modeling will be necessary. This implies a high work effort for the utilization of simulation as a tool for planning support when compared to classical planning methods. Adaptions to different projects require simulation specialists for programming modifications of the model structure. This capability would have to be built up or bought in most organizations.

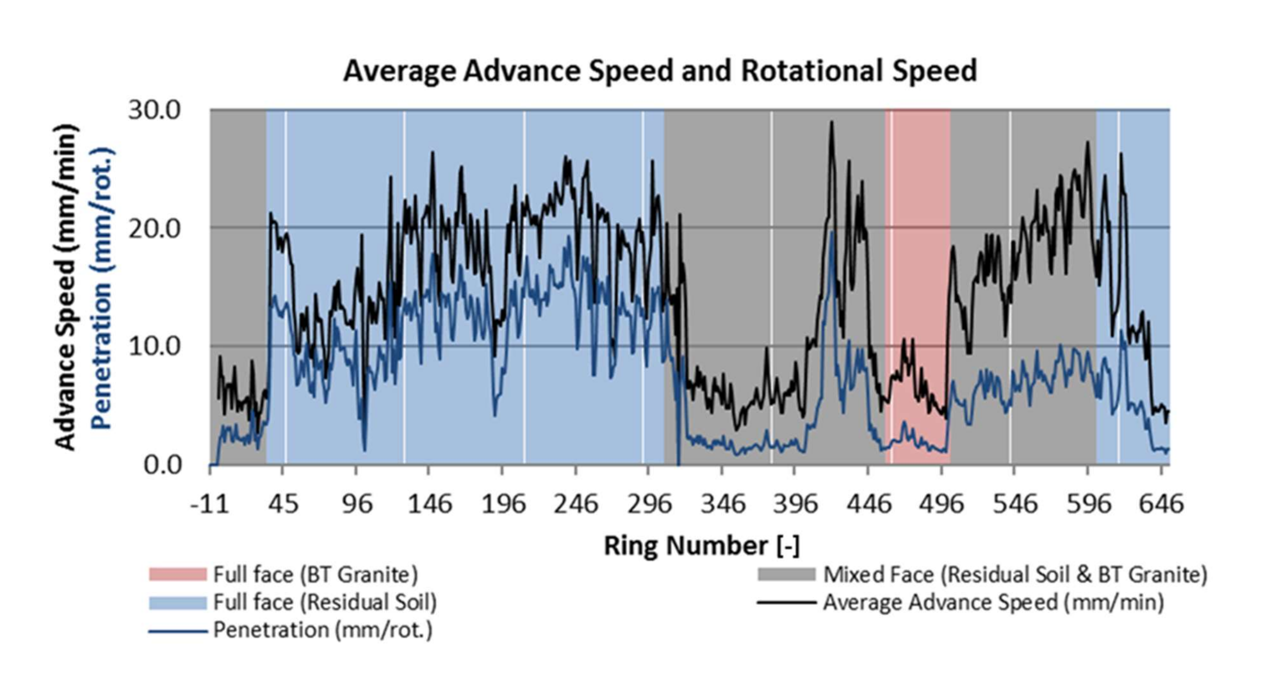


Figure 8-16: Performance data of an actual TBM project in comparable geology (Herrenknecht AG, 2015)

8.4.4 Verification and Validation

Simulation models are inherently different to the real world. To ensure that the characteristics which we are in the focus of interest are correctly reflecting the real world systems they depict, methods for verification and validation have been established. They support gathering indicators to judge a models credibility. By employing verification and validation techniques throughout the whole modeling process, mistakes can be avoided in early stages. A number of criteria have been identified by (Rabe, Spieckermann, & Wenzel, 2008), which have been applied throughout the simulation study of the example project. They have been addressed in each of the steps outlined in Table 8-1. The criteria outlined in Table 8-1 indicate that the presented model is fit for its purpose and the results represent the real jobsite close enough to provide sound information for planners. The table outlines, which verification and validation steps have been taken throughout modeling the example jobsite.

Table 8-1: Verification and validation techniques employed in the model of the example project (Rabe, Spieckermann, & Wenzel, 2008)

Criteria	Discussion
Completeness	Completeness judges the level of similarity between model and reality. In order to ensure completeness, a formalized system analysis has been performed and before implementing the model in a simulation software, formal modeling has been undertaken using SysML. A review of the SysML model has been performed, in which its elements have been compared to the performance defining features of actual logistics systems on site. This procedure ensures that all relevant elements of the example project have been considered.
Consistency	The real jobsite structure has been analyzed and embedded into a formal SysML model. As the structure of the executable model reflects this structure, the semantics and terminology used throughout the model structure are consistent. An important aspect is, that all simulation experiments are executed based on the same set of input parameters. This has been ensured by first creating a complete simulation model and subsequently deactivating part of the model for individual experiments that focus on particular areas of the system. To analyze the internal elements of the TBM for example, the elements of the supply chain have been deactivated for the respective simulation runs.
Applicability	Since the presented simulation model has been purpose built for the simulation of the described example it is well applicable to support planning decisions in tunneling. Especially decisions related to the payoff of additional investments can be judged, as simulation studies using the presented model of a TBM jobsite allow determining the influence of a single components performance onto the jobsite as a complete system. For the analysis of other TBM jobsites, the presented model would have to be modified though to exactly reflect the actual structure and conditions of the construction site in question.
Accessibility	Simulation studies increasingly have become essential parts of many planning processes. Although in the construction industry few planners make wider use of simulation techniques today, their use is widening. Therefore, the availability of the underlying data as well as the possibility to gather all necessary data for future studies is given with a realistic assumption for the economic boundary conditions.

Accuracy	Accuracy encompasses the level of detail, suitability of input data as well as the absence of programming errors. The level of detail has been defined in section 6.2.1 to contain all major elements of the logistic system. This definition has been followed throughout the modelling process and has proven correct for purpose. Input data has been analyzed generously to determine its probability distributions. For modelling the example project, probability distributions of directly comparable technical systems have been used. These distributions have been measured on jobsites with similar boundary conditions. Model reviews have been performed by following chains of events and compare them between executable model and theoretical on paper model. One major discrepancy between the presented model and actual construction sites is the absence of component failure related downtime on the simulation model. Figure 8-16 shows the cycle durations of an actual tunneling project with comparable geology and TBM type to the example project. When compared to the simulation results shown in Figure 8-12, this lack becomes obvious, as the simulation model yields shorter cycle durations that only include the logistics related downtime.
Relevance	Relevance, sometimes cited as well as currency proves the correctness of simulation experiment content and structure for the task of the model. The simulation model of the example project has been implemented to compare the capabilities and results of simulation model based logistics planning in tunneling with those of analytic planning methods. The results allow comparing both planning tools and prove the suitability of simulation to support logistics planning in tunneling.
Plausibility	The results of the simulation study can be compared to the results of a analytic planning process. When using the same parameters for process durations, both deliver the exact same results. When comparing them to the actual reference data presented in Figure 8-16, both yield comparable results when considering the lack of equipment failures in the simulation model.
Clarity	The results of the simulation study have been presented in a comparable structure to industry standards in the tunneling industry. Although the software code is not readable to most construction managers, the modelling approach in steps from an informal system description, via a formal theoretical model towards an executable simulation model allow users and stakeholders to transparently evaluate the modelling steps.

9 Conclusion and Outlook

Revisiting the research goals outlined in section 2.2, this thesis aimed at investigating a field which is defined by three pillars. The analytic planning methods for jobsite logistics in TBM tunneling which are used in the industry have been condensed into a structured planning approach which allows planners to prove the viability of a logistical system. Chapter 7 performs this planning process step by step. To create a solid foundation for future analytic or simulation based planning, a structured body of reference data has been collected and the relevant performance defining parameters as well as the probability distributions for process durations have been determined. Based on the same example project as the analytic planning procedure, an executable simulation model has been developed which has been used to perform a simulation study on the jobsite logistics. In summary, the three defined key objectives have been met as:

- Development of a systematic analytic planning approach for site managers.
- Collection, evaluation and statistical analysis of reference data for TBM logistics processes.
- Development and evaluation of a simulation based planning approach for TBM tunneling logistics.

This study reveals valuable additional information which cannot be revealed by analytic planning methods. Although the presented case study describes a specific example project, the presented methodology as well as many of the model elements can be adapted to any possible tunneling project. The following section 9.1 compares the different planning methods regarding their capabilities and advantages.

9.1 Evaluation of Planning Tools

Different planning tools have different strengths and weaknesses. While analytic planning offers a quicker result and can be performed by a larger number of professionals, many detailed questions regarding the performance of logistic systems can be answered only by using simulation studies. The detailed differences between the workflow and results of analytic and simulation based logistics planning approaches have been discussed in each simulation experiment documented in section 8.3. Further discussion of the differences is presented in the overall discussion of simulation results and comparison to analytic planning resulys in section 8.4. Table 9-1 presents a summary of the main differences.

Table 9-1: Comparison of TBM logistics planning tools

Aspect	Analytic Planning	Simulation based Planning
Generate a quick overview	Suitable for rough dimensioning	Required modeling effort decreases with reuse of models
Holistic view of logistic system	Only critical points can be calculated manually	yes
Consider stochastic effects on overall system	no (with exception to isolated problems)	yes
Consideration of non-intuitive or unknown effects	No. Only specifically modeled effects can be calculated	Yes. Due to agent based system, the real behavior can be observed
Consideration of handling, organization and communication strategy	Very limited	Yes, organizational aspects are integral part of executable model
Required amount of data	Medium detailed	Highly detailed data required
Ease of use	Easy to medium. Excel is widespread available	Medium to difficult, simulation software and programming skills required

9.2 Recommendations for Logistics Planning

Based on the experience of the presented planning methods in this thesis, a number of practical recommendations for logistics planning can be given. Many benefits of simulation may only be fully utilized when repeatedly performing simulation studies and therefore gathering the related organizational and practical experience. Also developing a growing body of reference data over time benefits future studies more and more.

The presented comparison of planning methods shows that when performed systematically, analytic planning is a powerful tool for roughly dimensioning the logistic system of a jobsite. This should be done and documented on any TBM jobsite. The sources of input data should be from other jobsites and not from datasheets of the equipment. Also, sufficient buffers for smaller processes or unplanned processes shall be kept as they significantly lower the performance of planned processes without appearing in most planning documents. Only this can guarantee a robust logistic chain.

Simulation studies prove to be a very valuable support tool for planners. However, the related knowledge and experience in using simulation software does not exist in most construction companies. Therefore, this knowledge has to be developed strategically. Especially in projects which either very limited space or very large scale, simulation studies deliver increasingly valuable insights compared to analytic planning. Developing simulation models as a proof of concept for the performance of the logistic system is clearly recommendable in such cases.

As section 8.3.5 shows, an outstanding strength of simulation studies is the possibility to compare different technical setups in detail. Once a model of the jobsite is available, changes require relatively little work and simulation studies allow quickly comparing different scenarios from a holistic point of view.

A recommendable starting point for simulation based logistics planning in TBM tunneling are isolated problems such as the analysis of potential bottlenecks in the shaft or access tunnels. As experience grows, the analysis should be widened to a more holistic view.

In summary, the practical recommendations for logistics planning can be expressed as following with regards to analytic and simulation based planning of TBM jobsite logistics:

- Perform well documented analytic planning for all TBM jobsites within an organization.
- Gather and use actual timing data for the relevant processes.
- Perform comparisons during projects to identify and study deviations from planning assumptions.
- Introduce and regularly use simulation as a tool for logistics planning.
- Thus developing a body of experience as well as the related personal skills within an organization.
- Follow up on comparing running jobsites to their planning stage models and update models to reflect real sites.
- Institutionalize the associated learning on processes and their structures.

9.3 Future Research

Planning methods for TBM jobsite logistics have been developed throughout this thesis. The aim to evaluate the use of simulation studies for logistics planning has led to a clear conclusion that the added knowledge which can be gained from these studies offers large advantages. However, for a wider deployment there are a number of steps to be taken which require further research. Accompanying a tunneling project with simulation studies throughout the whole planning and construction phase would greatly benefit the ongoing planning as well as deliver valuable information on process durations and interactions. To equip the logistic equipment with data acquisition systems that allow the automated determination of crane movement speeds, cycle times, vehicle movement speeds and cargo types could reveal the information which is necessary to further refine simulation models. This would also help to perfectly adapt models to a specific jobsite and support decisions regarding technical improvements for performance increases.

Another important step in future research is the further standardization of interfaces to create better possibility to integrate simulation into other trends of digitalization in construction. Advances in the utilization of BIM or RFID tracking on construction sites offer promising possibilities for data exchange and cross functional studies. This includes interfaces to process data management systems that gather the machine data of TBMs as well.

Simulation studies of the construction process bear great potential to increase productivity in the tunneling industry and lead to higher quality planning processes. As for all models of reality, their benefit grows with increased practical use on site and growing experience which can be fed back into the model. Therefore, the author wishes to encourage practitioners to make use of and grow this potential.

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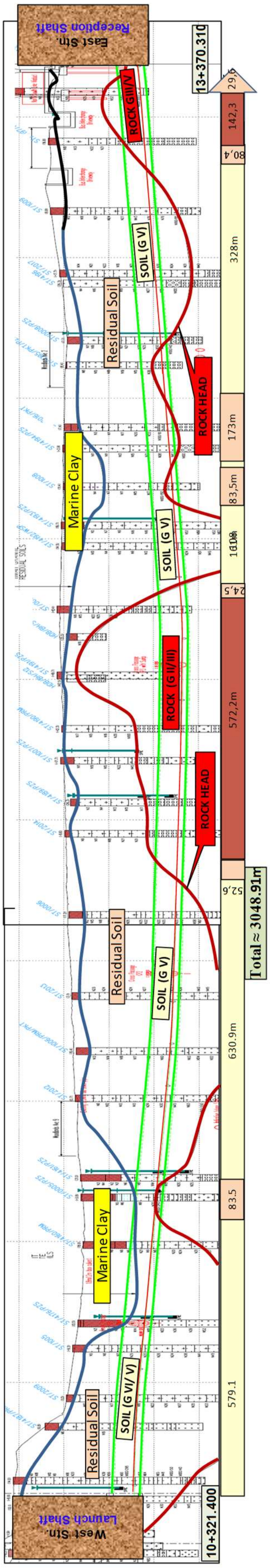
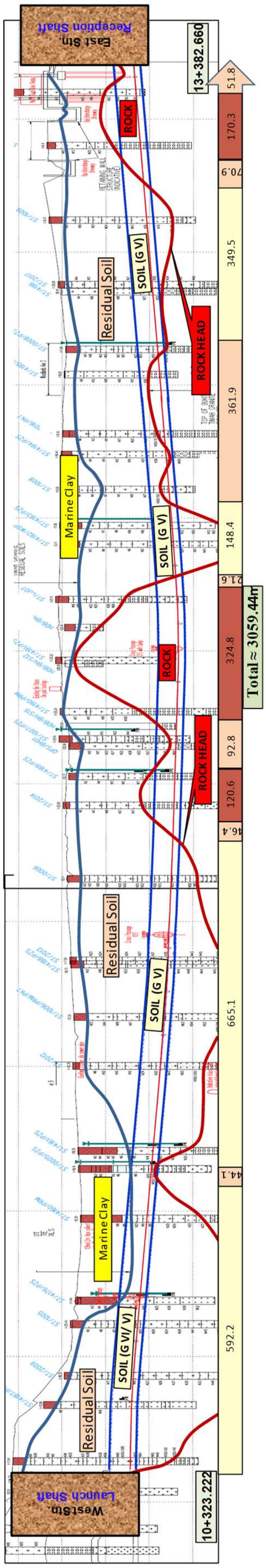
Appendix 1 – Example Project Geology



Twin Bore Metro Tunnel Contract, North Tunnel



Twin Bore Metro Tunnel Contract, South Tunnel

Twin Bore Metro Tunnel Contract, North Tunnel

Track Chainage		Length [m]	Soil/ Rock Discription	Remarks
From	To			
10,321.40	10,687.10	365.70	Soil (Residual)	Full Face soil in G VI
10,687.10	10,900.49	213.39	Soil (Residual + Marine Clay)	Full face mixed soil (residual + Marine Clay)
10,900.49	10,984.01	83.52	Mixed	Mixed face (G V + G III)
10,984.01	11,614.94	630.93	Soil	Full Face soil in G VI
11,614.94	11,667.50	52.56	Mixed	Mixed face (G V + G III)
11,667.50	12,239.66	572.16	Rock	Full face Rock (Granite)
12,239.66	12,264.20	24.54	Mixed	Mixed face (G V + G III)
12,264.20	12,425.24	161.04	Soil	Full Face soil in G VI
12,425.24	12,533.48	108.24	Mixed	Mixed face (G V + G III)
12,533.48	12,616.97	83.49	Soil	Full Face soil in G VI
12,616.97	12,790.01	173.04	Mixed	Mixed face (G V + G III)
12,790.01	13,118.00	327.99	Soil	Full Face soil in G VI
13,118.00	13,198.43	80.43	Mixed	Mixed face (G V + G III)
13,198.43	13,340.69	142.26	Rock	Full face Rock (Granite)
13,340.69	13,370.31	29.62	Mixed	Mixed face (G V + G III)
Total Length		**3,048.91**		

Residual (Soil)	G V/ VI
Mixed	G V/ VI + G II/III
Rock	G I/ II/ III

Soil/ Rock	**TBM [m] & [%]**	
	Length (m)	Distribution %
Soil (Residual)	1782.54	58.46%
Mixed (Soil + Rock)	551.95	18.10%
Rock (Granite)	714.42	23.43%
Total (m)	**3048.91**	

Twin Bore Metro Tunnel Contract, South Tunnel

Track Chainage		Length [m]	Soil/ Rock Discription	Remarks
From	To			
10,323.22	10,671.07	347.84	Soil (Residual)	Full Face soil in G VI
10,671.07	10,915.42	244.35	Soil (Marine Clay + Residual)	Full face Mixed soil in GVI + Marine Clay
10,915.42	10,958.56	43.14	Mixed	Mixed face (G V + G III)
10,958.56	11,623.66	665.10	Soil	Full face soil (G V/ VI)
11,623.66	11,670.04	46.38	Mixed	Mixed face (G V + G III)
11,670.04	11,790.67	120.63	Rock	Rock (Granite)
11,790.67	11,883.46	92.79	Mixed	Mixed face (G V + G III)
11,883.46	12,208.21	324.75	Rock	Rock (Granite)
12,208.21	12,229.84	21.63	Mixed	Mixed face (G V + G III)
12,229.84	12,378.28	148.44	Soil	Full face soil (G V/ VI)
12,378.28	12,740.14	361.86	Mixed	Mixed face (G V + G III)
12,740.14	13,089.64	349.50	Soil	Full face soil (G V/ VI)
13,089.64	13,160.56	70.92	Mixed	Mixed face (G V + G III)
13,160.56	13,330.87	170.31	Rock (Granite)	Rock (Granite)
13,330.87	13,382.66	51.79	mixed face (Soil +rock)	Mixed face (G V + G III)
Total Length		**3,059.44**		

Residual (Soil)	G V/ VI
Mixed	G V/ VI + G II/III
Rock (Granite)	G I/II/III

Soil/ Rock	**TBM [m] & [%]**	
	Length (m)	Distribution %
Soil (Residual)	1755.23	57.37%
Mixed (soil + rock)	688.51	22.50%
Rock (Granite)	615.69	20.12%
Total (m)	**3059.44**	

		Unit	Bukit Timah Granite Formation							
			G VI		G V			G IV	G III	G II / G I
SPT-N	lows/300mr		≤30	>30	≤30	>30 and ≤60	>60	-	-	-
Unit Weight	γ	kN/m³	19	20	19	20		21	23	24
Effective Cohesion	c′	kN/m²	5	10	5	10	15	30	100	200
Effective Angle of Friction	ϕ′	Deg	32	32	32	32	32	38	45	50
Undrained Shear Strength	c_u	kN/m²	5N and ≤120	4N and ≤250	5N and ≤120	4N and ≤250		400	3000	15000
At Rest Earth Pressure Coefficient	K_0	-	0.8							
Youngs Modulus	E_u	MN/m²	2.5N and ≤250					250	2500	5000
	E′		Eu/1.2							
Permeability	K0	m/s	10^{-7}					10^{-7}	10^{-6}	-

		Unit	Fill	Kallang Formation			
				M	E	F2	F1
SPT-N	lows/300mr		-	-	-	-	-
Unit Weight	γ	kN/m³	18.5	15.5	15	19	19
Effective Cohesion	c′	kN/m²	0	0	0	0	0
Effective Angle of Friction	ϕ′	Deg	30	22	22	28	32
Undrained Shear Strength	c_u	kN/m²	30	14	15	30	-
At Rest Earth Pressure Coefficient	K_0	-	0.5	1	1	1	0.7
Youngs Modulus	E_u	MN/m²	12	$300c_u$	$250c_u$	$300c_u$	-
	E′		10	$E_u/1.2$	$E_u/1.2$	$E_u/1.2$	2N/1.2
Permeability	K0	m/s	10^{-9}	10^{-9}	10^{-8}	10^{-6}	10^{-6}

Appendix 2 – Jobsite Logistics Survey Forms

Logistic Elements Overview

Project Name

Materials	Storage Facilities	Fixed Infrastructure	Resources

Fixed Infrastructure Description

Project Name

Name	Name of the facility
Description	Description including purpose, interactions and use. For example for railways, roads, muck pits etc. This may overlap with the equipment resources.
Type	Type if it can be specified
Location	Location on site
Dimensions	Dimensions and capacity
Picture	

Materials Description	
Project Name	
Name	Name of the Resource. For example “Segments”
Description	Description of the material and its purpose. If any special considerations apply for the handling and using this resource, they should be described here.
Type	If any type specification of the material is available, it should be specified here
Estimated Consumption Pattern	The consumption amount and pattern should be stated here. What does the amount of consumption depend on?
Weight / Dimensions	Transport weight and dimensions must be known for planning transport capacities
Path through System	A preliminary plan for how to transport and handle the resource. This is redundant with the description of the equipment and adds an additional point of view to the description
Picture	A picture helps understanding the processes and plans better

Storage Facilities Description	
Project Name	
Name	Name of the facility
Description	Description including shape, accessibility, special considerations, general purpose and boundary conditions
Type	Type if it can be specified
Location	Location on site
Dimensions	Dimensions and capacity
Materials stored here	List of what is stored here
Picture	

Logistic Processes Description

Project Name

Logistic Equipment Description

Project Name

Name	
Description	
Type	
Performance Data	
Main Processes	
Picture	

Process Conflict Matrix

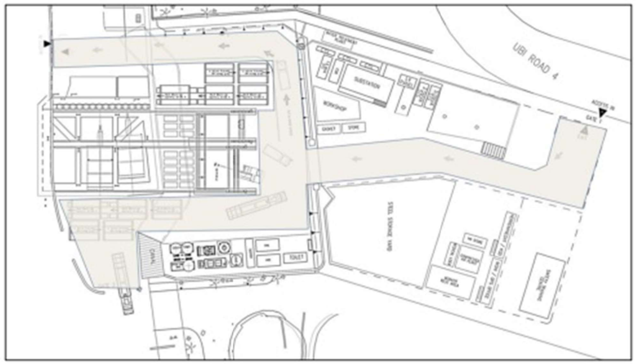
Resource	Material	Start	End	Process	ID	*ID1*	*ID2*	*ID3*	*ID4*
Resource 1	Material 1	Start Point	End Point	Process Name	*ID1*	Resource Conflict			
Resource 2	Material 2	Start Point	End Point	Process Name	*ID2*	Space Conflict			
Resource 3	Material 3	Start Point	End Point	Process Name	*ID3*	No Conflict			
Resource 4	Material 4	Start Point	End Point	Process Name	*ID4*	Situationally Depending			

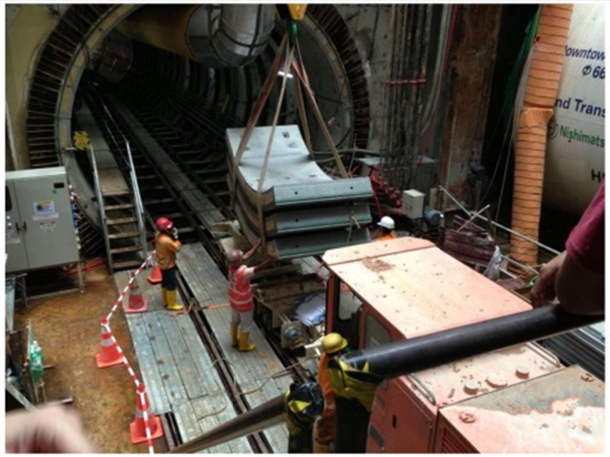
Appendix 3 - Logistic System of the Example Project

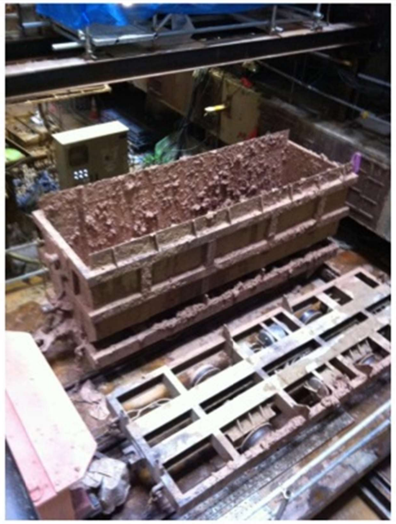
Logistic Elements Overview

Logistic Elements Overview			
Example Project			
Materials	**Storage Facilities**	**Fixed Infrastructure**	**Resources**
Muck	General Storage Area	Grout Batching Plant	Gantry Crane
Segments	Segment Storage Yard	Surface Access Roads	Mobile Crane
Rails, Sleepers, Assembly mat.	Liquids Storage	Tunnel Rails	Trucks
Ventilation Duct	Grout Silo	Shunting Platform	Trains
HV Cable	Bridge Area Storage		Rail Crane
Tunnel Pipe	TBM Gantry Storage		Segment Crane
Walkway Material	Muck Pit		Barrel Crane
Tenside			Tenside Crane
Grease			Grout Transfer Pump
Grout			Segment Feeder
			Excavator

Fixed Infrastructure

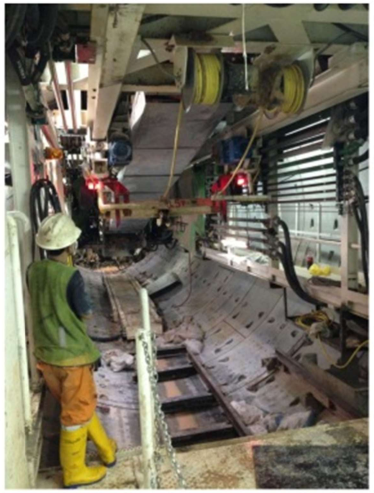
Fixed Infrastructure Description	
Example Project	
Name	Access / Jobsite Roads
Description	• There are two main access gates. • Gate one is used as an access gate and exit gate • Gate two is only used as exit gate, mainly for mucking • One additional temporary access gate for TBM assembly • One way traffic for muck transports and two way traffic for other material transports • Access to the Storage areas in areas covered by mobile crane allow unloading of trucks
Type	• Concrete paved road • speed limit 5km/h
Location	As marked on site plan
Dimensions	8m width
Picture	

Fixed Infrastructure Description	
Example Project	
Name	Tunnel Rail
Description	• Each of the twin tunnel is fitted with a single railway track. • California switches each 600m allow trains to pass each other • Speed Limit is 20km/h • A switch before the shaft branches into a twin rail for the last 50m before the shaft and into the shaft
Type	• 35kg/m type
Location	• Tunnel flow and shaft
Dimensions	
Picture	

Fixed Infrastructure Description	
Example Project	
Name	Shunting Platform
Description	• Shunting Platform allows to place more muck cars within the reach of the gantry crane as otherwise the shaft would be too small. • Features two parallel tracks • Movement within 1 min per shunt
Type	• Built on Site
Location	• Shaft bottom at the end of Rail section
Dimensions	• Length = 8m • 2 Parallel tracks
Picture	

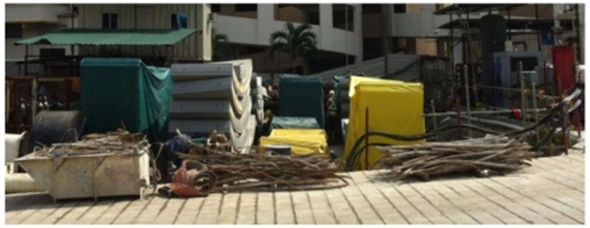
Fixed Infrastructure Description	
Example Project	
Name	Grout Batching Plant
Description	• Grout batching plant for tailskin grouting • Deliveries by truck include cement, fly ash and sand • Batching in grout plant and pumping transfer into grout silo
Type	• TAC – Pacific grouting plant
Location	• Located between general storage area and liquids storage area
Dimensions	• 15m x 7m footprint
Picture	

Storage Facilities

Storage Facilities Description	
Example Project	
Name	Bridge Area Storage
Description	• Storage area in Bridge Area of the TBM for Rails
Type	• Tunnel Floor temporary storage
Location	• TBM Bridge
Dimensions	• 8mx1m
Materials stored here	• Tunnel and Gantry Rails and their Assembly Material
Picture	

Storage Facilities Description	
Example Project	
Name	TBM Gantry Storage
Description	• Material storage in the TBM´s gantries. • Gantry 1: Grease barrel storage area next to grease pumps, grout tank • Gantry 2 Spare Tenside container storage area next to Tenside pump • Gantry 5 Water and air pipes stored on gantry floor, Tunnel rails stored on floor
Type	• Storage space on Gantries, Tanks, Storage on tunnel floor
Location	• Various locations throughout the gantries
Dimensions	-
Materials stored here	• Gantry 1: Grease barrels, Grout • Gantry 2 Tenside Containers • Gantry 5 Water Pipes, Air Pipes, Rails, Walkway Material,
Picture	

Storage Facilities Description	
Example Project	
Name	Grout SIlo
Description	• Grout silo for storage of readily mixed grout. From here its pumped into the groutcars in the shaft. Storage for Sand, cement,and flyash is also available
Type	• TAC Grout Tank
Location	• Location on site
Dimensions	• Approx. 100m³ capacity
Materials stored here	• Grout • Fly Ash • Cement • Sand
Picture	

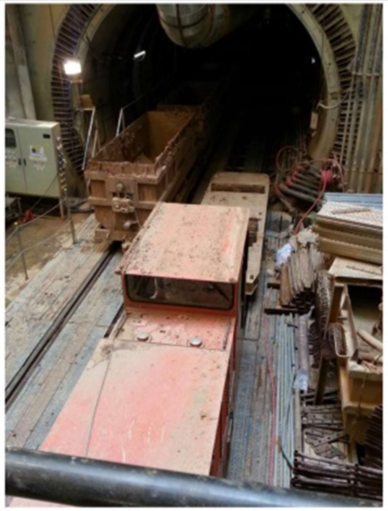
Storage Facilities Description	
Example Project	
Name	Name of the facility
Description	• General Storage area for Spare Parts, Equipment, Steel works, Rails and other materials
Type	• Open Storage
Location	• Opposite Gate 1
Dimensions	• Approx. 400m²
Materials stored here	• Rails and Assembly Material • Walkway Material • Water Pipes • Air Pipes • HV Cables • Ventilation Duct • Spare and Wear Parts
Picture	

Storage Facilities Description	
Example Project	
Name	Muck Pit
Description	• Muck cars are emptied into the pit and loaded by excavator into trucks to transport it to a landfill.
Type	• Muckpits are constructed from concrete on site
Location	• Next to the shaft within the reach of the gantry crane
Dimensions	• Approx. 500m³
Materials stored here	• Muck and smaller amounts of wastewater
Picture	

Storage Facilities Description	
Example Project	
Name	Liquids Storage
Description	• Storage area on site surface for consumables which are delivered in barrels and containers
Type	• Open storage area
Location	• Next to the shaft and grout batching plant.
Dimensions	• 150m² footprint • 40 barrels storagecapacity • 10 canisters of 1m³ storage capacity
Materials stored here	• Tailskin grease barrels • Lubrication grease barrels • Tenside containers
Picture	

Storage Facilities Description	
Example Project	
Name	Segment Storage Yard
Description	• Segment storage yard located next to the shaft. • Within reach of mobile crane on site • Segment gaskets are installed in the yard
Type	• Open storage area
Location	• Between shaft and east boundary of the site
Dimensions	• Capacity for 30 rings •
Materials stored here	• Universal segments in stacks of 5 + 1
Picture	

Resources

Logistic Equipment Description	
Example Project	
Name	Trains
Description	• Trains in both tunnels deliver all material to the machines
Type	• 1 loco, 1 segment car, 1 flat car, 5 muck cars •
Performance Data	• Max speed ca. 20km/h avg. speed ca. 10km/h
Main Processes	• Commuting between TBM and shaft • Shunting for unloading
Picture	

Logistic Equipment Description
Example Project

Name	Barrel Crane
Description	• Crane to lift grease barrels from train to gantry
Type	• Manual swivel crane with chain block hoist
Performance Data	• Approx. 3 min per lifting cycle
Main Processes	• Lift Tailskin grease barrels from train to gantry 1 • Lift lubrication grease barrels from train to gantry 1 • Change grease barrel on gantry
Picture	

Logistic Equipment Description
Example Project

Name	Trucks
Description	• Trucks for External Delivery
Type	• Muck Trucks • Material Delivery Trucks for all Consumables and Segments
Performance Data	• $14m^3$ of muck • 1 ring Segments • 36 rails / 50 sleepers / • 4 Ventilation Ducts • 2 HV cables • 100 pipes • 25 barrels • 12 containers • 20t grout raw material
Main Processes	• Muck discharge from site • Delivery of consumables and material to site
Picture	

Logistic Equipment Description	
Example Project	
Name	Gantry Crane
Description	• Gantry crane is covering the shaft and muck pit and does the mucking for both TBMs
Type	• DEMAG
Performance Data	• Round trip with muck bucket in 7-8 min
Main Processes	• Hook Bucket • Lift Full Muck Bucket • Horizontally move full bucket • Empty bucket • Horizontally move empty bucket • Lower Bucket • Place Bucket on train
Picture	

Logistic Equipment Description	
Example Project	
Name	Excavator
Description	• Excavator for muck loading
Type	• 1,1m³ shovel volume
Performance Data	• Ca. 40sec per cycle
Main Processes	• Muck transfer from muck pit to waiting truck •
Picture	

Logistic Equipment Description Example Project	
Name	Mobile Crane
Description	• Mobile crane for various loading and unloading operations as well as segment and consumables delivery
Type	• Crawler type
Performance Data	• Lifting/Lowering speed (empty): 110 mpm • Rotation speed: 2 rad/s
Main Processes	• Segment unloading and delivery to segment storage • Segment lowering to train • Unloading of assembly material, rails and consumables from trucks • Delivery of all material to train in shaft • Various assembly operations
Picture	

Logistic Equipment Description Example Project	
Name	Grout Transfer Pump
Description	• Pump for transferring Grout from Train Grout Car to TBM Grout Tank
Type	• KSP25
Performance Data	• 24m³/h
Main Processes	• Pumping • Disconnecting and cleaning
Picture	

Logistic Equipment Description
Example Project

Name	Segment Crane
Description	• Segment crane iin gantry one and bridge
Type	• Two track mechanical gripping crane
Performance Data	• Driving speed between 30m/min to 60m/min • Lifting speed between 4 and 10m/min
Main Processes	• Lifting Segments from train and place on feeder • Lift rails from train to bridge area floor
Picture	

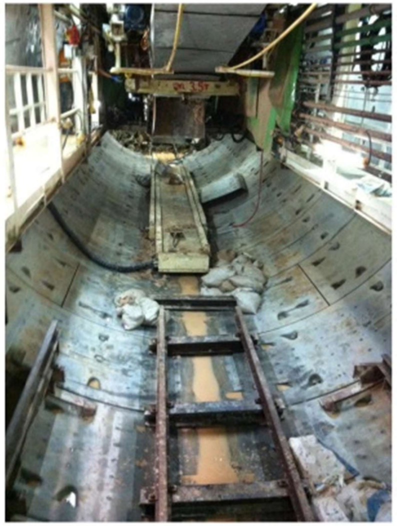
Logistic Equipment Description
Example Project

Name	Rail Crane
Description	• Rail crane for disassembly of gantry rails behind the TBM
Type	• Manual svivel crane with chainblock
Performanc e Data	• Approx. 3min per cycle
Main Processes	• Lifting rails during disassembly • Lift rails on train from tunnel floor
Picture	

Logistic Equipment Description
Example Project

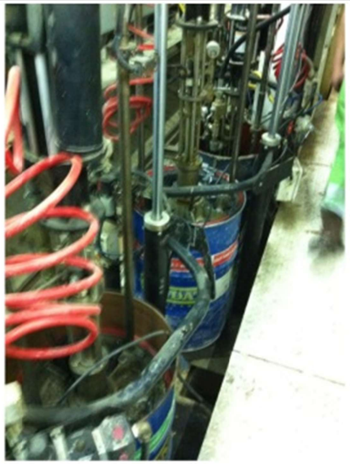
Name	Tenside Crane
Description	• Manual Svivel crane to load and unload tenside containers between gantry 2 and train
Type	• Manual svivel crane with chainblock
Performance Data	• 4min / lifting cycle
Main Processes	• Lift container from train to gantry • Move container from gantry to train
Picture	

Logistic Equipment Description
Example Project

Name	Segment Feeder
Description	• Segment feeder w. 6pos to transfer segments to the erector
Type	• 6pos hydraulic
Performance Data	• 6m/min
Main Processes	• Feed segment • Retract sledge
Picture	

Materials

Materials Description	
Example Project	
Name	• Walkway Material
Description	• Material to build walkway for people in the tunnel.
Type	• Planks • Scaffolds • Segment Fixtures • Connectors
Estimated Consumption Pattern	• Permanently laid in the tunnel
Weight / Dimensions	• 4m length per section • 120kg in total material per section
Path through System	Source/Delivery Truck – Mobile Crane – General Storage Area – Mobile Crane – Train – Rail Crane – Gantry 5 Tunnel Floor – Walkway/Sink
Picture	

Materials Description	
Example Project	
Name	Grease
Description	• Grease for TBM operation in barrels
Type	• Tailskin Grease • Lubrication Grease
Estimated Consumption Pattern	• Lubrication: 5kg/ring • Tailskin: 100kg/ring
Weight / Dimensions	• 200kg barrels
Path through System	• Source/Delivery Truck – Mobile Crane – Liquids Storage Area – Mobile Crane – Train – Barrel Crane – TBM Gantry 2 grease station – Tunnel/Sink
Picture	

Materials Description	
Example Project	
Name	HV Cable
Description	• Cable for TBM electricity supply
Type	• DN50 cable, delivered on drums
Estimated Consumption Pattern	• 1 cable throughout the whole tunnel
Weight / Dimensions	• 1,5mx1,2mx1,5m
Path through System	• Source/Delivery Truck – Mobile Crane – General Storage Area – Mobile Crane – Train – Cable Reel/sink
Picture	

Materials Description	
Example Project	
Name	Grout
Description	• Grout For Backfilling. • Mixed in the Batching plant from Cemenmt, Sand, Water and Flyash.
Type	• Single component Grout
Estimated Consumption Pattern	• Ca.4,5m³ per ring
Weight / Dimensions	• Ca 1,2t/m³
Path through System	• Source/Delivery Truck – Grout Batching Plant – Train – Grout Transfer Pump – TBM Grout Tank–Tunnel/Sink
Picture	

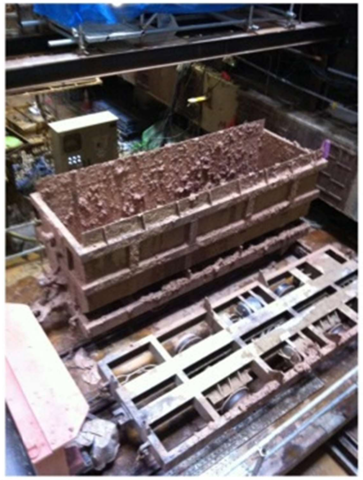
Materials Description

Example Project

Name	Rails
Description	• Tunnel Rails for Trains and Rails for Gantries incl. Assembly Material. Both are built in Bridge area and Gantry rails are disassembled after passing of TBM
Type	• 35kg/k rails
Estimated Consumption Pattern	• 1 pair of rails through whole tunnel • Circulating rails in gantry area
Weight / Dimensions	• L=6m • 35kg/m rail
Path through System	• Source/Delivery Truck – Mobile Crane – General Storage Area – Mobile Crane – Train – Segment Crane – Tunnel Floor Bridge – Rail/Sink • Source/Rail Crane – Train – Segment Crane – Tunnel Floor Bridge – Rail/Sink
Picture	

Materials Description

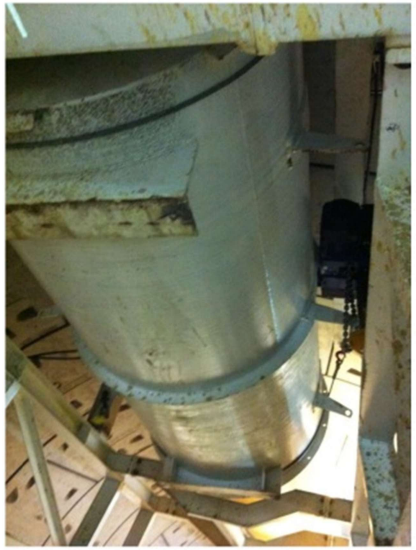
Example Project

Name	Muck
Description	• Muck from Tunneling
Type	• Watery Clay mixed with soil conditioning
Estimated Consumption Pattern	• Ca. 75m³/ring including bulk factor
Weight / Dimensions	• 2t/m³
Path through System	• Source/TBM – Muck Car on Train – Gantry Crane – Muck Pit – Excavator – Dump Truck/Sink
Picture	

Materials Description	
Example Project	
Name	Tenside Container
Description	• Container with Tenside for Soil Conditioning
Type	• 300l container
Estimated Consumption Pattern	• Approx.. 100l per ring
Weight / Dimensions	• 600x600x600 container
Path through System	• Source/Delivery Truck – Mobile Crane - General Storage Area – Mobile Crane – Train – Tenside Crane – Gantry 2
Picture	

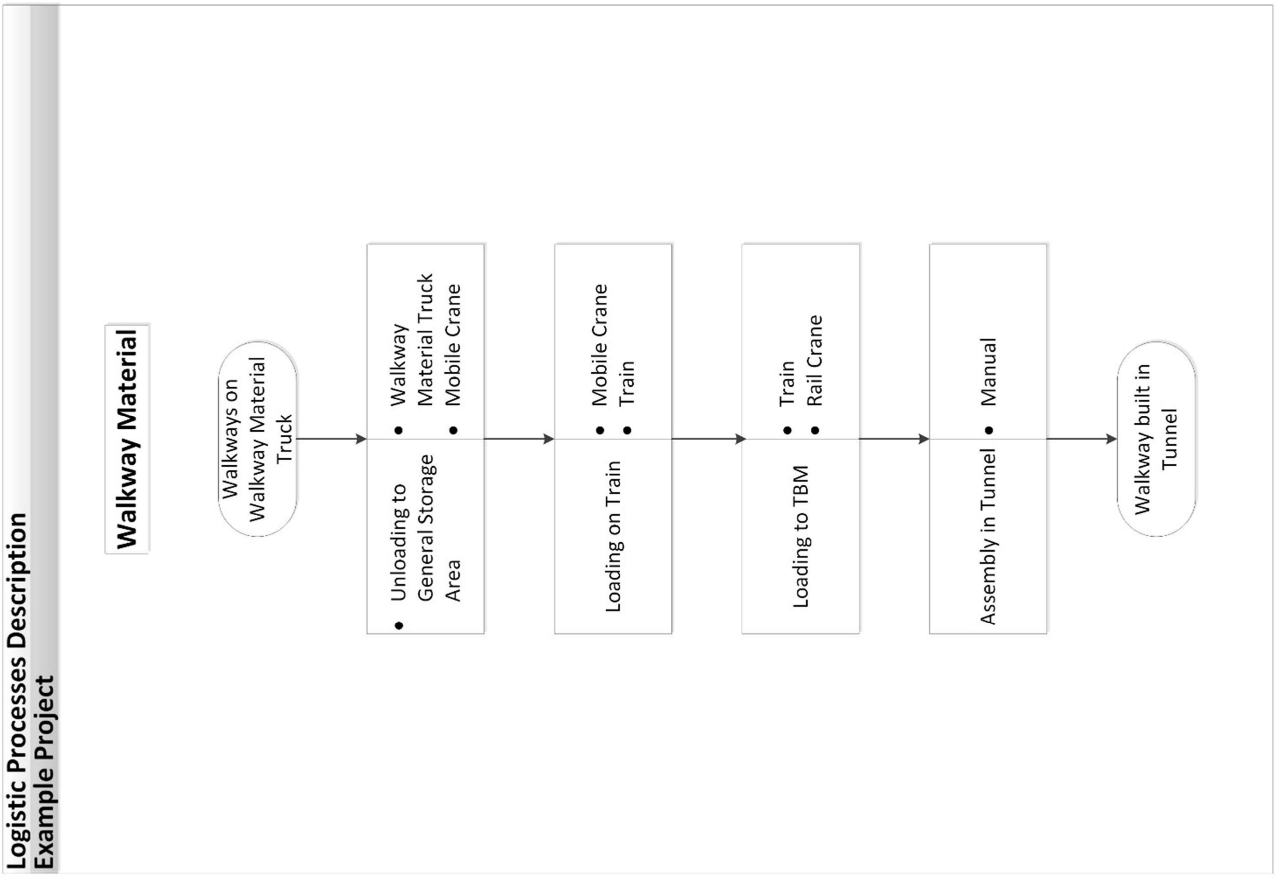
Materials Description	
Example Project	
Name	Segments
Description	• Segments for Tunnel Construction
Type	• DI=5800, DA=6350, L=1400 • Max.3.5t • 5+1 configuration
Estimated Consumption Pattern	• 1 ring of 6 segments every 1,4m
Weight / Dimensions	(see table below)
Path through System	Source/Delivery Truck – Mobile Crane – Segment Storage Area – Mobile Crane – Train – Segment Crane – Segment Feeder – Erector – Tunnel/Sink
Picture	

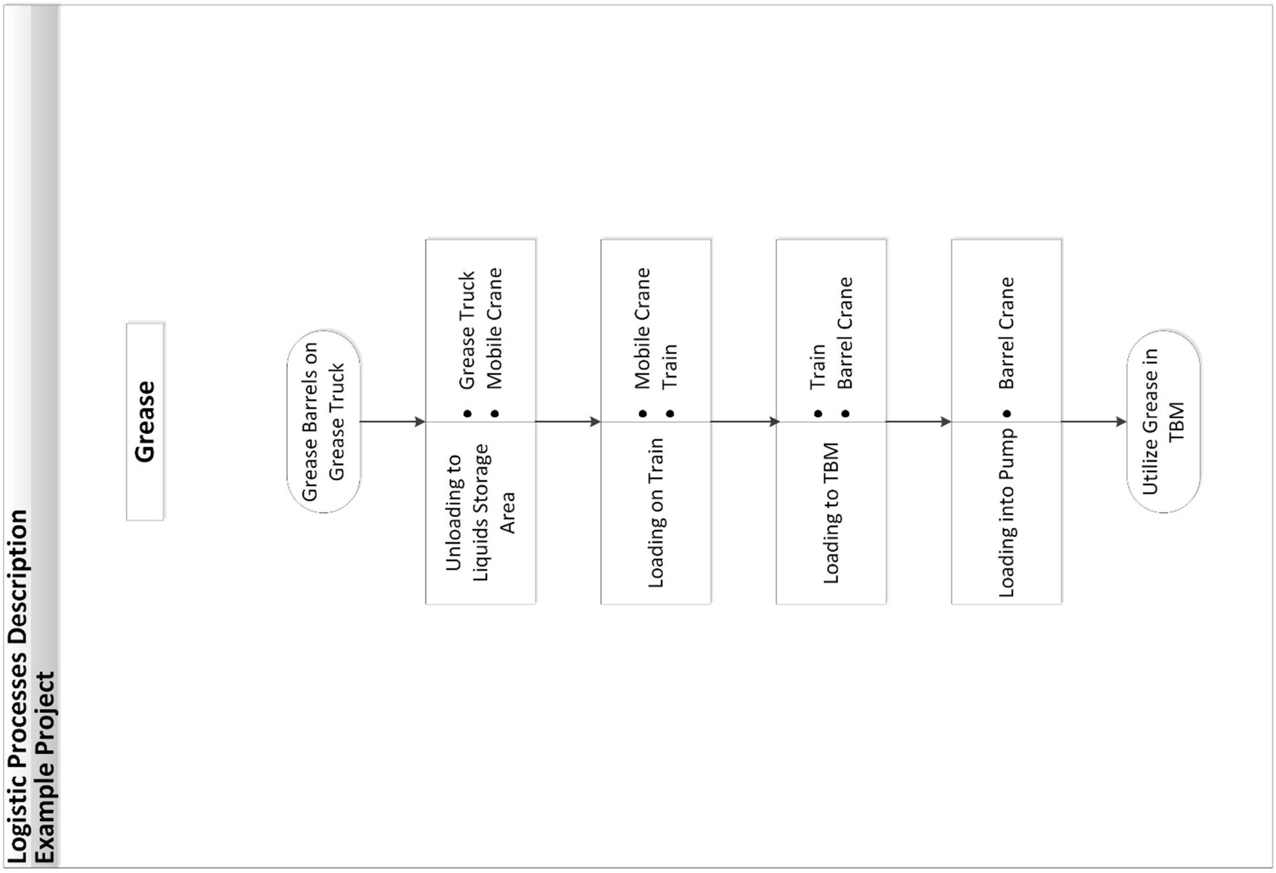
Segment ID	$Ø_{SID}$	=	5800 mm
Segment length	L_S	=	1400 mm
Segment configuration			5 + 1
Calculation			
Ring cross section	S_R	=	5.25 m²
Segment cross section	S_S	=	0.98 m²
Key cross section	S_{KS}	=	0.33 m²
Segment volume	V_S	=	1.38 m³
Key volume	V_{KS}	=	0.46 m³
Segment weight	M_S	=	3.44 t
Keystone weight	M_{KS}	=	1.15 t

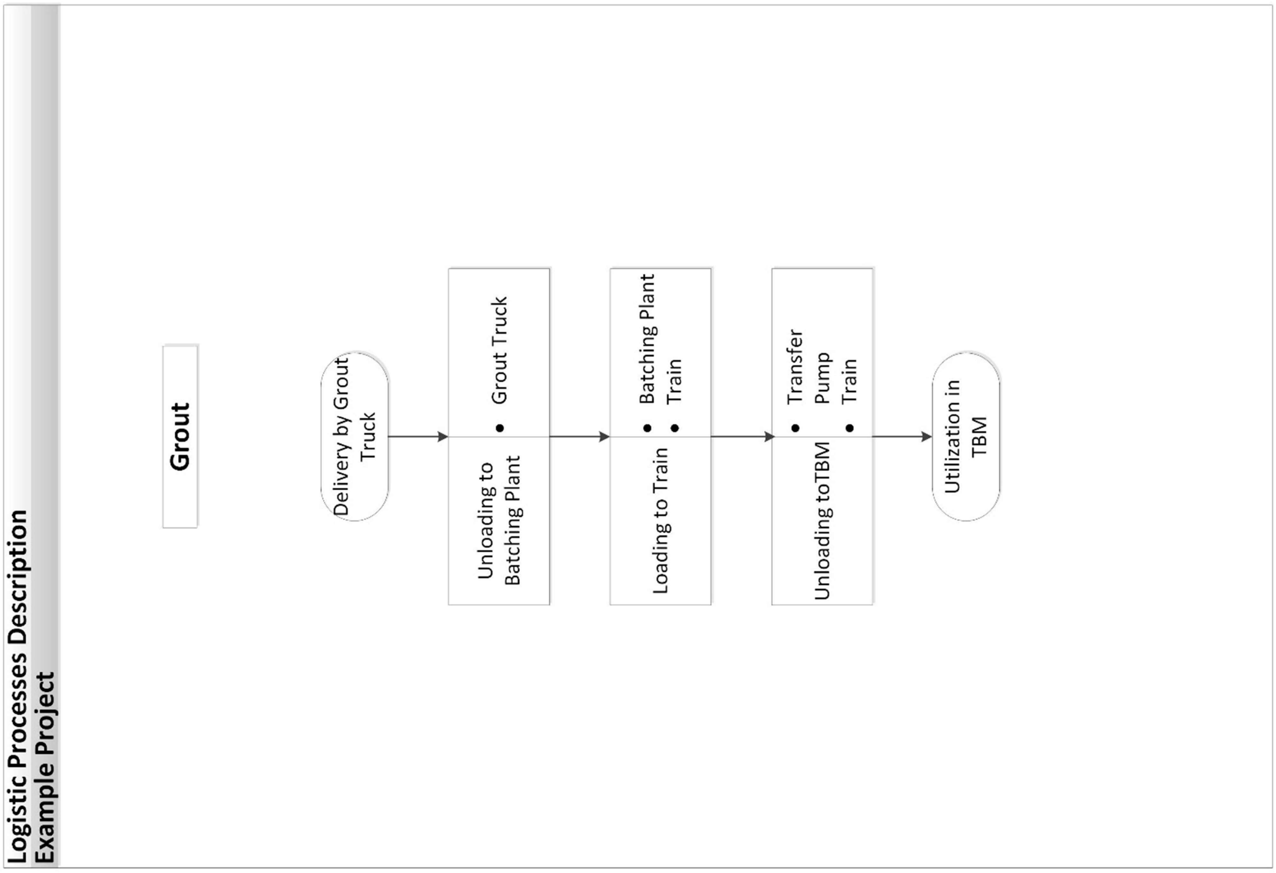
Materials Description	
Example Project	
Name	Ventilation Duct
Description	• Ventilation Duct for Tunnel Air
Type	• DN800 Cassette
Estimated Consumption Pattern	• 1 line throughout the whole tunnel
Weight / Dimensions	• 1000x1000x3000 per cassette • 150m length
Path through System	• Source/Delivery Truck – Mobile Crane - General Storage Area – Mobile Crane – Train – Casette holder/Sink
Picture	

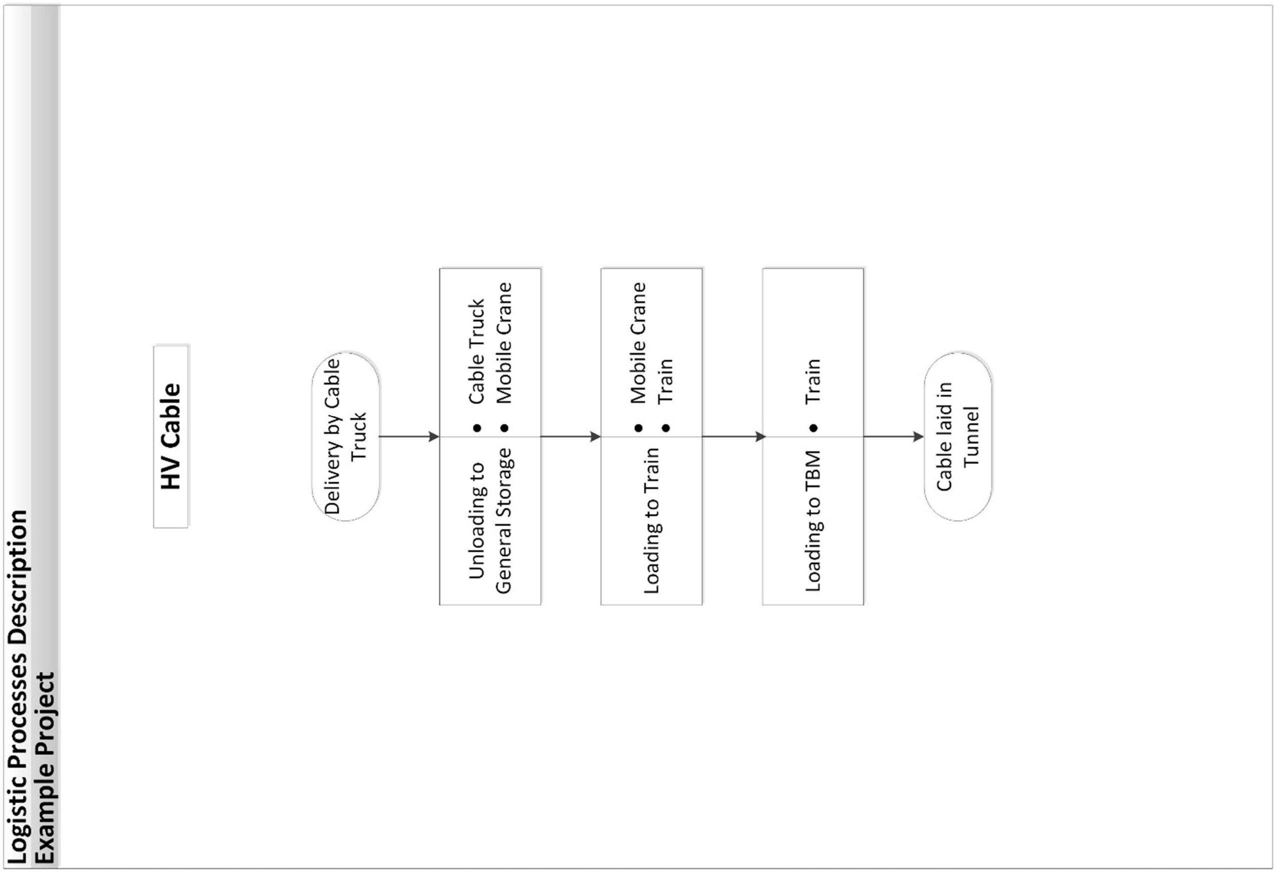
Materials Description	
Example Project	
Name	Tunnel Pipe
Description	• Tunnel Water Pipes for TBM Supply • Air Pipes for compressed air supply
Type	• DN100 water • DN50 Air • L=6m
Estimated Consumption Pattern	• 2 water lines over the whole tunnel length • 3 air pipes over the whole tunnel length
Weight / Dimensions	• L=6m, 40kg/pipe
Path through System	• Source/Delivery Truck – Mobile Crane – General Storage Area – Mobile Crane – Train – Manual Unloading – Tunnel Floor Gantry 5 – Pipeline/Sink
Picture	

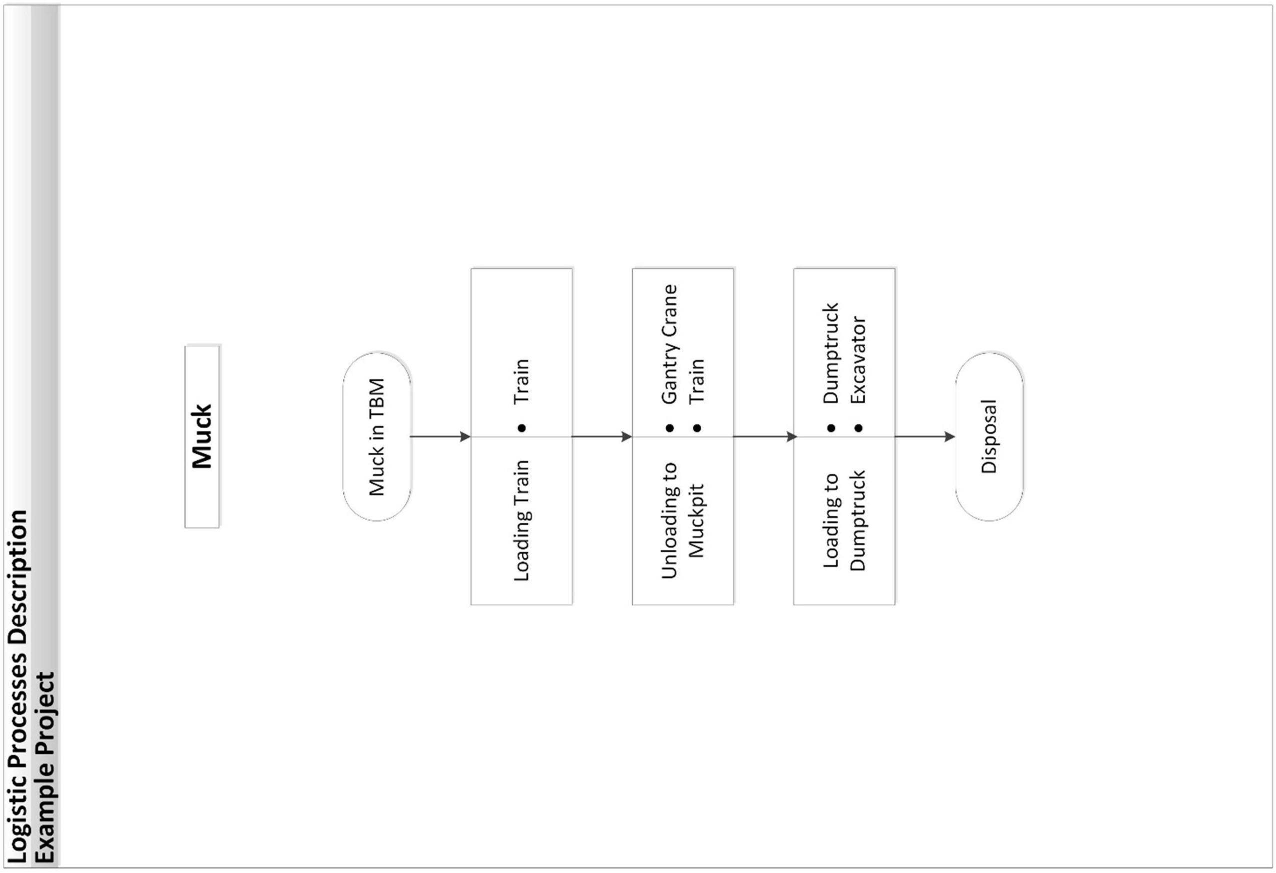
Processes

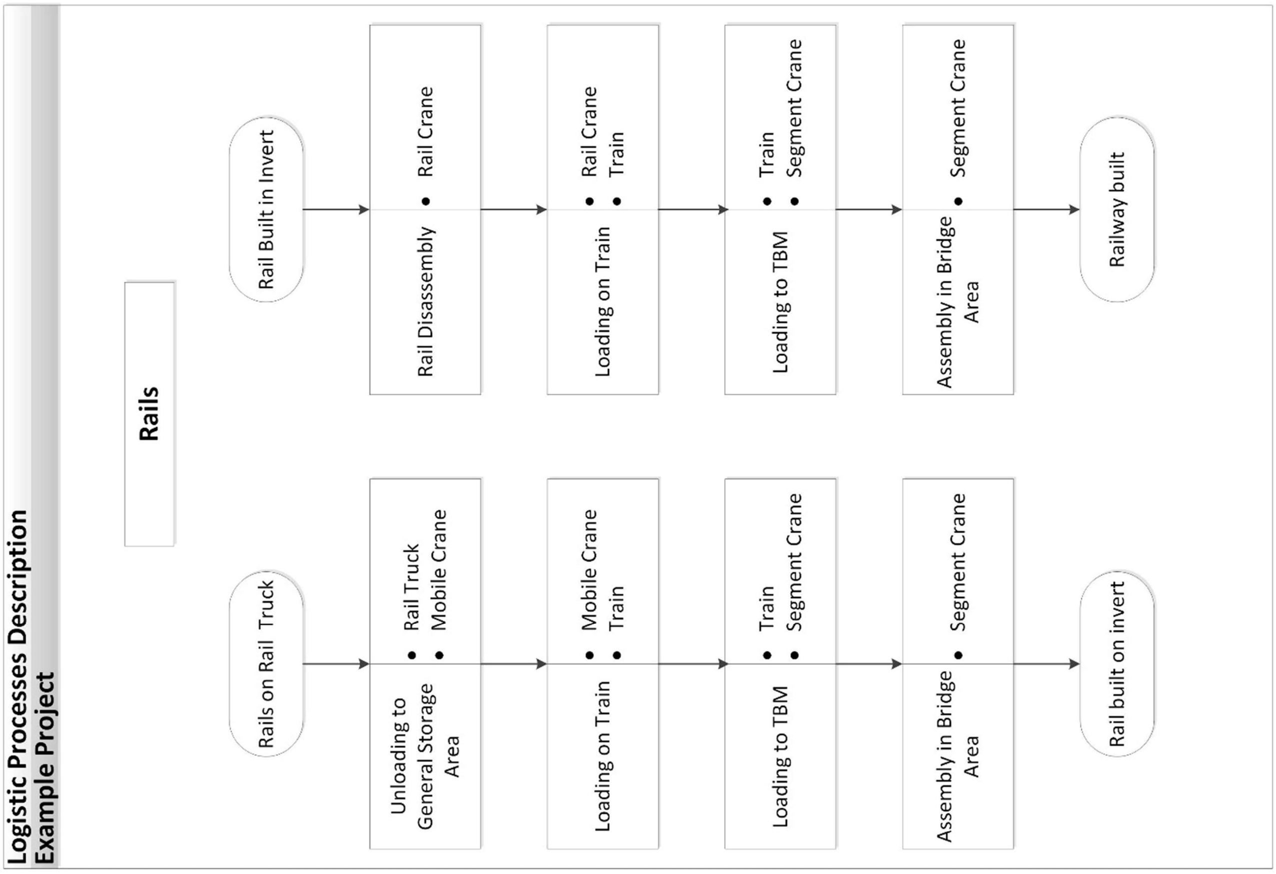

Logistic Processes Description
Example Project
Walkway Material
Walkways on Walkway Material Truck
Unloading to General Storage Area
Walkway Material Truck
Mobile Crane
Loading on Train
Mobile Crane
Train
Loading to TBM
Train
Rail Crane
Assembly in Tunnel
Manual
Walkway built in Tunnel

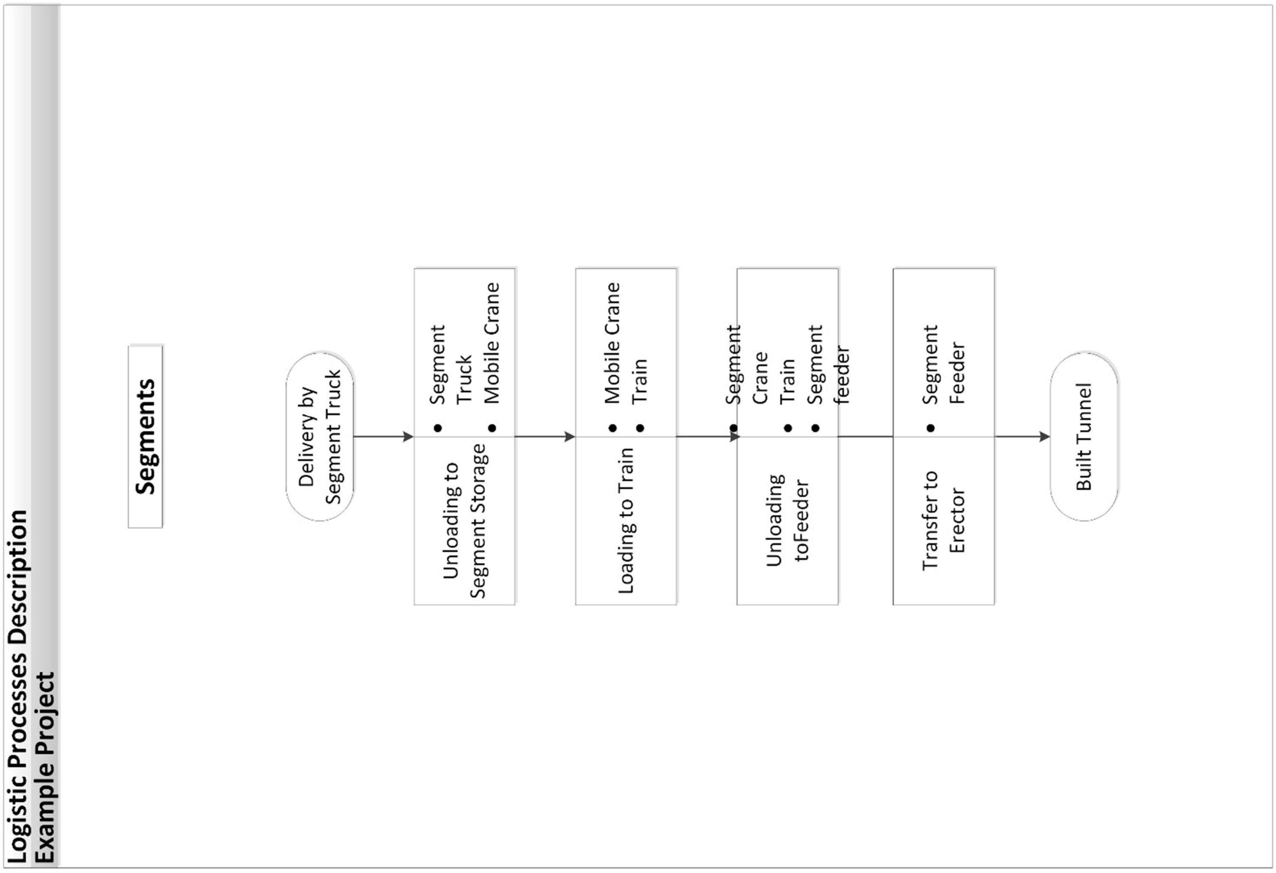

Logistic Processes Description
Example Project
Grease
Grease Barrels on Grease Truck
Unloading to Liquids Storage Area
Grease Truck
Mobile Crane
Loading on Train
Mobile Crane
Train
Loading to TBM
Train
Barrel Crane
Loading into Pump
Barrel Crane
Utilize Grease in TBM

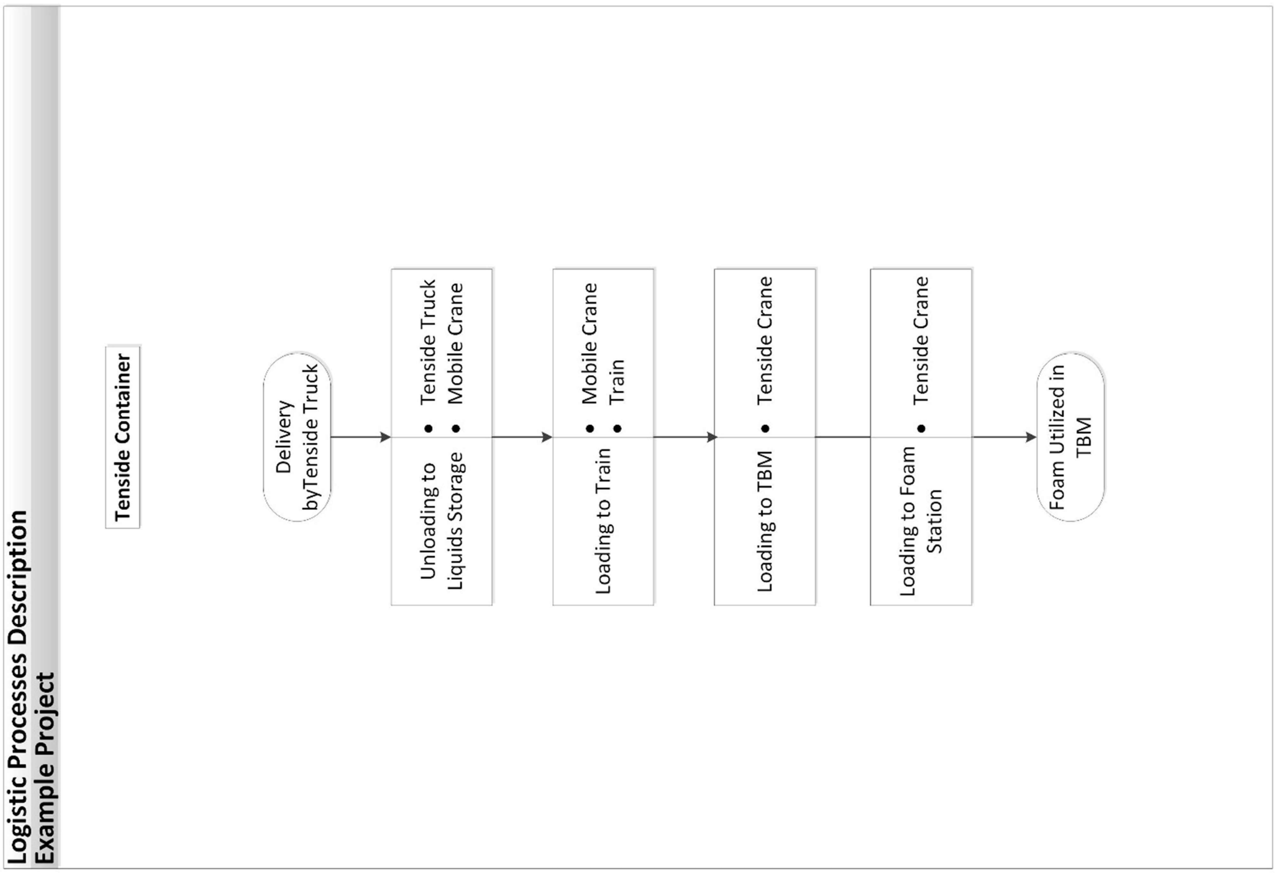

Logistic Processes Description
Example Project
Grout
Delivery by Grout Truck
Unloading to Batching Plant
• Grout Truck
Loading to Train
• Batching Plant
• Train
Unloading toTBM
• Transfer Pump
• Train
Utilization in TBM

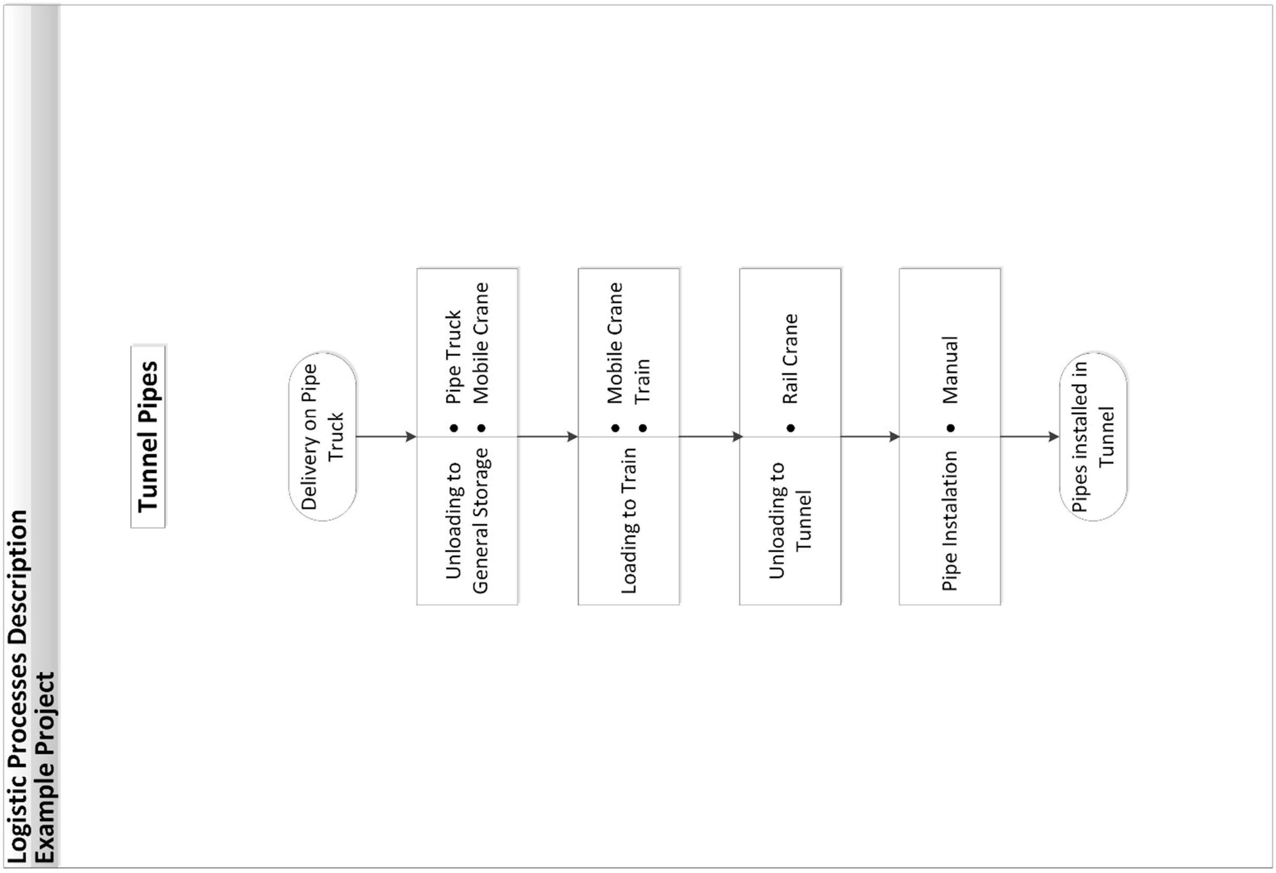

Logistic Processes Description
Example Project
HV Cable
Delivery by Cable Truck
Unloading to General Storage
• Cable Truck
• Mobile Crane
Loading to Train
• Mobile Crane
• Train
Loading to TBM
• Train
Cable laid in Tunnel


Logistic Processes Description
Example Project
Muck
Muck in TBM
Loading Train
• Train
Unloading to Muckpit
• Gantry Crane
• Train
Loading to Dumptruck
• Dumptruck
• Excavator
Disposal


Logistic Processes Description
Example Project
Rails
Rails on Rail Truck
Unloading to General Storage Area
• Rail Truck
• Mobile Crane
Loading on Train
• Mobile Crane
• Train
Loading to TBM
• Train
• Segment Crane
Assembly in Bridge Area
• Segment Crane
Rail built on invert
Rail Built in Invert
Rail Disassembly
• Rail Crane
Loading on Train
• Rail Crane
• Train
Loading to TBM
• Train
• Segment Crane
Assembly in Bridge Area
• Segment Crane
Railway built


Logistic Processes Description
Example Project
Segments
Delivery by Segment Truck
Unloading to Segment Storage
Segment Truck
Mobile Crane
Loading to Train
Mobile Crane
Train
Unloading toFeeder
Segment Crane
Train
Segment feeder
Transfer to Erector
Segment Feeder
Built Tunnel


Logistic Processes Description
Example Project
Tenside Container
Delivery byTenside Truck
Unloading to Liquids Storage
Tenside Truck
Mobile Crane
Loading to Train
Mobile Crane
Train
Loading to TBM
Tenside Crane
Loading to Foam Station
Tenside Crane
Foam Utilized in TBM


Logistic Processes Description
Example Project
Tunnel Pipes
Delivery on Pipe Truck
Unloading to General Storage
Pipe Truck
Mobile Crane
Loading to Train
Mobile Crane
Train
Unloading to Tunnel
Rail Crane
Pipe Instalation
Manual
Pipes installed in Tunnel

Process Conflicts

(Legend on following page)

D	ID1	ID2	ID3	ID4	ID5	ID6	ID7	ID8	ID9	ID10	ID11	ID12	ID13	ID14	ID15	ID16	ID17	ID18	ID19	ID20	ID21	ID22	ID23	ID24	ID25	ID26	ID27	ID28	ID29	ID30	ID31	ID32	ID33	ID34	ID35	ID36	ID37	ID38	ID39	ID40	ID41	ID42	ID43	ID44	ID45	ID46	ID47	ID48
ID1	1																																															
ID2	2	1																																														
ID3		1	1																																													
ID4				1																																												
ID5				1	1																																											
ID6						1																																										
ID7							1																																									
ID8								1																																								
ID9									1																																							
ID10		1	1						2	1																																						
ID11		1	1							1	1																																					
ID12												1																																				
ID13													1																																			
ID14			2								2			1																																		
ID15															1																																	
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ID17									2								1																															
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ID37		1	1							1	1			2					1						1	1					1	1				1	1											
ID38																						1																1										
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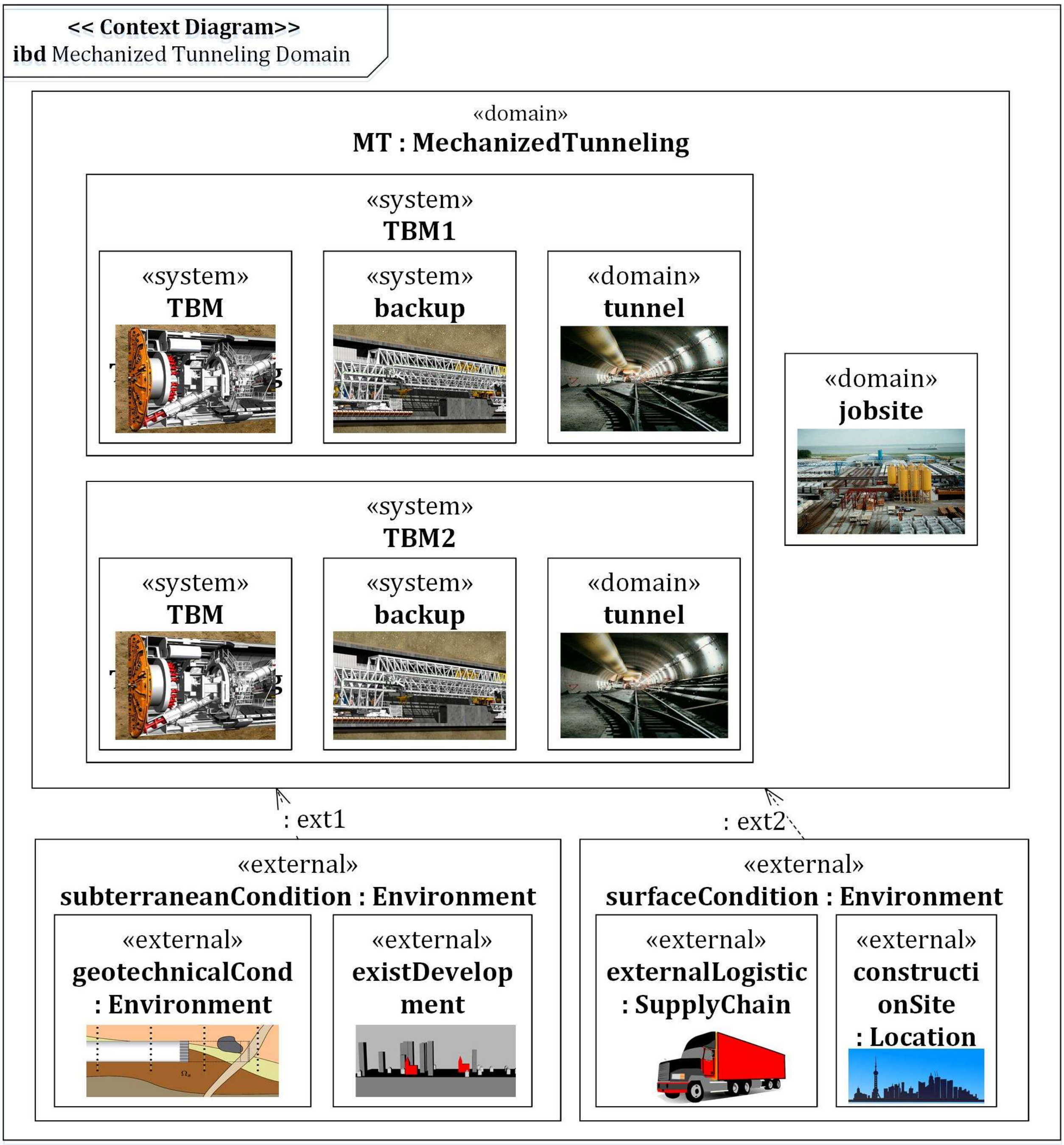
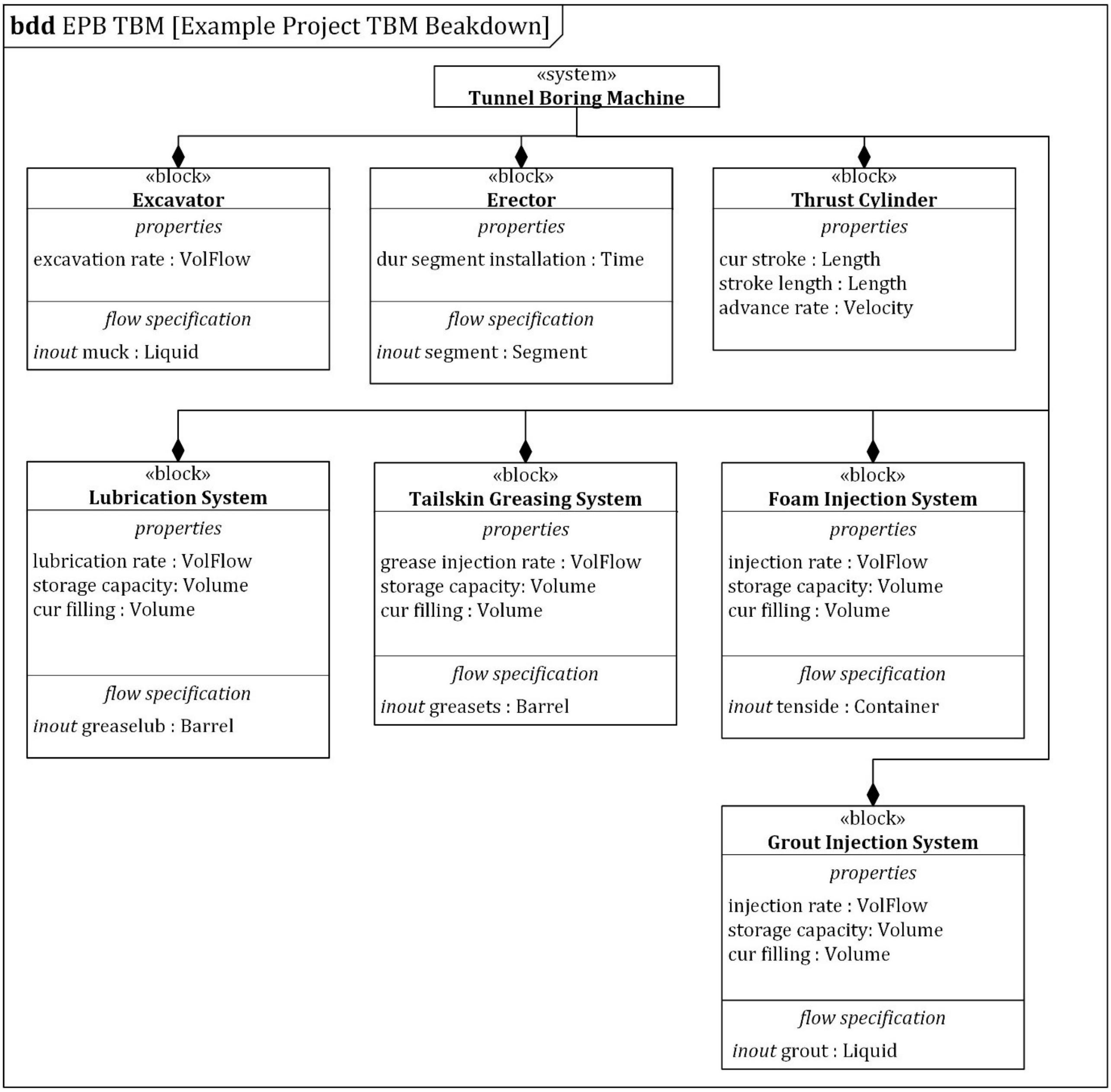
ID40									2								2	2																	2					1								
ID41		1	1						2	1	1						2		1						1	1					1	1			2	1	1			2	1							
ID42										1	1			2					1						1	1					1	1				1	1				1	1						
ID43												1																															1					
ID44									2								2	2																	2					2				1				
ID45		1	1						2	1	1						2		1						1	1					1	1			2	1	1			2	1	1		2	1			
ID46		1	1							1	1			2					1						1	1					1	1				1	1				1	1			1	1		
ID47																						1																1	1								1	
ID48																						1																1	1								1	1

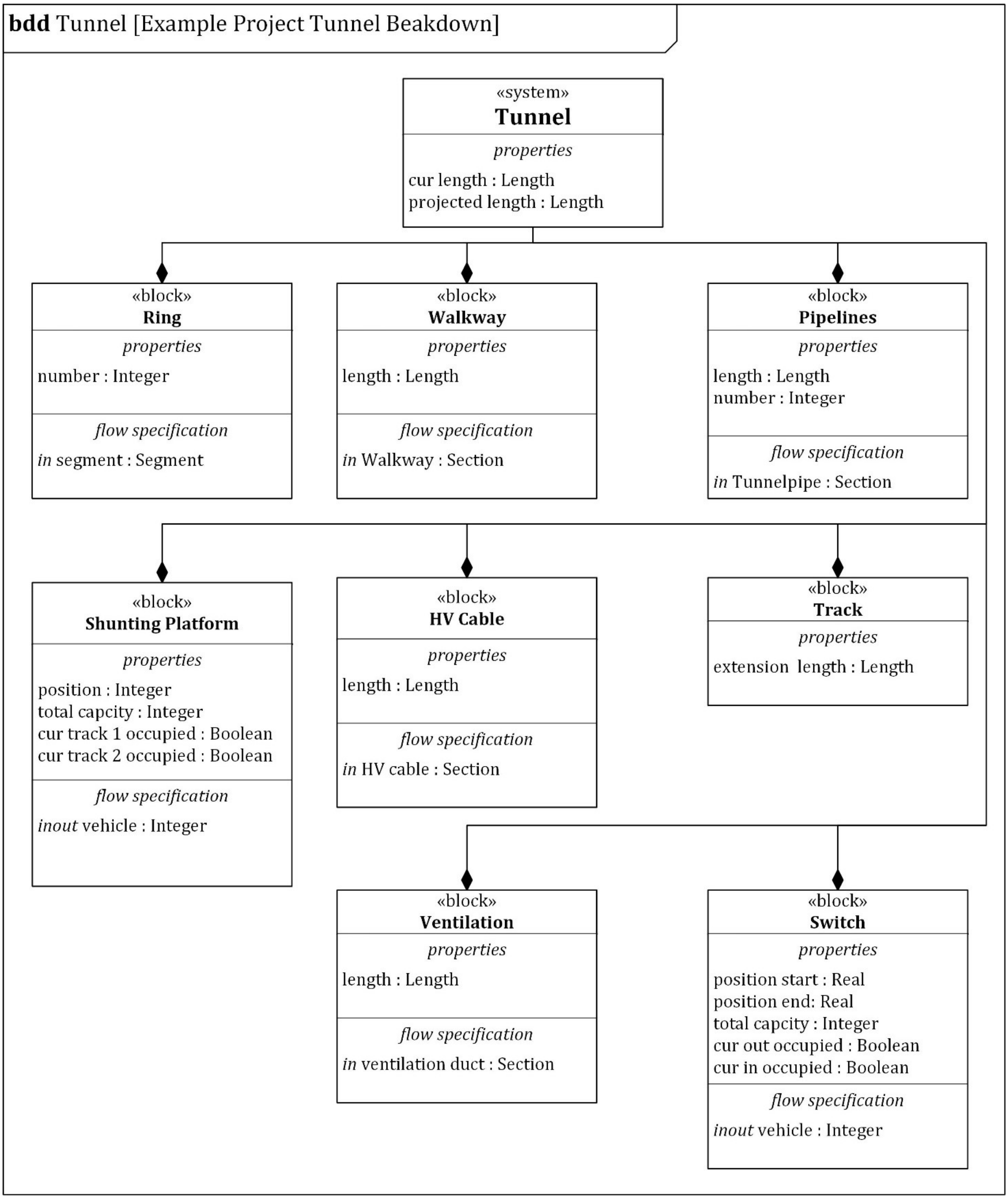
Resource	Material	Start	End	Process	ID
Grease Truck	Grease	Gate 1	Liquids Storage	Grease Delivery	*ID1*
Mobile Crane	Grease	Grease Truck	Liquids Storage	Grease Unloading	*ID2*
Mobile Crane	Grease	Liquids Storage	Train	Grease Loading	*ID3*
Grease Crane	Grease	Train	TBM Gantry	Grease Transfer	*ID4*
Grease Crane	Grease	TBM Gantry	Grease Pump	Grease Replenishing	*ID5*
Grout Truck	**Grout**	**Gate 1**	**Batching Plant**	**Grout Delivery**	***ID6***
Batching Plant	**Grout**	**Grout Silo**	**Train**	**Grout Loading**	***ID7***
Grout Transfer Pump	**Grout**	**Train**	**TBM Grout Tank**	**Grout Transfer**	***ID8***
Cable Truck	**HV Cable**	**Gate 1**	**General Storage**	**Cable Delivery**	***ID9***
Mobile Crane	**HV Cable**	**Cable Truck**	**General Storage**	**Cable Unloading**	***ID10***
Mobile Crane	**HV Cable**	**General Storage**	**Train**	**Cable Loading**	***ID11***
Train	**HV Cable**	**Train**	**TBM**	**Cable Installation**	***ID12***
TBM	**Muck**	**TBM**	**Train**	**Advance**	***ID13***
Gantry Crane	**Muck**	**Train**	**Muckpit**	**Muck Unloading**	***ID14***
Excavator	**Muck**	**Muckpit**	**Dumptruck**	**Muck Loading**	***ID15***
Dumptruck	**Muck**	**Muckpit**	**Gate 2**	**Muck Disposal**	***ID16***
Rail Truck	**Rails**	**Gate 1**	**General Storage**	**Rail Delivery**	***ID17***
Mobile Crane	**Rails**	**Rail Truck**	**General Storage**	**Rail Unloading**	***ID18***
Mobile Crane	**Rails**	**General Storage**	**Train**	**Rail Loading**	***ID19***
Segment crane	**Rails**	**Train**	**Bridge Storage**	**Rail Transfer**	***ID20***
Segment crane	**Rails**	**Bridge Storage**	**Tunnel Floor**	**Rail Assembly**	***ID21***
Rail Crane	**Rails**	**Tunnel Floor**	**Tunnel Floor**	**Rail Disassembly**	***ID22***
Rail Crane	**Rails**	**Tunnel Floor**	**Train**	**Rail Reloading**	***ID23***
Segment Truck	**Segments**	**Gate 1**	**Segment Storage**	**Segment Delivery**	***ID24***
Mobile Crane	**Segments**	**Segment Truck**	**Segment Storage**	**Segment Unloading**	***ID25***
Mobile Crane	**Segments**	**Segment Storage**	**Train**	**Segment Loading**	***ID26***
Segment Crane	**Segments**	**Train**	**Segment Feeder**	**Segment Transfer**	***ID27***
Segment Feeder	**Segments**	**Segment Feeder**	**Erector**	**Segment Feeding**	***ID28***
Erector	**Segments**	**Erector**	**Tunnel**	**Ringbuilding**	***ID29***
Tenside Truck	**Tenside**	**Gate 1**	**Liquids Storage**	**Tenside Delivery**	***ID30***
Mobile Crane	**Tenside**	**Tenside Truck**	**Liquids Storage**	**Tenside Unloading**	***ID31***
Mobile Crane	**Tenside**	**Liquids Storage**	**Train**	**Tenside Loading**	***ID32***
Tenside Crane	**Tenside**	**Train**	**TBM Gantry**	**Tenside Transfer**	***ID33***
Tenside Crane	**Tenside**	**TBM Gantry**	**Foam Station**	**Tenside Replenish**	***ID34***
Pipe Truck	**Tunnel Pipes**	**Gate 1**	**General Storage**	**Pipes Delivery**	***ID35***
Mobile Crane	**Tunnel Pipes**	**Pipe Truck**	**General Storage**	**Pipes Unloading**	***ID36***
Mobile Crane	**Tunnel Pipes**	**General Storage**	**Train**	**Pipes Loading**	***ID37***
Rail Crane	**Tunnel Pipes**	**Train**	**Tunnel Floor**	**Pipes Transfer**	***ID38***
Rail Crane	**Tunnel Pipes**	**Tunnel Floor**	**Tunnel**	**Pipe Extension**	***ID39***
Duct Truck	**V. Duct**	**Gate 1**	**General Storage**	**V. Duct Delivery**	***ID40***
Mobile Crane	**V. Duct**	**Duct Truck**	**General Storage**	**V. Duct Unloading**	***ID41***
Mobile Crane	**V. Duct**	**General Storage**	**Train**	**V. Duct Loading**	***ID42***
Train	**V. Duct**	**Train**	**TBM**	**V. Duct Installation**	***ID43***
W. Material Truck	**Walkway Material**	**Gate 1**	**General Storage**	**W. Material Delivery**	***ID44***
Mobile Crane	**Walkway Material**	**W. Material Truck**	**General Storage**	**W. Material Unloading**	***ID45***
Mobile Crane	Walkway Material	General Storage	Train	W. Material Loading	*ID46*
Rail Crane	Walkway Material	Train	Tunnel Floor	W. Material Transfer	*ID47*
Rail Crane	Walkway Material	Tunnel Floor	Tunnel	Walkway Extension	*ID48*

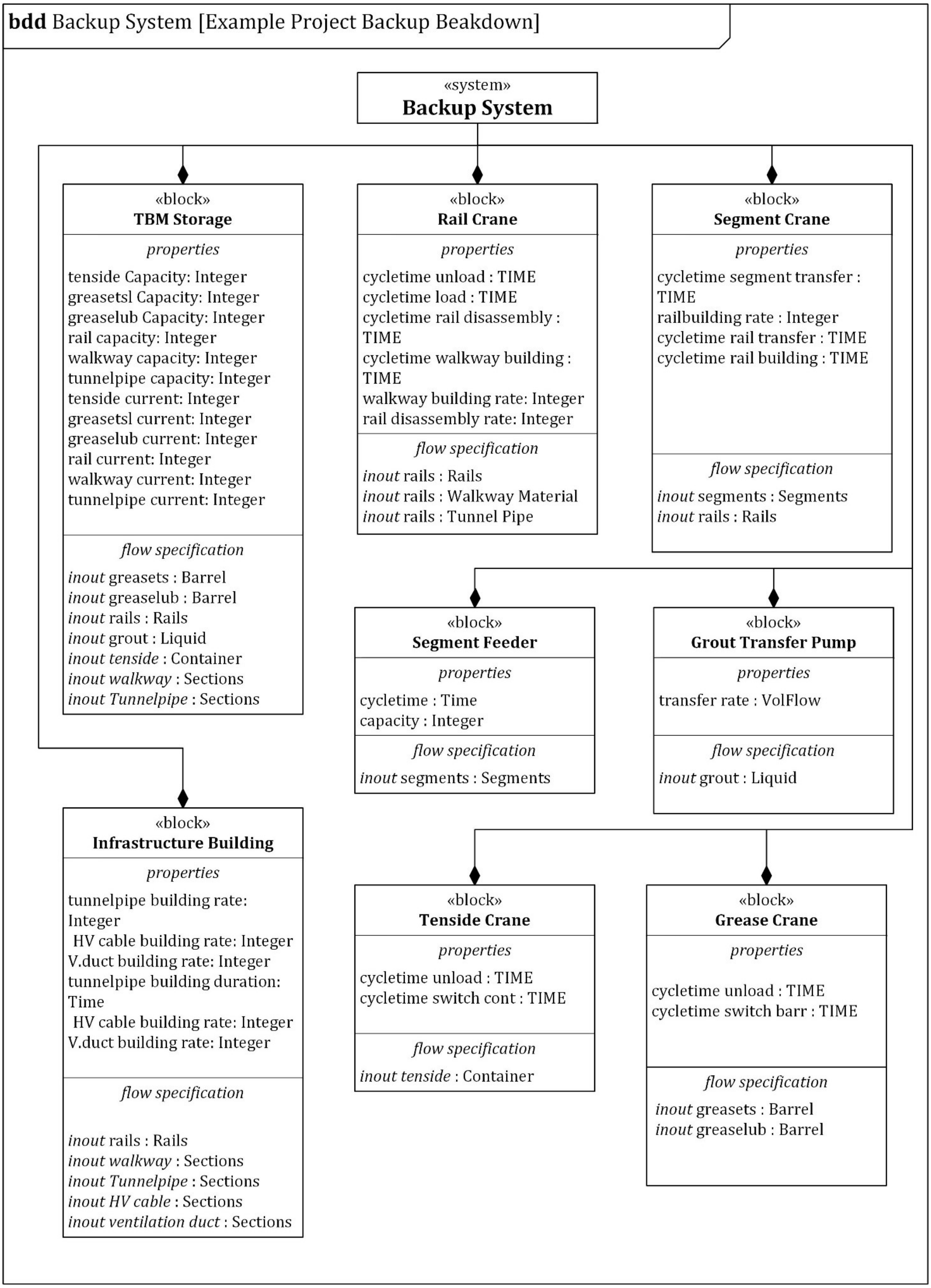
Appendix 4 – SysML Model of the Example Project

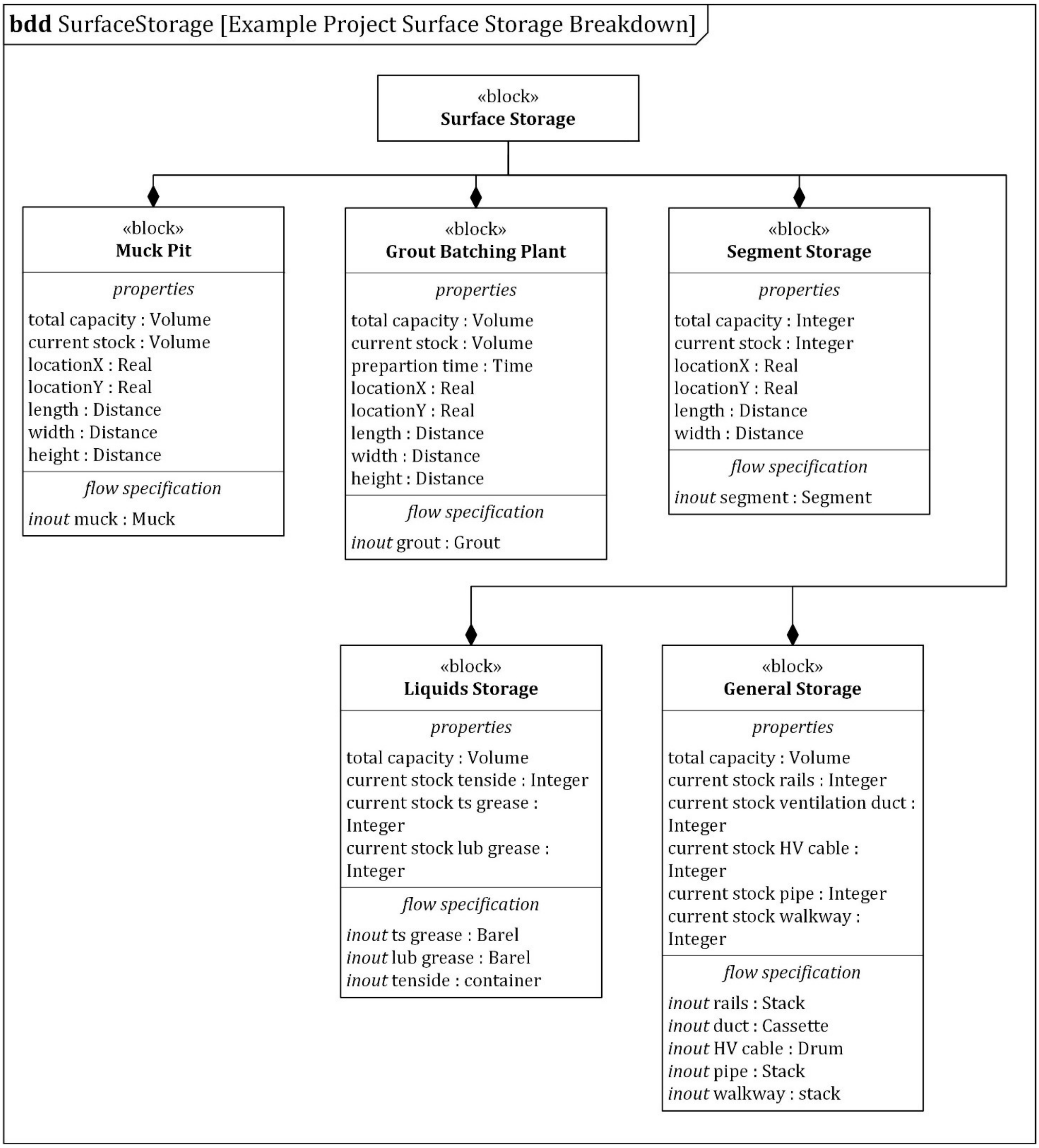
Block Definition Diagrams

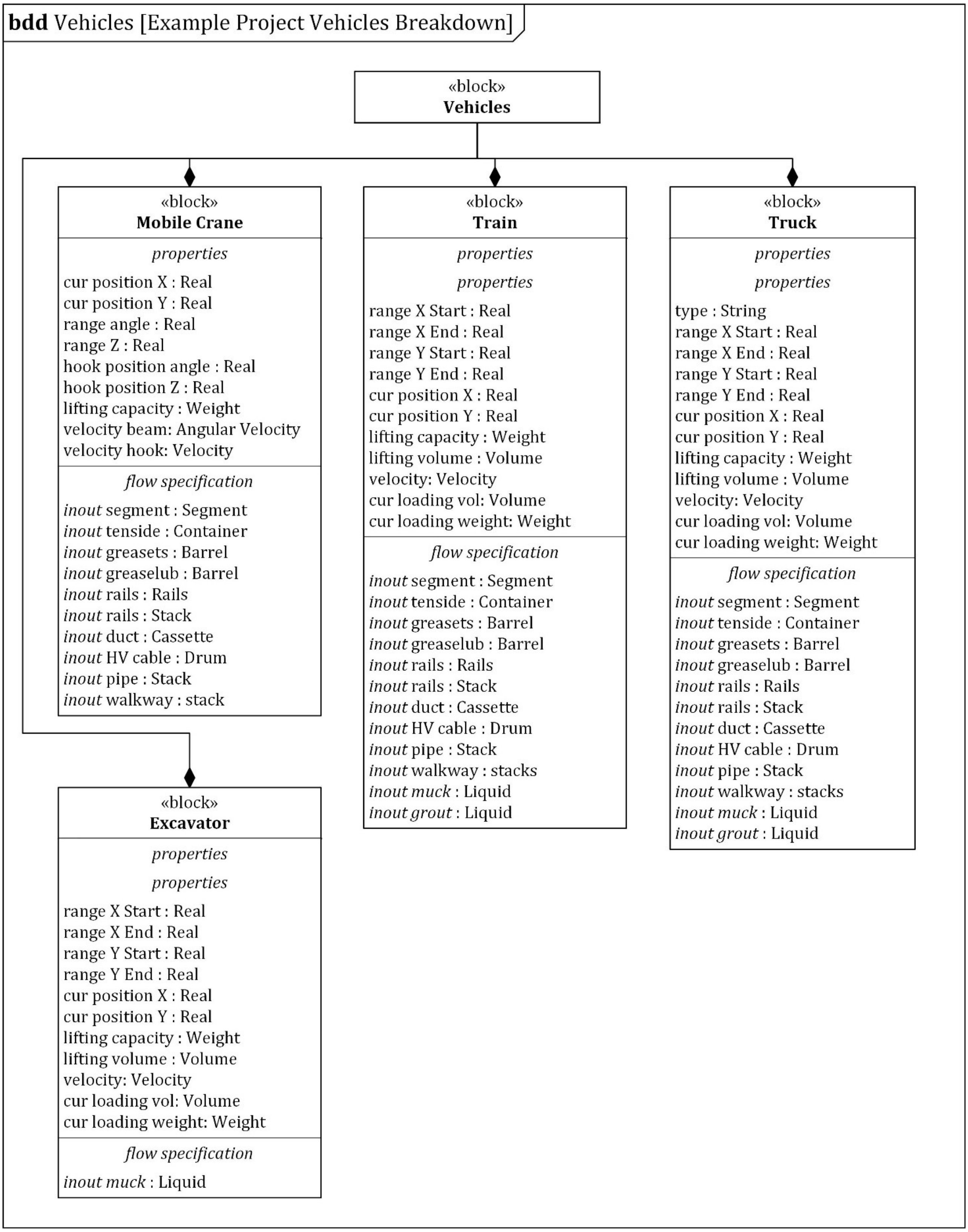


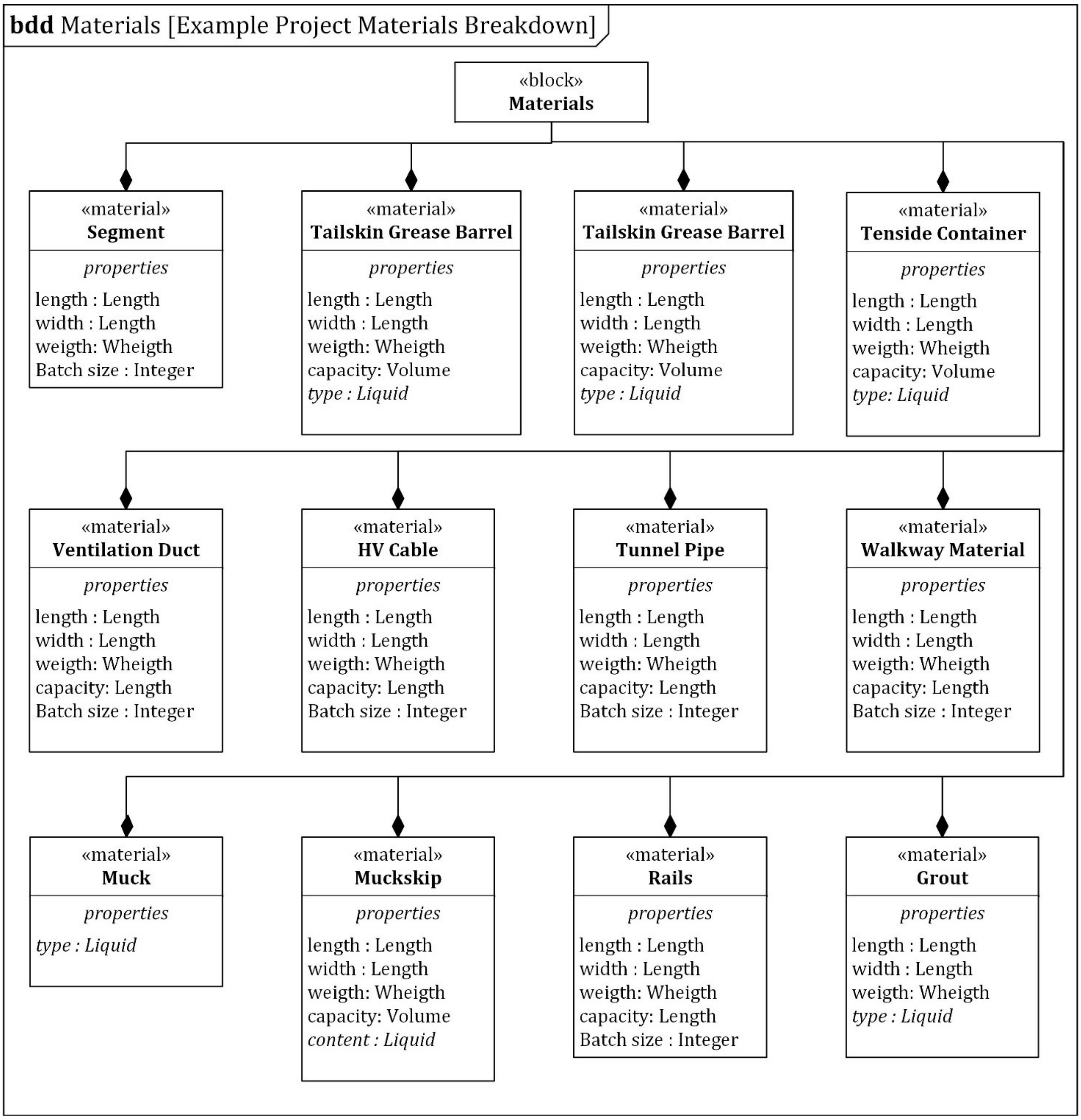

bdd EPB TBM [Example Project TBM Beakdown]
«system»
Tunnel Boring Machine
«block»
Excavator
properties
excavation rate : VolFlow
flow specification
inout muck : Liquid
«block»
Erector
properties
dur segment installation : Time
flow specification
inout segment : Segment
«block»
Thrust Cylinder
properties
cur stroke : Length
stroke length : Length
advance rate : Velocity
«block»
Lubrication System
properties
lubrication rate : VolFlow
storage capacity: Volume
cur filling : Volume
flow specification
inout greaselub : Barrel
«block»
Tailskin Greasing System
properties
grease injection rate : VolFlow
storage capacity: Volume
cur filling : Volume
flow specification
inout greasets : Barrel
«block»
Foam Injection System
properties
injection rate : VolFlow
storage capacity: Volume
cur filling : Volume
flow specification
inout tenside : Container
«block»
Grout Injection System
properties
injection rate : VolFlow
storage capacity: Volume
cur filling : Volume
flow specification
inout grout : Liquid

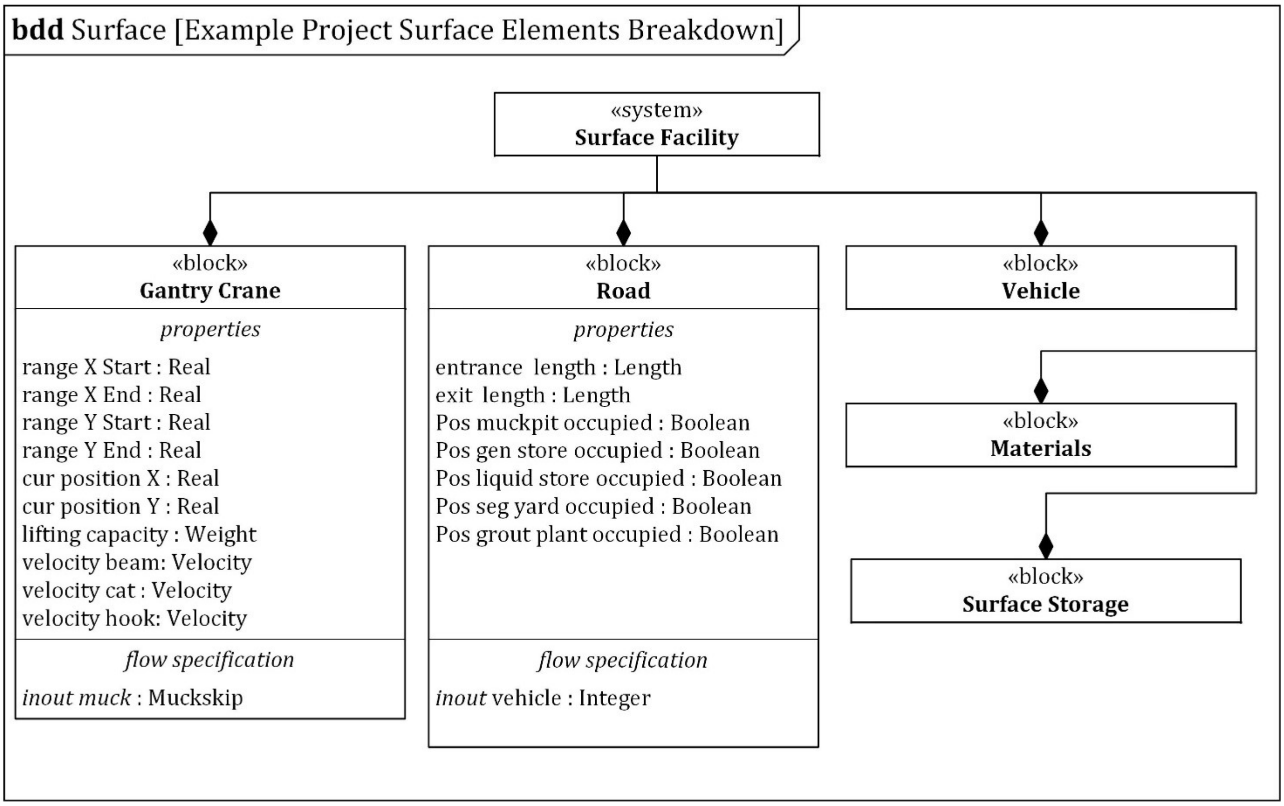

bdd Tunnel [Example Project Tunnel Beakdown]
«system»
Tunnel
properties
cur length : Length
projected length : Length
«block»
Ring
properties
number : Integer
flow specification
in segment : Segment
«block»
Walkway
properties
length : Length
flow specification
in Walkway : Section
«block»
Pipelines
properties
length : Length
number : Integer
flow specification
in Tunnelpipe : Section
«block»
Shunting Platform
properties
position : Integer
total capcity : Integer
cur track 1 occupied : Boolean
cur track 2 occupied : Boolean
flow specification
inout vehicle : Integer
«block»
HV Cable
properties
length : Length
flow specification
in HV cable : Section
«block»
Track
properties
extension length : Length
«block»
Ventilation
properties
length : Length
flow specification
in ventilation duct : Section
«block»
Switch
properties
position start : Real
position end: Real
total capcity : Integer
cur out occupied : Boolean
cur in occupied : Boolean
flow specification
inout vehicle : Integer


bdd Backup System [Example Project Backup Beakdown]
«system»
Backup System
«block»
TBM Storage
properties
tenside Capacity: Integer
greasetsl Capacity: Integer
greaselub Capacity: Integer
rail capacity: Integer
walkway capacity: Integer
tunnelpipe capacity: Integer
tenside current: Integer
greasetsl current: Integer
greaselub current: Integer
rail current: Integer
walkway current: Integer
tunnelpipe current: Integer
flow specification
inout greasets : Barrel
inout greaselub : Barrel
inout rails : Rails
inout grout : Liquid
inout tenside : Container
inout walkway : Sections
inout Tunnelpipe : Sections
«block»
Rail Crane
properties
cycletime unload : TIME
cycletime load : TIME
cycletime rail disassembly : TIME
cycletime walkway building : TIME
walkway building rate: Integer
rail disassembly rate: Integer
flow specification
inout rails : Rails
inout rails : Walkway Material
inout rails : Tunnel Pipe
«block»
Segment Crane
properties
cycletime segment transfer : TIME
railbuilding rate : Integer
cycletime rail transfer : TIME
cycletime rail building : TIME
flow specification
inout segments : Segments
inout rails : Rails
«block»
Segment Feeder
properties
cycletime : Time
capacity : Integer
flow specification
inout segments : Segments
«block»
Grout Transfer Pump
properties
transfer rate : VolFlow
flow specification
inout grout : Liquid
«block»
Infrastructure Building
properties
tunnelpipe building rate: Integer
HV cable building rate: Integer
V.duct building rate: Integer
tunnelpipe building duration: Time
HV cable building rate: Integer
V.duct building rate: Integer
flow specification
inout rails : Rails
inout walkway : Sections
inout Tunnelpipe : Sections
inout HV cable : Sections
inout ventilation duct : Sections
«block»
Tenside Crane
properties
cycletime unload : TIME
cycletime switch cont : TIME
flow specification
inout tenside : Container
«block»
Grease Crane
properties
cycletime unload : TIME
cycletime switch barr : TIME
flow specification
inout greasets : Barrel
inout greaselub : Barrel

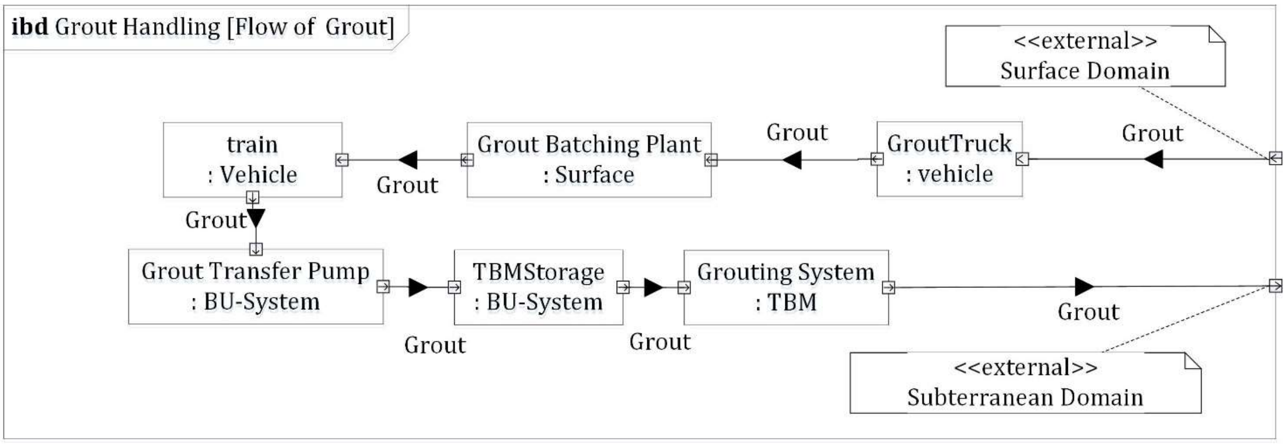

bdd SurfaceStorage [Example Project Surface Storage Breakdown]
«block»
Surface Storage
«block»
Muck Pit
properties
total capacity : Volume
current stock : Volume
locationX : Real
locationY : Real
length : Distance
width : Distance
height : Distance
flow specification
inout muck : Muck
«block»
Grout Batching Plant
properties
total capacity : Volume
current stock : Volume
prepartion time : Time
locationX : Real
locationY : Real
length : Distance
width : Distance
height : Distance
flow specification
inout grout : Grout
«block»
Segment Storage
properties
total capacity : Integer
current stock : Integer
locationX : Real
locationY : Real
length : Distance
width : Distance
flow specification
inout segment : Segment
«block»
Liquids Storage
properties
total capacity : Volume
current stock tenside : Integer
current stock ts grease : Integer
current stock lub grease : Integer
flow specification
inout ts grease : Barel
inout lub grease : Barel
inout tenside : container
«block»
General Storage
properties
total capacity : Volume
current stock rails : Integer
current stock ventilation duct : Integer
current stock HV cable : Integer
current stock pipe : Integer
current stock walkway : Integer
flow specification
inout rails : Stack
inout duct : Cassette
inout HV cable : Drum
inout pipe : Stack
inout walkway : stack

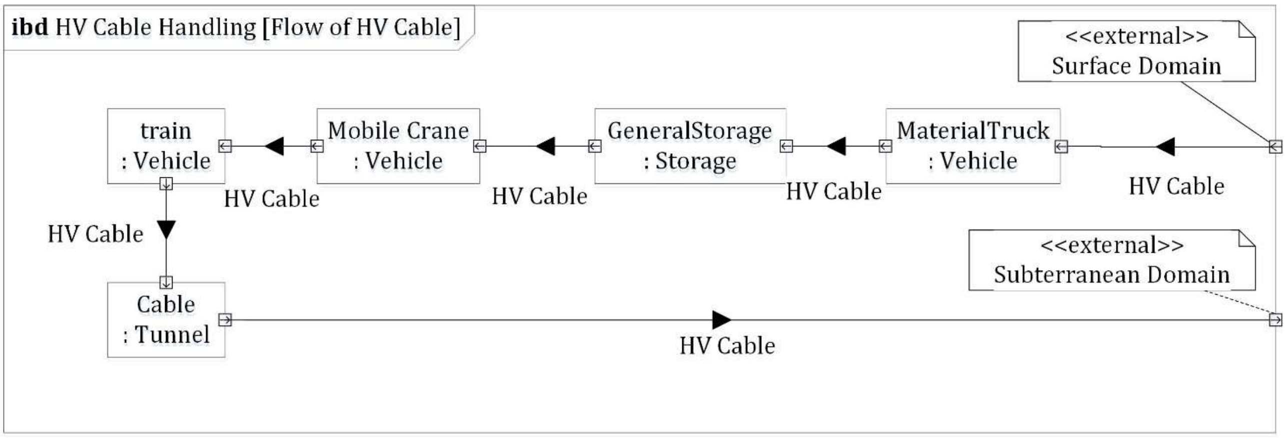

bdd Vehicles [Example Project Vehicles Breakdown]
«block»
Vehicles
«block»
Mobile Crane
properties
cur position X : Real
cur position Y : Real
range angle : Real
range Z : Real
hook position angle : Real
hook position Z : Real
lifting capacity : Weight
velocity beam: Angular Velocity
velocity hook: Velocity
flow specification
inout segment : Segment
inout tenside : Container
inout greasets : Barrel
inout greaselub : Barrel
inout rails : Rails
inout rails : Stack
inout duct : Cassette
inout HV cable : Drum
inout pipe : Stack
inout walkway : stack
«block»
Train
properties
properties
range X Start : Real
range X End : Real
range Y Start : Real
range Y End : Real
cur position X : Real
cur position Y : Real
lifting capacity : Weight
lifting volume : Volume
velocity: Velocity
cur loading vol: Volume
cur loading weight: Weight
flow specification
inout segment : Segment
inout tenside : Container
inout greasets : Barrel
inout greaselub : Barrel
inout rails : Rails
inout rails : Stack
inout duct : Cassette
inout HV cable : Drum
inout pipe : Stack
inout walkway : stacks
inout muck : Liquid
inout grout : Liquid
«block»
Truck
properties
properties
type : String
range X Start : Real
range X End : Real
range Y Start : Real
range Y End : Real
cur position X : Real
cur position Y : Real
lifting capacity : Weight
lifting volume : Volume
velocity: Velocity
cur loading vol: Volume
cur loading weight: Weight
flow specification
inout segment : Segment
inout tenside : Container
inout greasets : Barrel
inout greaselub : Barrel
inout rails : Rails
inout rails : Stack
inout duct : Cassette
inout HV cable : Drum
inout pipe : Stack
inout walkway : stacks
inout muck : Liquid
inout grout : Liquid
«block»
Excavator
properties
properties
range X Start : Real
range X End : Real
range Y Start : Real
range Y End : Real
cur position X : Real
cur position Y : Real
lifting capacity : Weight
lifting volume : Volume
velocity: Velocity
cur loading vol: Volume
cur loading weight: Weight
flow specification
inout muck : Liquid

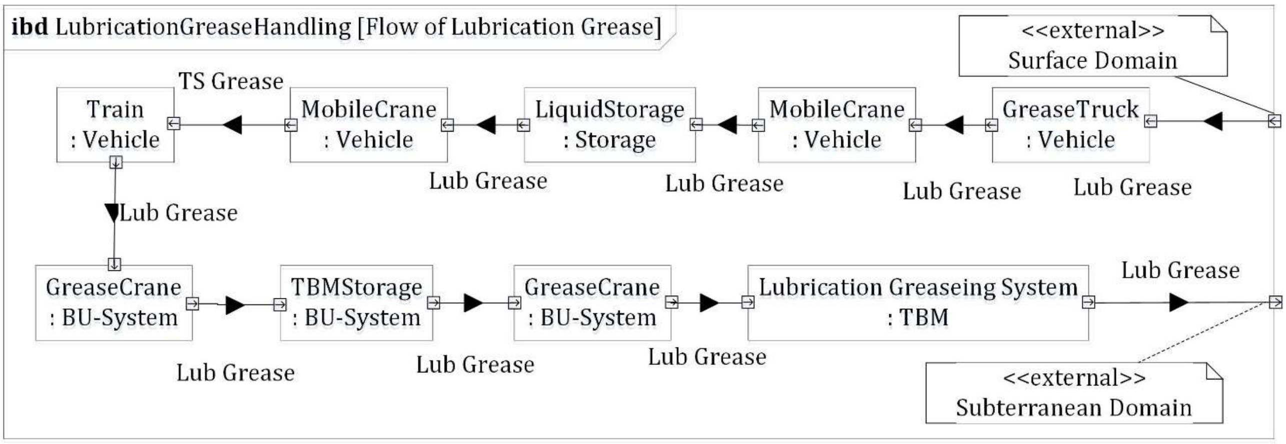

bdd Materials [Example Project Materials Breakdown]
«block»
Materials
«material»
Segment
properties
length : Length
width : Length
weigth: Wheigth
Batch size : Integer
«material»
Tailskin Grease Barrel
properties
length : Length
width : Length
weigth: Wheigth
capacity: Volume
type : Liquid
«material»
Tailskin Grease Barrel
properties
length : Length
width : Length
weigth: Wheigth
capacity: Volume
type : Liquid
«material»
Tenside Container
properties
length : Length
width : Length
weigth: Wheigth
capacity: Volume
type: Liquid
«material»
Ventilation Duct
properties
length : Length
width : Length
weigth: Wheigth
capacity: Length
Batch size : Integer
«material»
HV Cable
properties
length : Length
width : Length
weigth: Wheigth
capacity: Length
Batch size : Integer
«material»
Tunnel Pipe
properties
length : Length
width : Length
weigth: Wheigth
capacity: Length
Batch size : Integer
«material»
Walkway Material
properties
length : Length
width : Length
weigth: Wheigth
capacity: Length
Batch size : Integer
«material»
Muck
properties
type : Liquid
«material»
Muckskip
properties
length : Length
width : Length
weigth: Wheigth
capacity: Volume
content : Liquid
«material»
Rails
properties
length : Length
width : Length
weigth: Wheigth
capacity: Length
Batch size : Integer
«material»
Grout
properties
length : Length
width : Length
weigth: Wheigth
type : Liquid

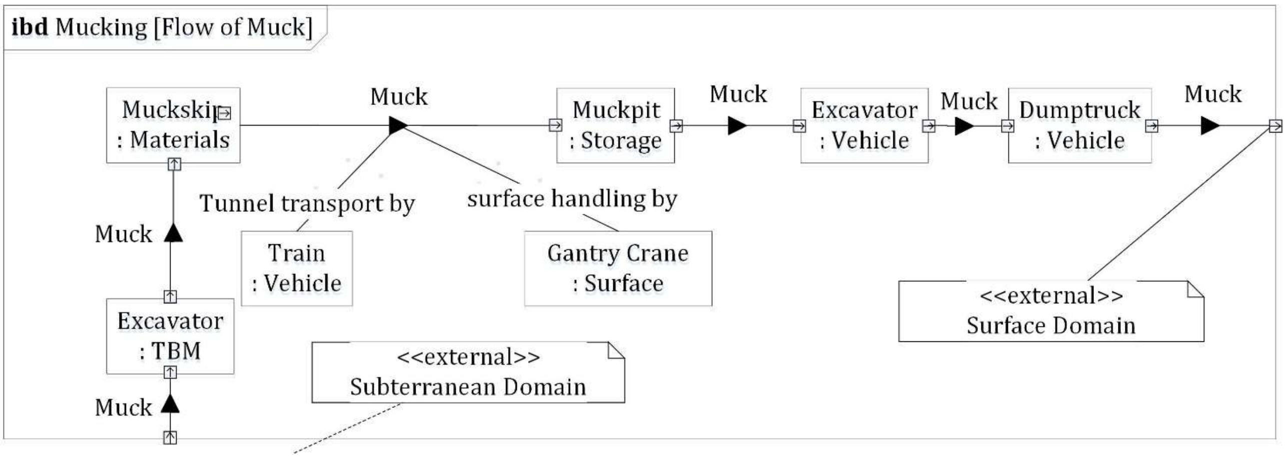

bdd Surface [Example Project Surface Elements Breakdown]
«system»
Surface Facility
«block»
Gantry Crane
properties
range X Start : Real
range X End : Real
range Y Start : Real
range Y End : Real
cur position X : Real
cur position Y : Real
lifting capacity : Weight
velocity beam: Velocity
velocity cat : Velocity
velocity hook: Velocity
flow specification
inout muck : Muckskip
«block»
Road
properties
entrance length : Length
exit length : Length
Pos muckpit occupied : Boolean
Pos gen store occupied : Boolean
Pos liquid store occupied : Boolean
Pos seg yard occupied : Boolean
Pos grout plant occupied : Boolean
flow specification
inout vehicle : Integer
«block»
Vehicle
«block»
Materials
«block»
Surface Storage

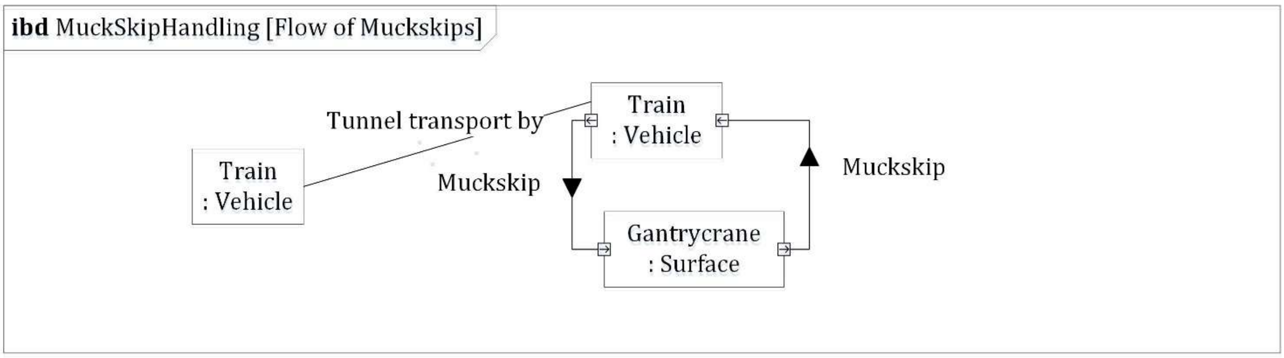
Material Flow Diagrams

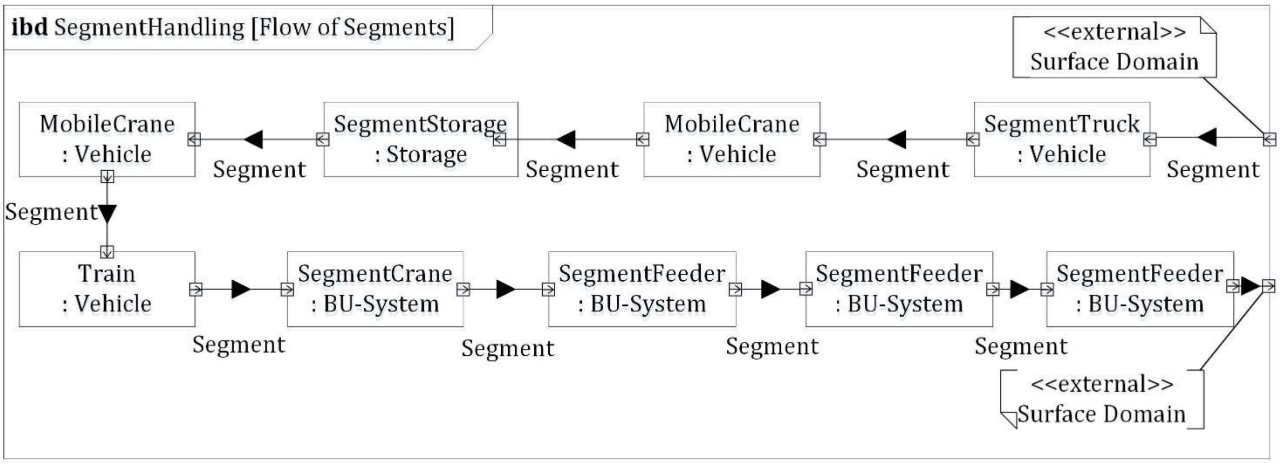


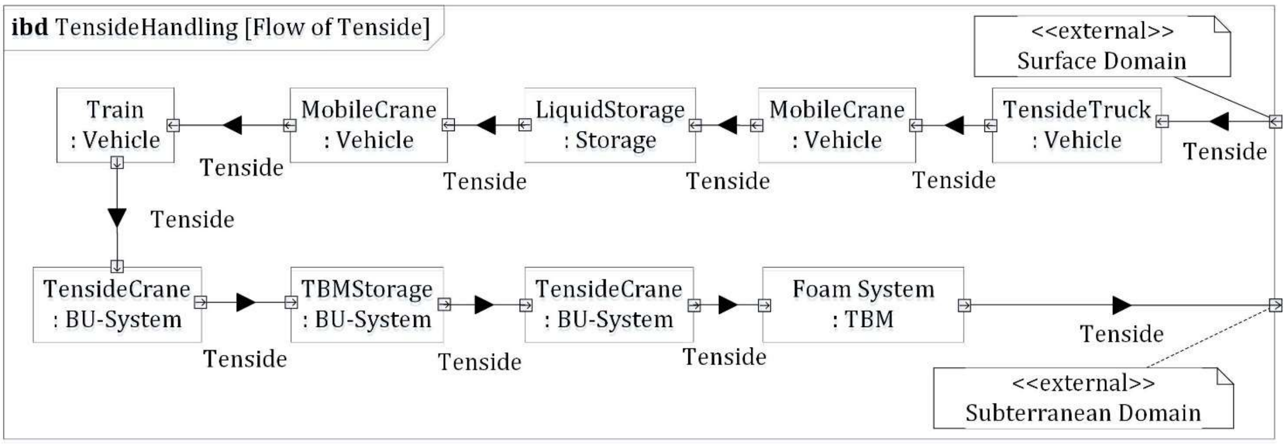


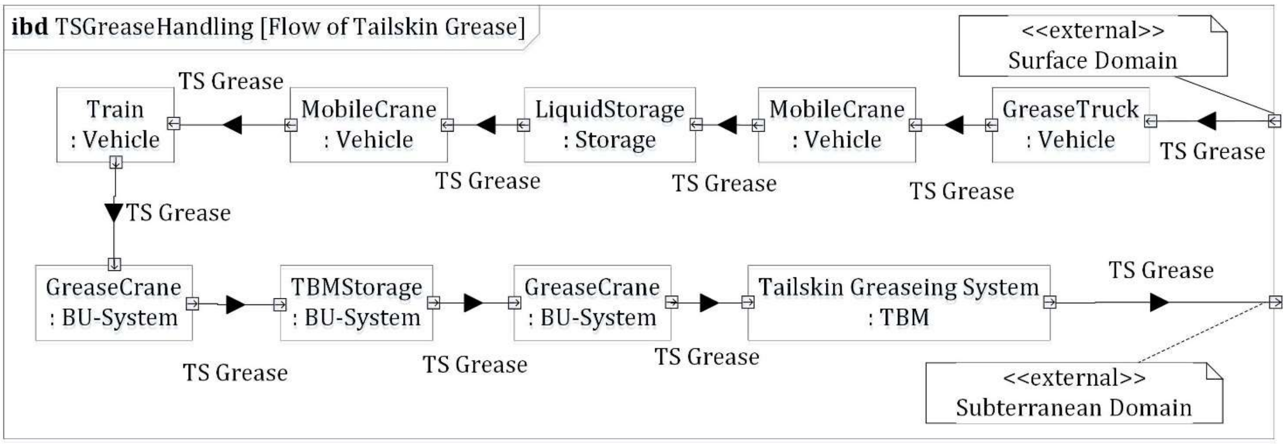


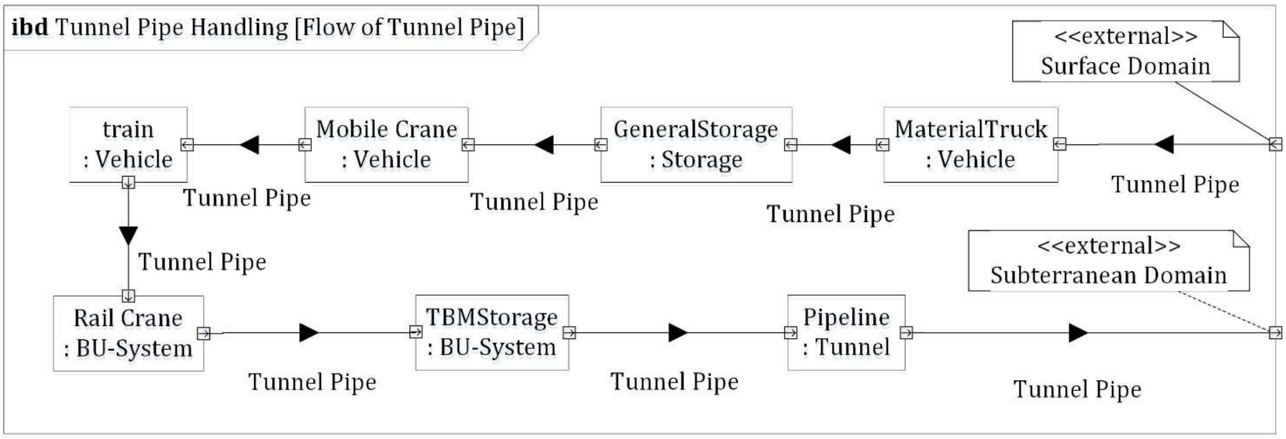

ibd Mucking [Flow of Muck]
Muckskip : Materials
Muck
Muckpit : Storage
Muck
Excavator : Vehicle
Muck
Dumptruck : Vehicle
Muck
Tunnel transport by
surface handling by
Muck
Train : Vehicle
Gantry Crane : Surface
<<external>> Surface Domain
Excavator : TBM
<<external>> Subterranean Domain
Muck

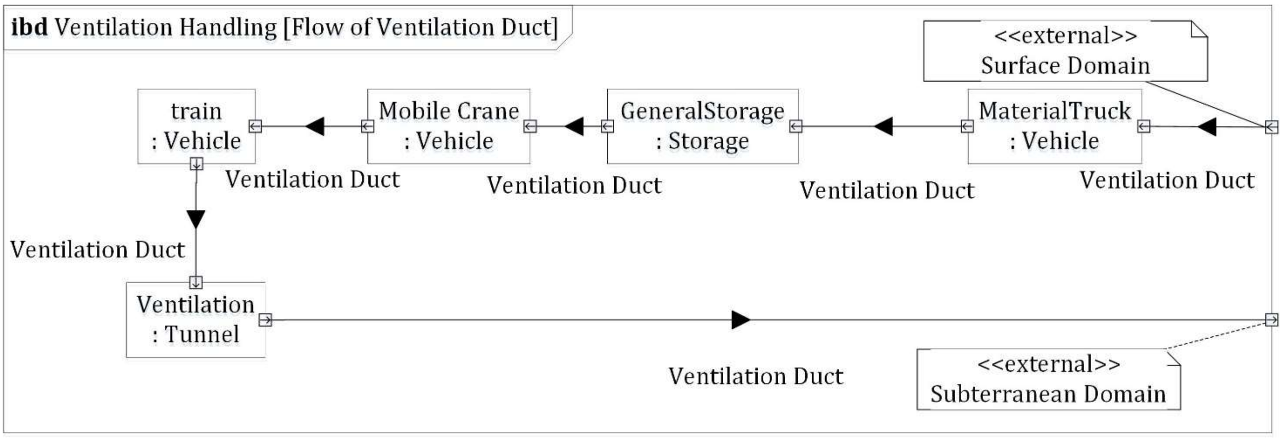

ibd MuckSkipHandling [Flow of Muckskips]
Train : Vehicle
Tunnel transport by
Train : Vehicle
Muckskip
Muckskip
Gantrycrane : Surface

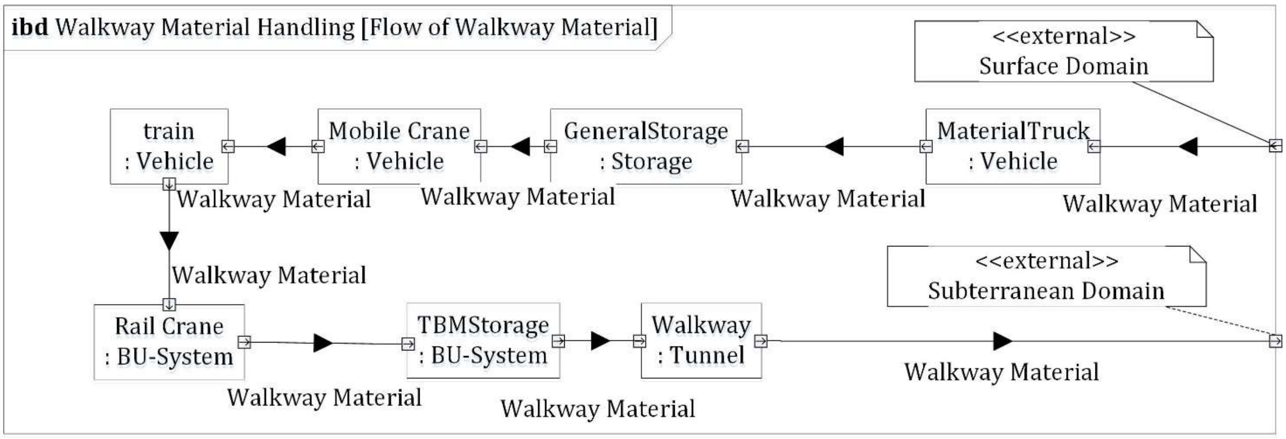

ibd SegmentHandling [Flow of Segments]
<<external>> Surface Domain
MobileCrane : Vehicle
SegmentStorage : Storage
MobileCrane : Vehicle
SegmentTruck : Vehicle
Segment
Segment
Segment
Segment
Segment
Train : Vehicle
SegmentCrane : BU-System
SegmentFeeder : BU-System
SegmentFeeder : BU-System
SegmentFeeder : BU-System
Segment
Segment
Segment
Segment
<<external>> Surface Domain

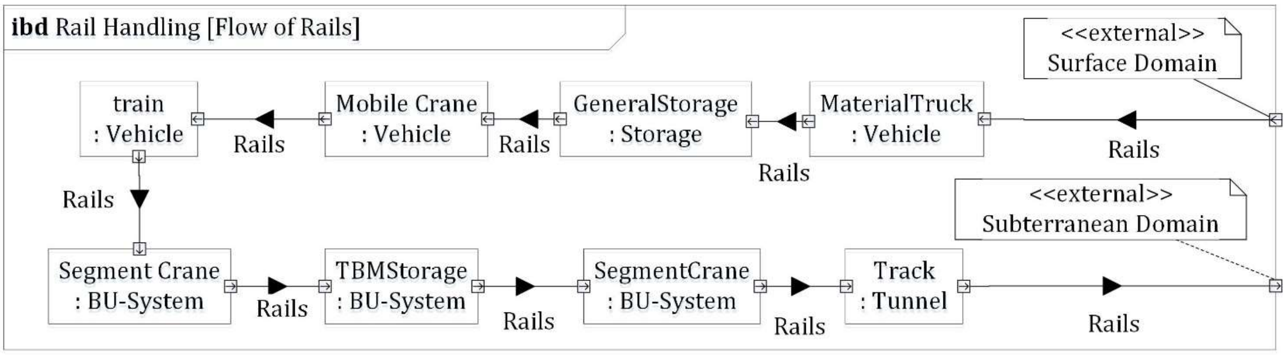

ibd TensideHandling [Flow of Tenside]
<<external>>
Surface Domain
Train
: Vehicle
MobileCrane
: Vehicle
LiquidStorage
: Storage
MobileCrane
: Vehicle
TensideTruck
: Vehicle
Tenside
Tenside
Tenside
Tenside
Tenside
Tenside
TensideCrane
: BU-System
TBMStorage
: BU-System
TensideCrane
: BU-System
Foam System
: TBM
Tenside
Tenside
Tenside
Tenside
<<external>>
Subterranean Domain

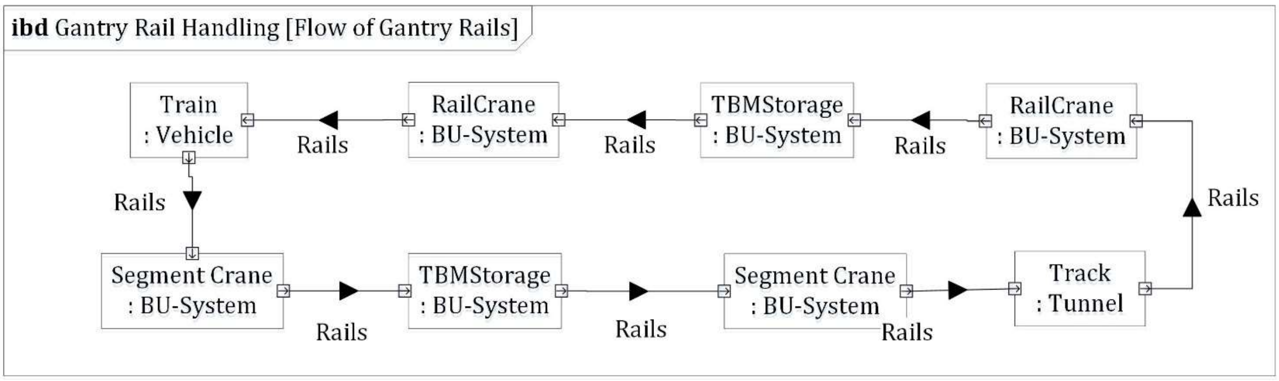

ibd TSGreaseHandling [Flow of Tailskin Grease]
<<external>>
Surface Domain
TS Grease
Train
: Vehicle
MobileCrane
: Vehicle
LiquidStorage
: Storage
MobileCrane
: Vehicle
GreaseTruck
: Vehicle
TS Grease
TS Grease
TS Grease
TS Grease
TS Grease
GreaseCrane
: BU-System
TBMStorage
: BU-System
GreaseCrane
: BU-System
Tailskin Greaseing System
: TBM
TS Grease
TS Grease
TS Grease
TS Grease
<<external>>
Subterranean Domain


ibd Tunnel Pipe Handling [Flow of Tunnel Pipe]
<<external>>
Surface Domain
train
: Vehicle
Mobile Crane
: Vehicle
GeneralStorage
: Storage
MaterialTruck
: Vehicle
Tunnel Pipe
Tunnel Pipe
Tunnel Pipe
Tunnel Pipe
Tunnel Pipe
<<external>>
Subterranean Domain
Rail Crane
: BU-System
TBMStorage
: BU-System
Pipeline
: Tunnel
Tunnel Pipe
Tunnel Pipe
Tunnel Pipe

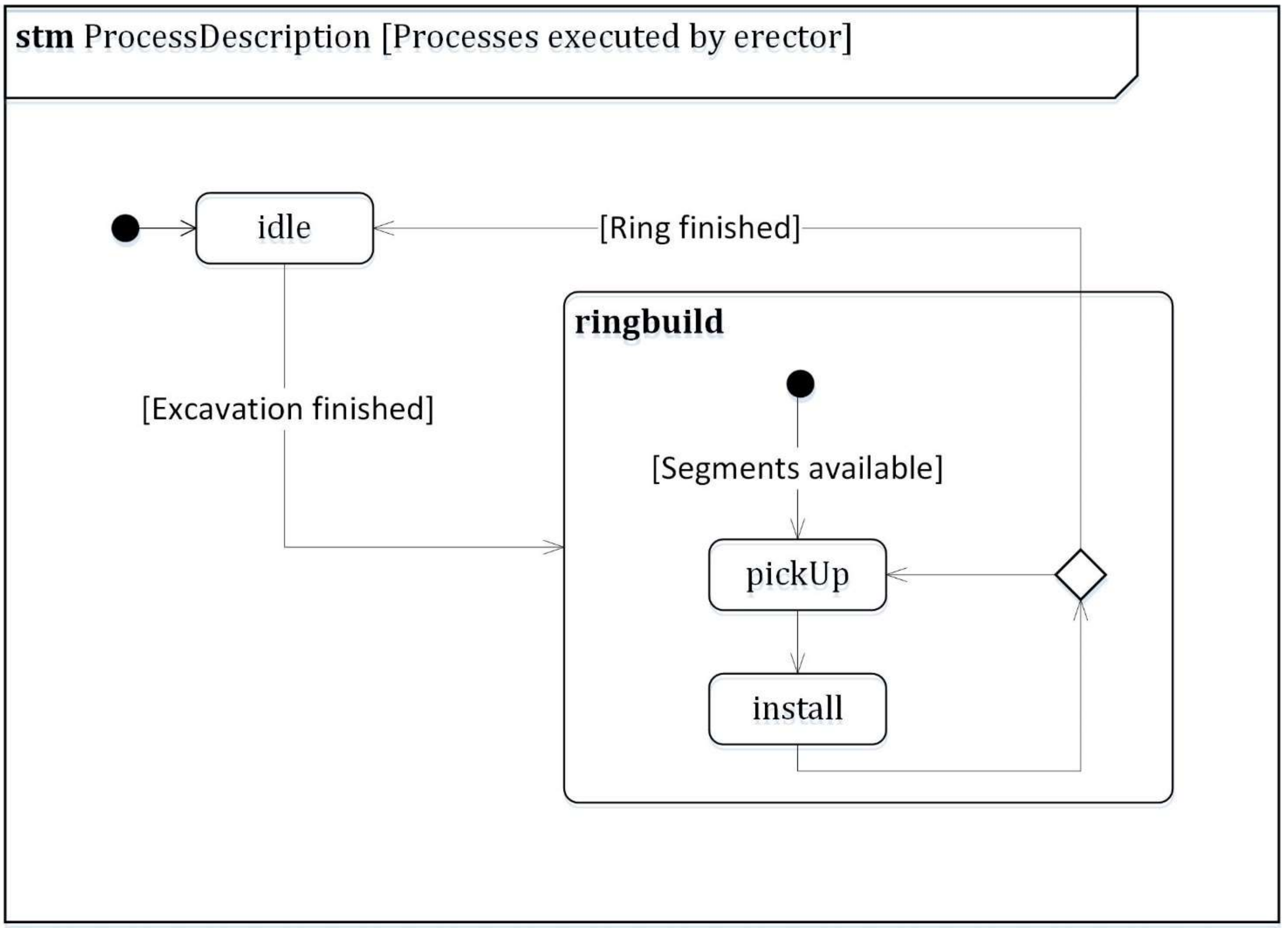

ibd Ventilation Handling [Flow of Ventilation Duct]
<<external>>
Surface Domain
train
: Vehicle
Mobile Crane
: Vehicle
GeneralStorage
: Storage
MaterialTruck
: Vehicle
Ventilation Duct
Ventilation Duct
Ventilation Duct
Ventilation Duct
Ventilation Duct
Ventilation
: Tunnel
Ventilation Duct
<<external>>
Subterranean Domain

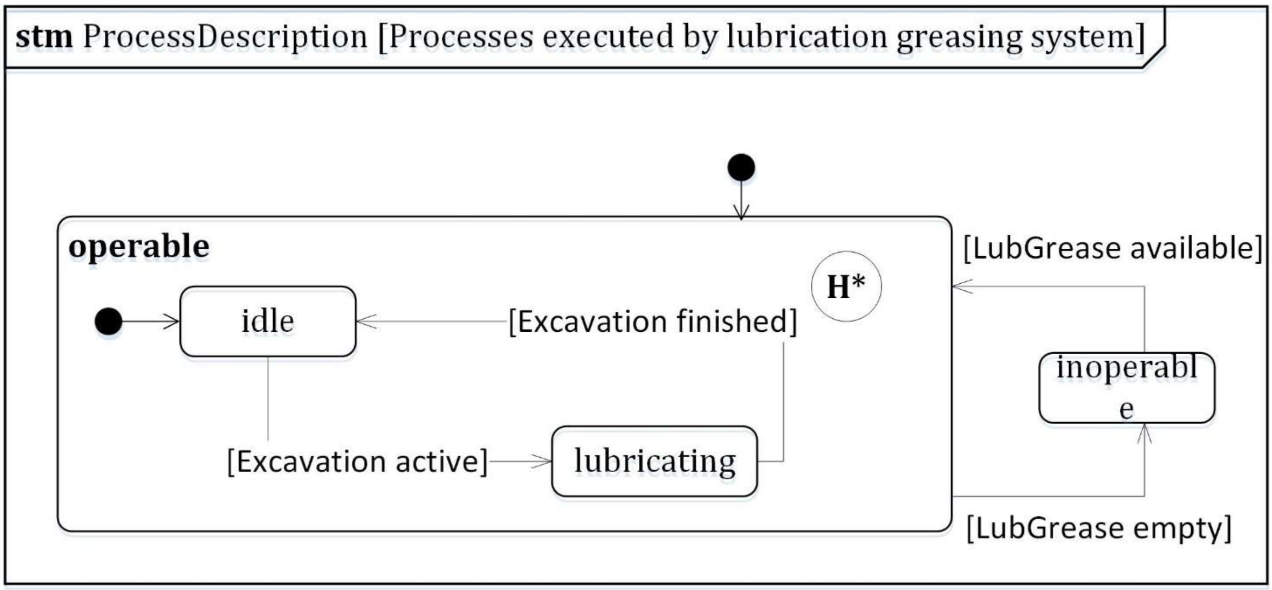

ibd Walkway Material Handling [Flow of Walkway Material]
<<external>>
Surface Domain
train
: Vehicle
Mobile Crane
: Vehicle
GeneralStorage
: Storage
MaterialTruck
: Vehicle
Walkway Material
Walkway Material
Walkway Material
Walkway Material
Walkway Material
<<external>>
Subterranean Domain
Rail Crane
: BU-System
TBMStorage
: BU-System
Walkway
: Tunnel
Walkway Material
Walkway Material
Walkway Material

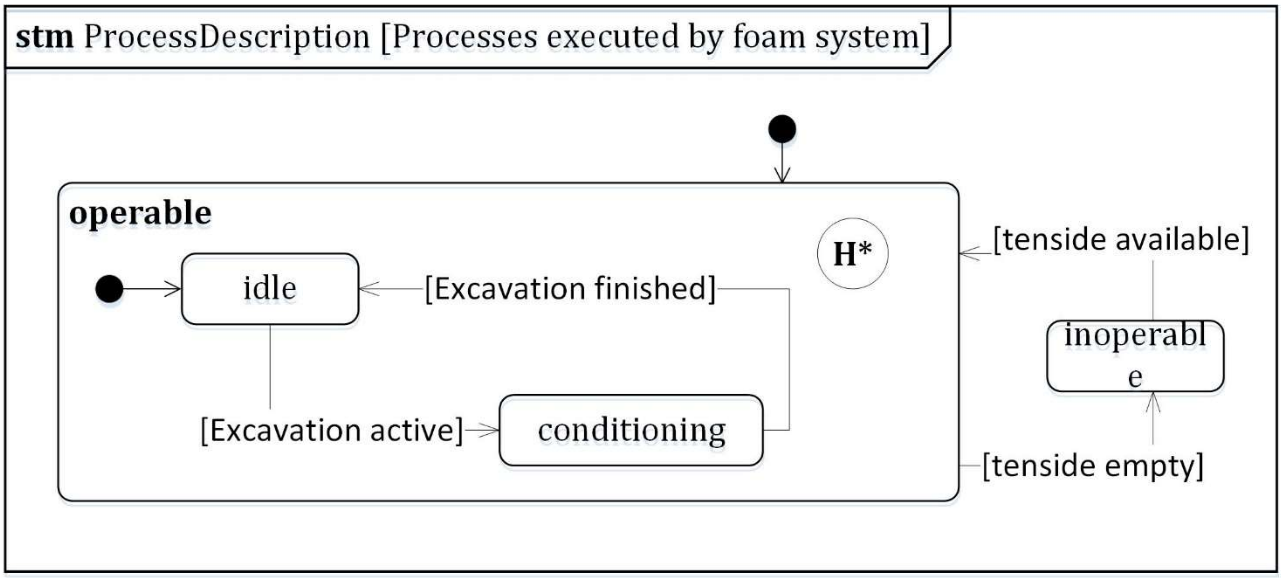

ibd Rail Handling [Flow of Rails]
<<external>>
Surface Domain
train
: Vehicle
Rails
Mobile Crane
: Vehicle
Rails
GeneralStorage
: Storage
MaterialTruck
: Vehicle
Rails
Rails
Rails
<<external>>
Subterranean Domain
Segment Crane
: BU-System
Rails
TBMStorage
: BU-System
Rails
SegmentCrane
: BU-System
Rails
Track
: Tunnel
Rails

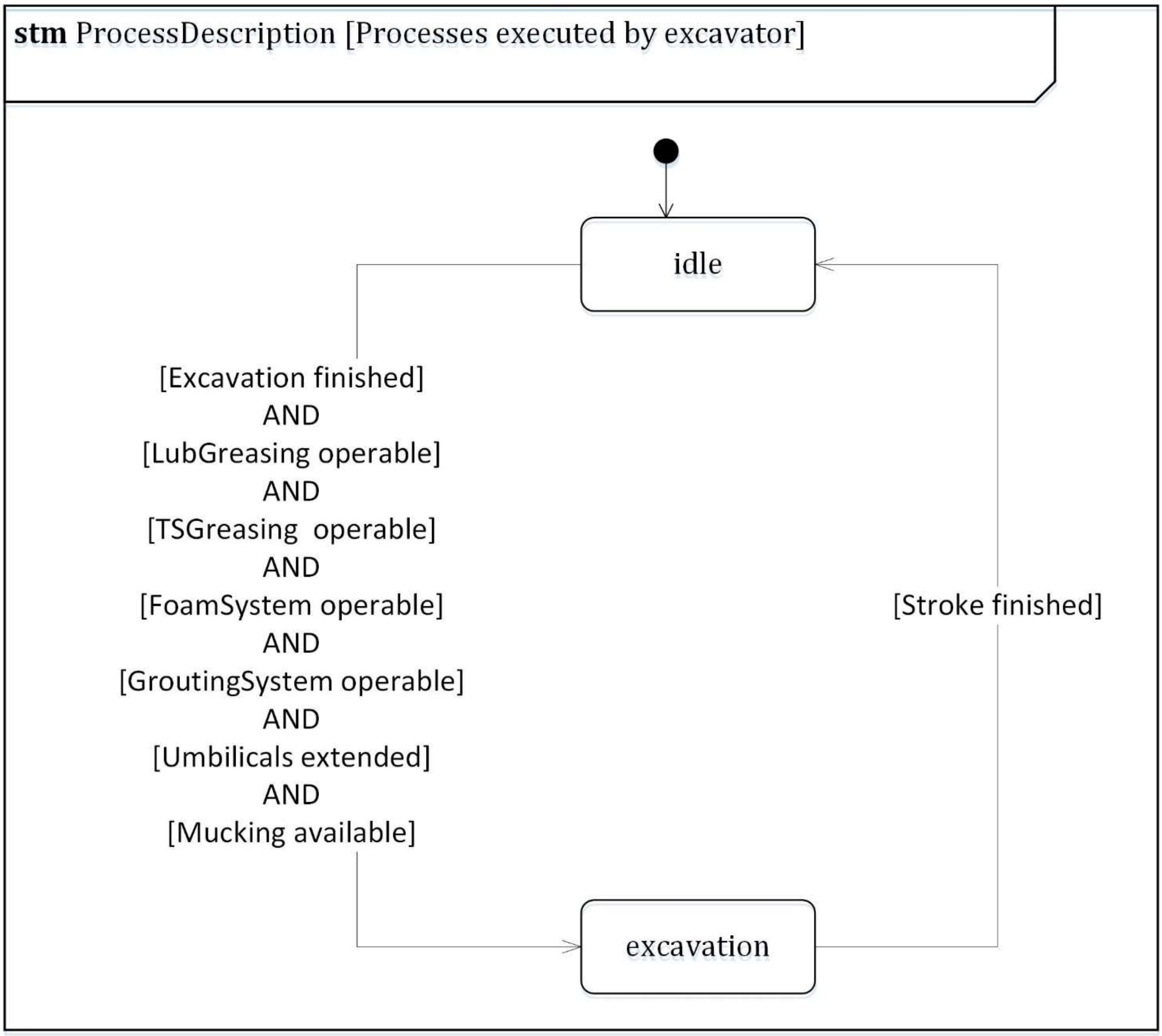

ibd Gantry Rail Handling [Flow of Gantry Rails]
Train
: Vehicle
Rails
RailCrane
: BU-System
Rails
TBMStorage
: BU-System
Rails
RailCrane
: BU-System
Rails
Rails
Segment Crane
: BU-System
Rails
TBMStorage
: BU-System
Rails
Segment Crane
: BU-System
Rails
Track
: Tunnel

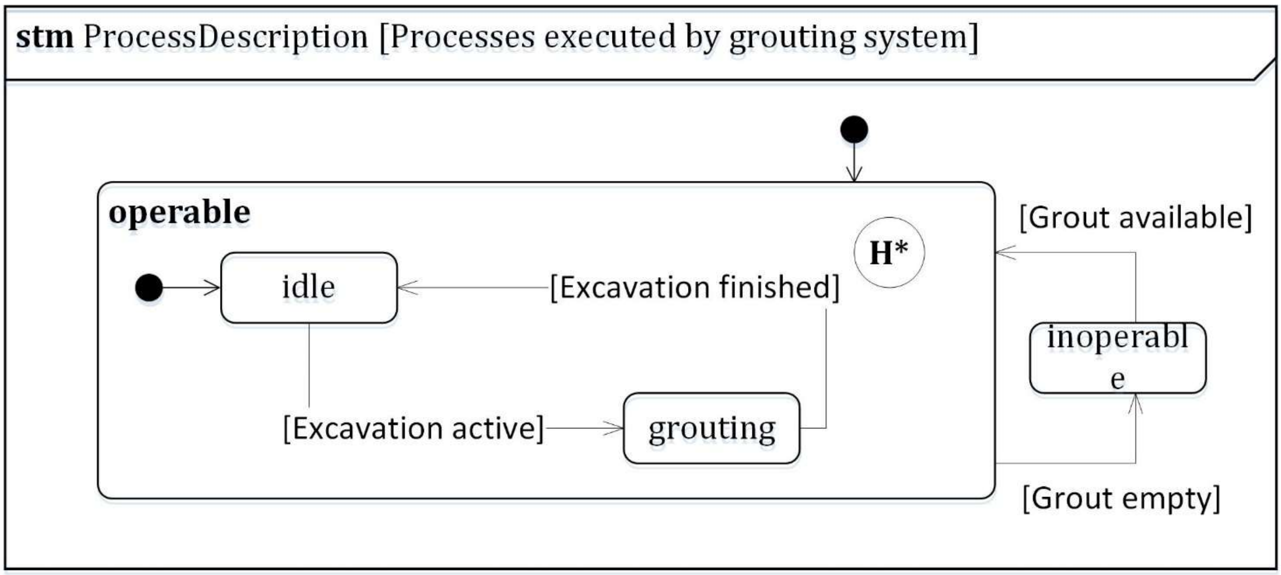
State Machine Diagrams

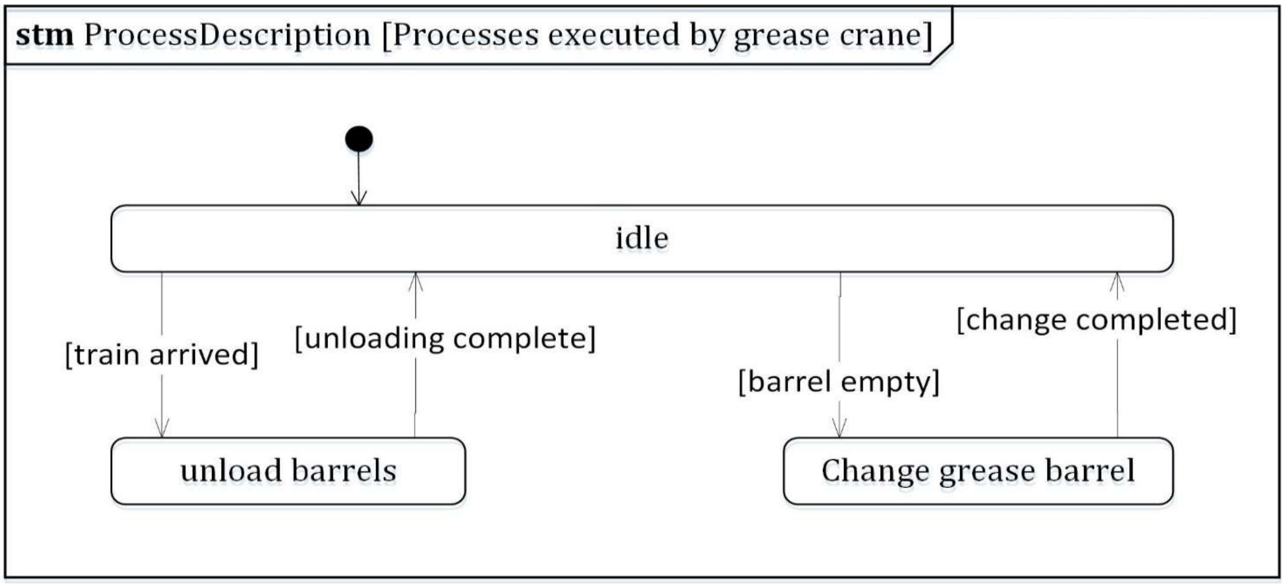


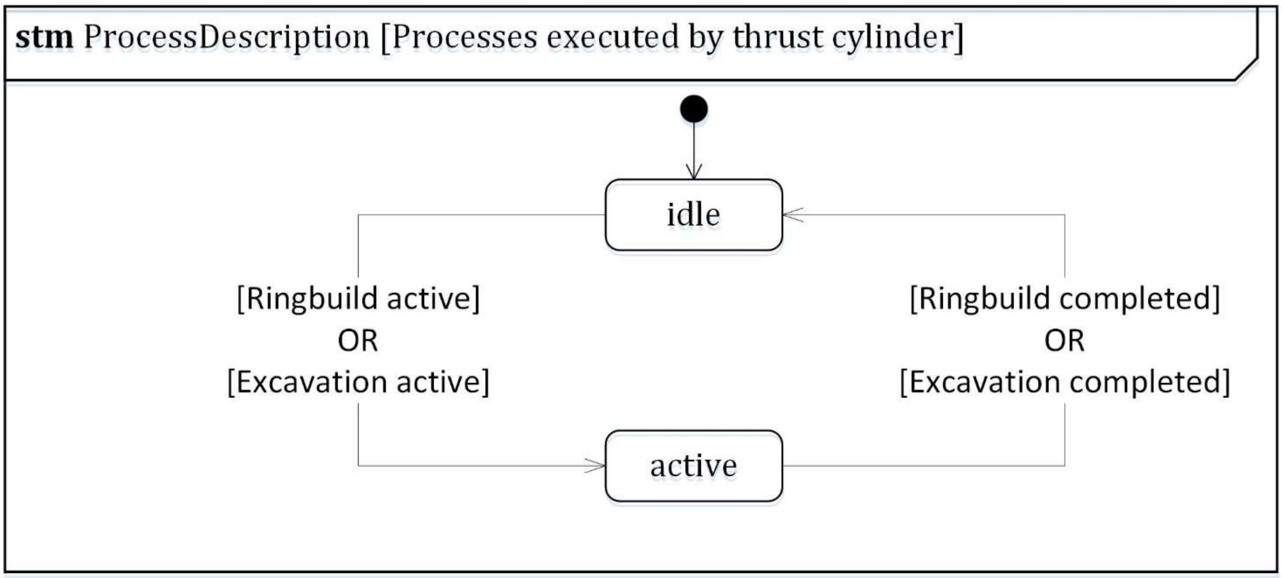


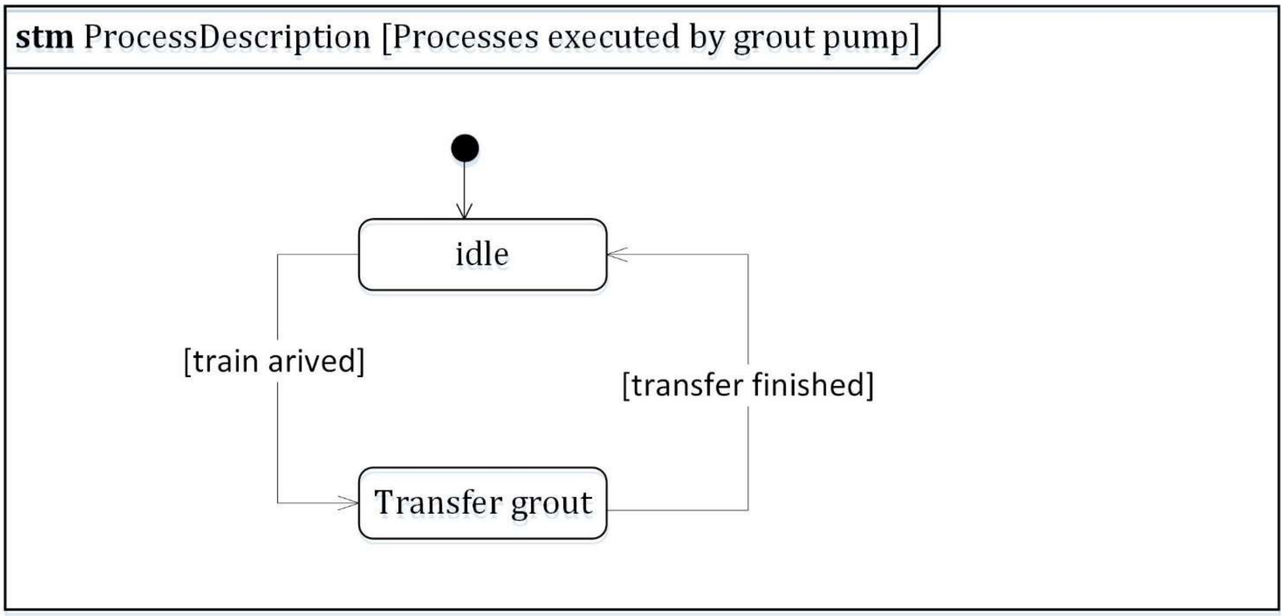

stm ProcessDescription [Processes executed by foam system]
operable
H*
idle
[Excavation finished]
[Excavation active]
conditioning
[tenside available]
inoperabl
e
[tenside empty]

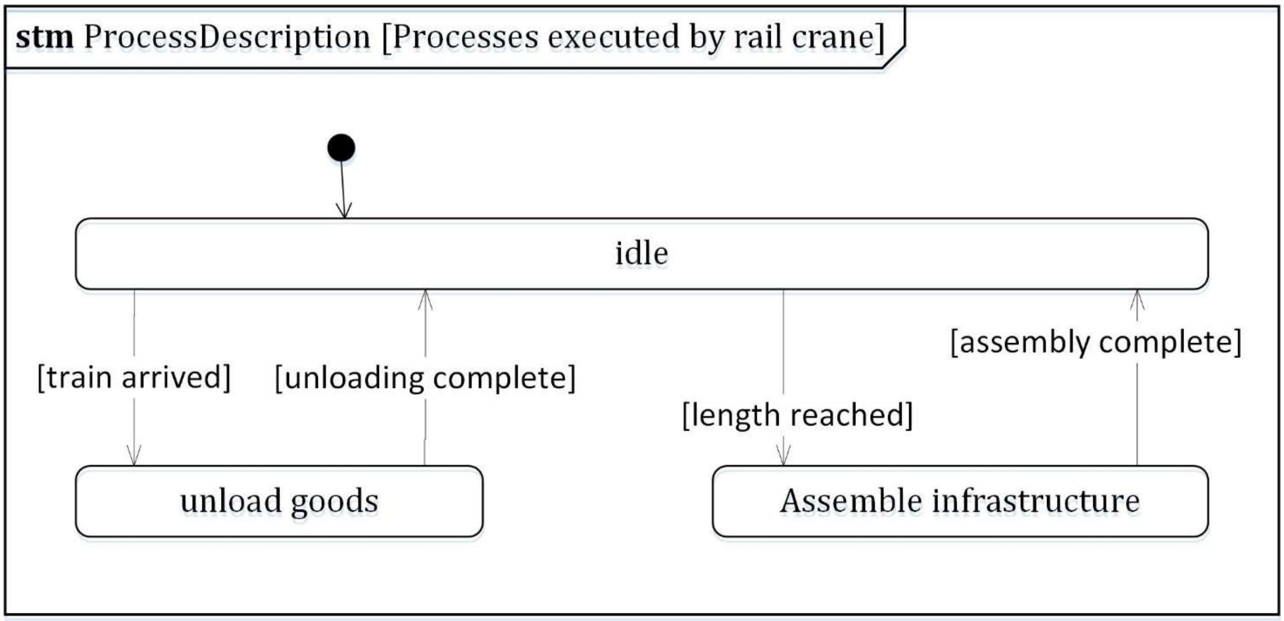

stm ProcessDescription [Processes executed by excavator]
idle
[Excavation finished]
AND
[LubGreasing operable]
AND
[TSGreasing operable]
AND
[FoamSystem operable]
AND
[GroutingSystem operable]
AND
[Umbilicals extended]
AND
[Mucking available]
[Stroke finished]
excavation

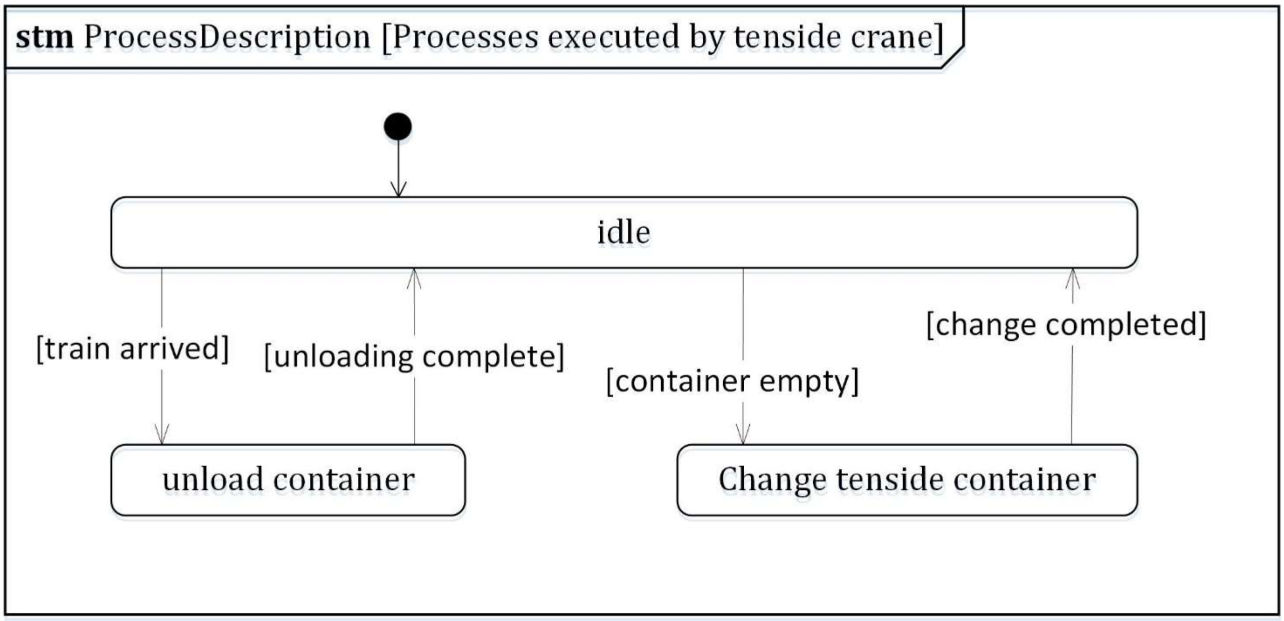

stm ProcessDescription [Processes executed by grouting system]
operable
H*
idle
[Excavation finished]
[Excavation active]
grouting
[Grout available]
inoperabl
e
[Grout empty]

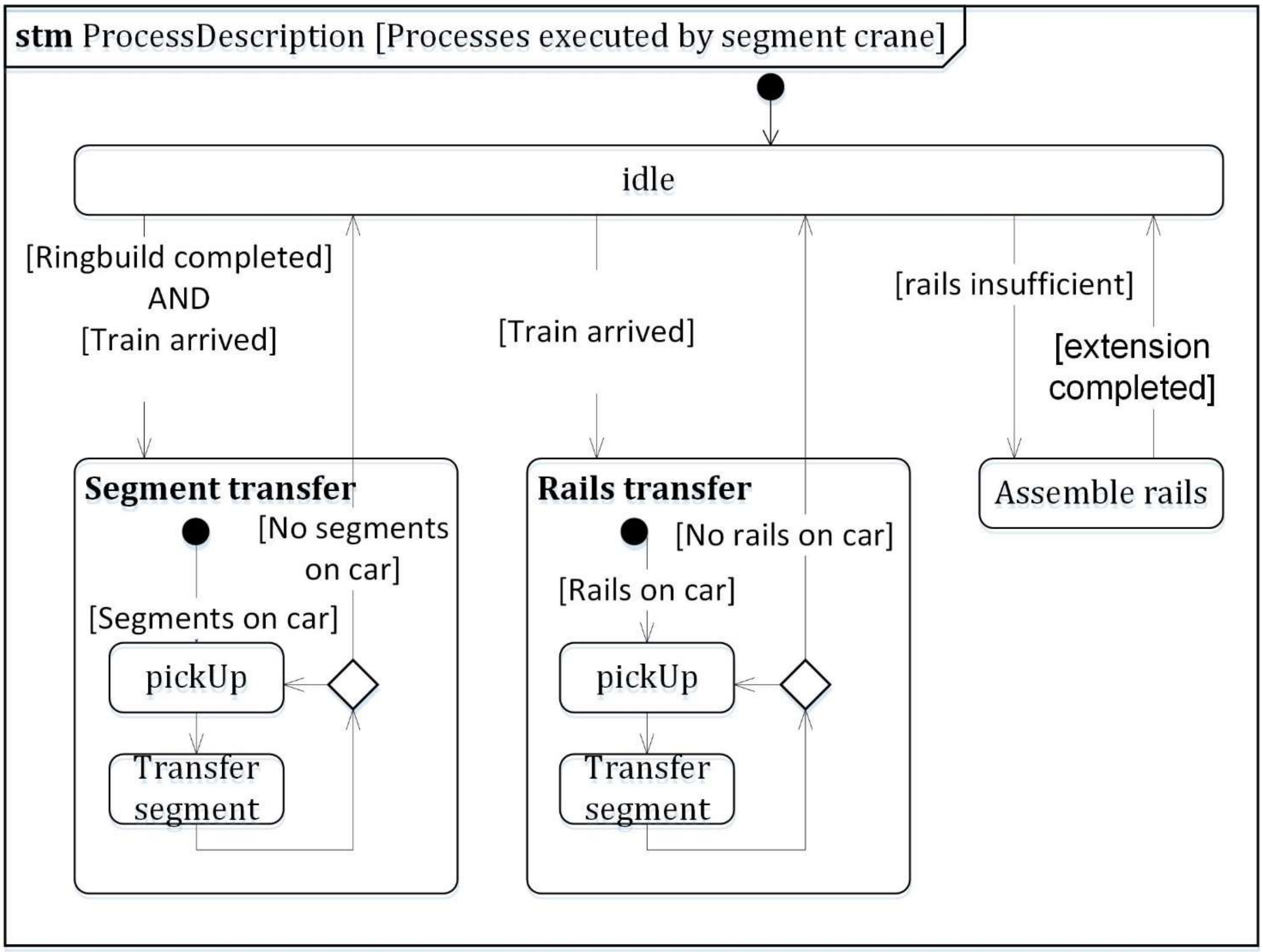

stm ProcessDescription [Processes executed by grease crane]
idle
[train arrived]
[unloading complete]
[barrel empty]
[change completed]
unload barrels
Change grease barrel

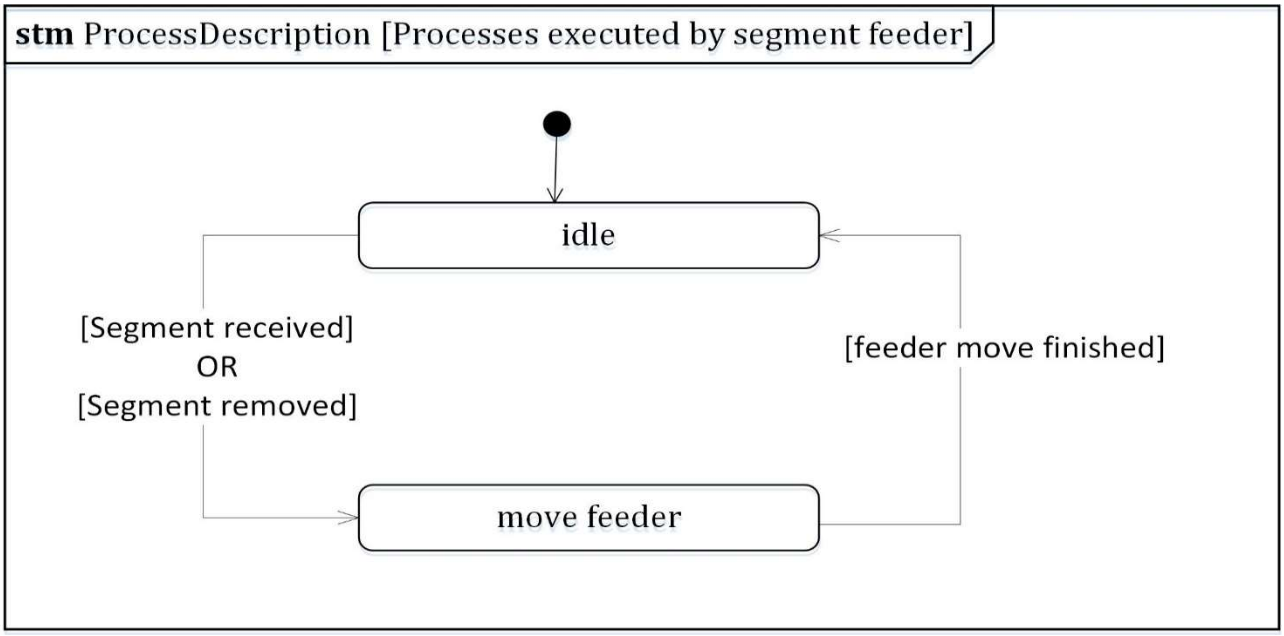

stm ProcessDescription [Processes executed by thrust cylinder]
idle
[Ringbuild active]
OR
[Excavation active]
[Ringbuild completed]
OR
[Excavation completed]
active

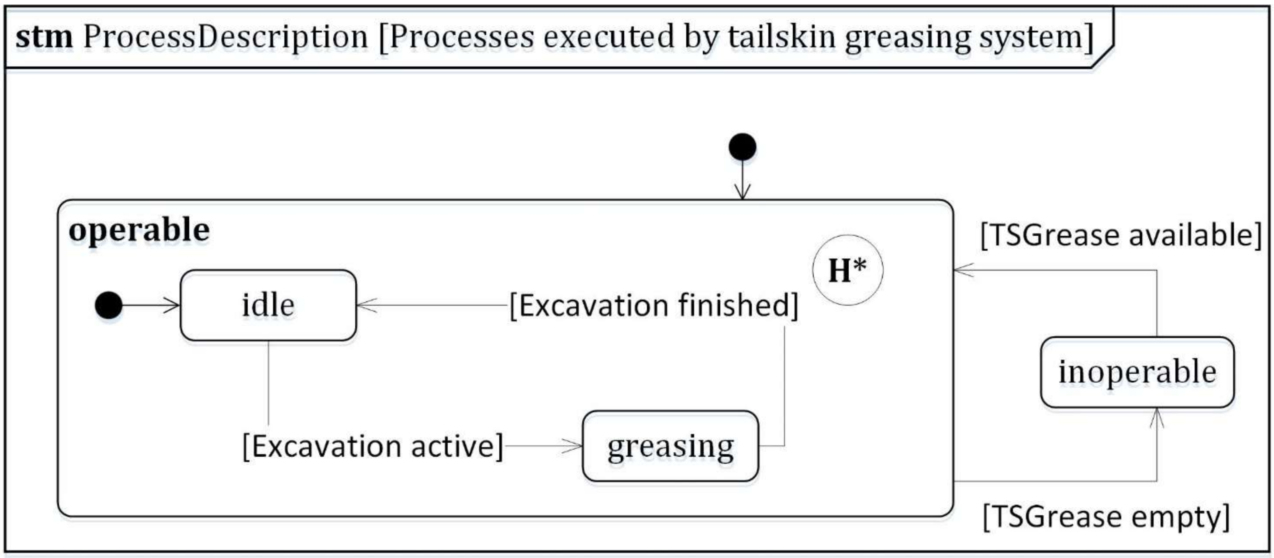

stm ProcessDescription [Processes executed by grout pump]
idle
[train arived]
[transfer finished]
Transfer grout

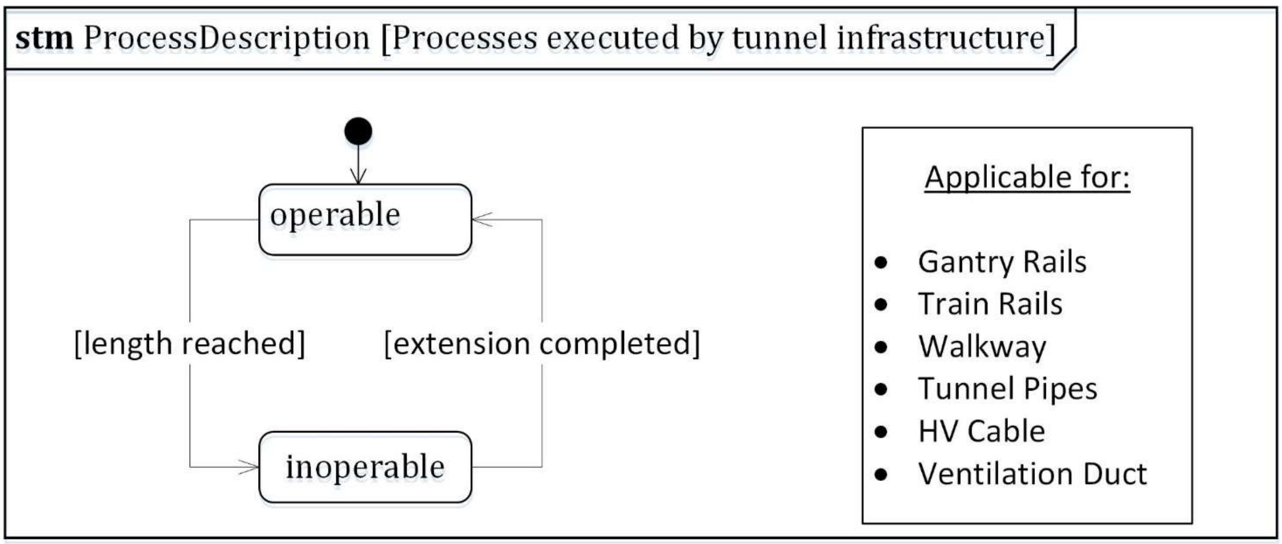

stm ProcessDescription [Processes executed by rail crane]
idle
[train arrived]
[unloading complete]
[assembly complete]
[length reached]
unload goods
Assemble infrastructure

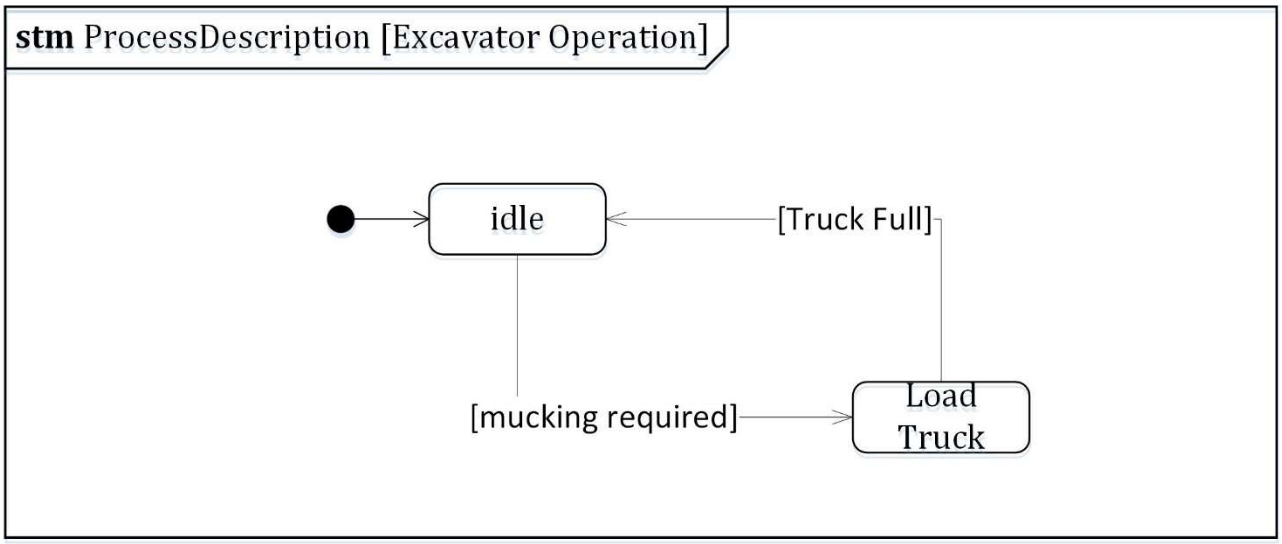

stm ProcessDescription [Processes executed by tenside crane]
idle
[train arrived]
[unloading complete]
[container empty]
[change completed]
unload container
Change tenside container

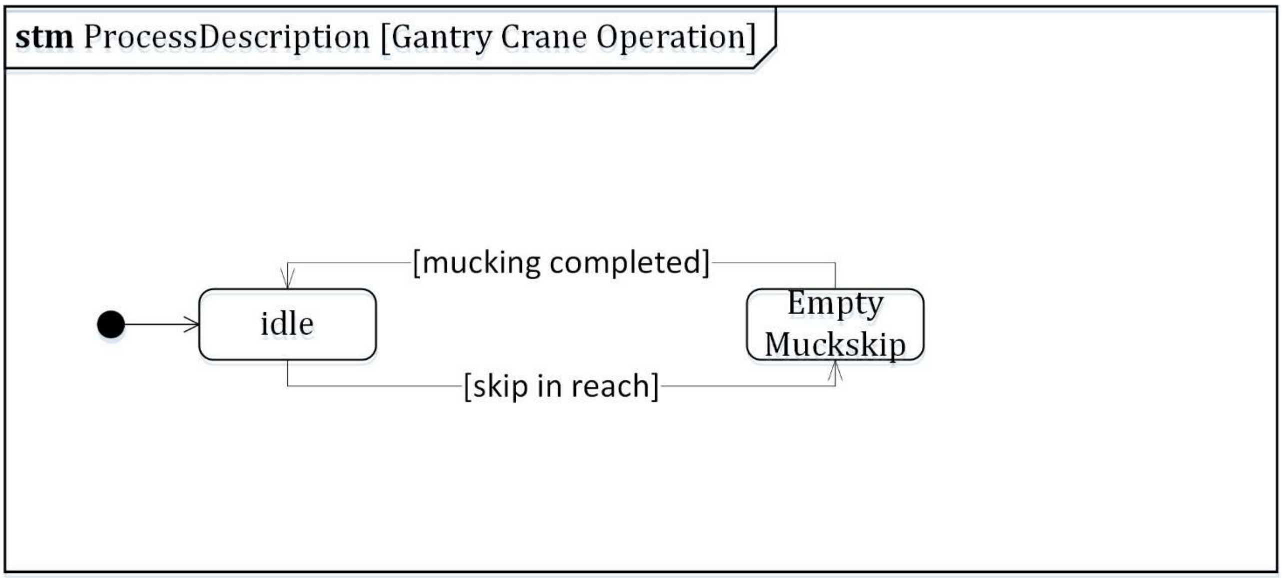

stm ProcessDescription [Processes executed by segment crane]
idle
[Ringbuild completed] AND [Train arrived]
[Train arrived]
[rails insufficient]
[extension completed]
Segment transfer
[No segments on car]
[Segments on car]
pickUp
Transfer segment
Rails transfer
[No rails on car]
[Rails on car]
pickUp
Transfer segment
Assemble rails

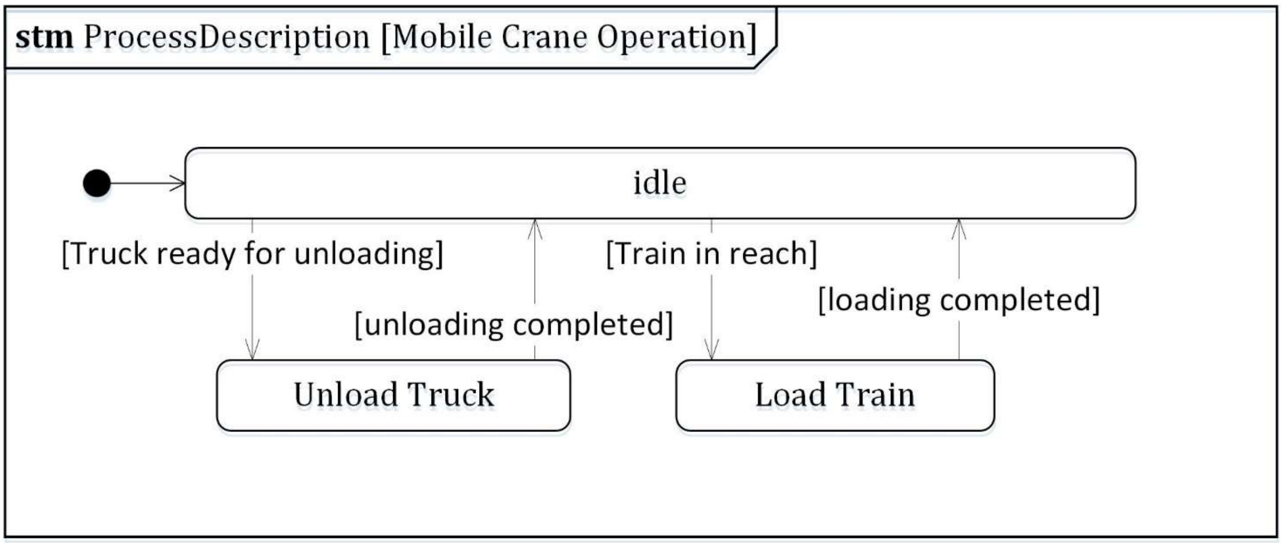

stm ProcessDescription [Processes executed by segment feeder]
idle
[Segment received]
OR
[Segment removed]
[feeder move finished]
move feeder

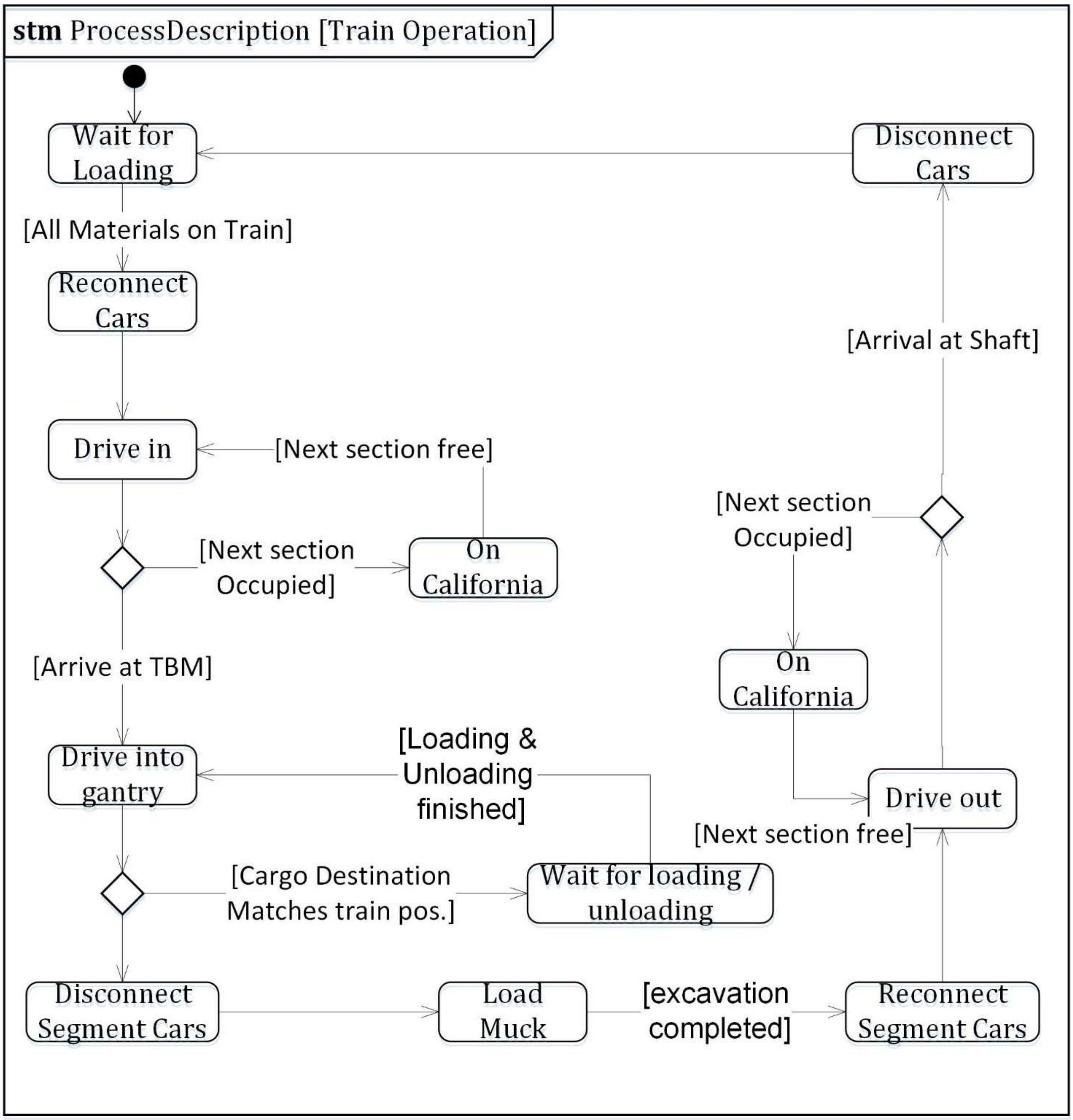

stm ProcessDescription [Processes executed by tailskin greasing system]
operable
H*
idle
[Excavation finished]
[Excavation active]
greasing
[TSGrease available]
inoperable
[TSGrease empty]


stm ProcessDescription [Processes executed by tunnel infrastructure]
operable
[length reached]
[extension completed]
inoperable
Applicable for:
Gantry Rails
Train Rails
Walkway
Tunnel Pipes
HV Cable
Ventilation Duct


stm ProcessDescription [Excavator Operation]
idle
[Truck Full]
[mucking required]
Load Truck


stm ProcessDescription [Gantry Crane Operation]
[mucking completed]
idle
Empty Muckskip
[skip in reach]


stm ProcessDescription [Mobile Crane Operation]
idle
[Truck ready for unloading]
[Train in reach]
[loading completed]
[unloading completed]
Unload Truck
Load Train


stm ProcessDescription [Train Operation]
Wait for Loading
[All Materials on Train]
Reconnect Cars
Drive in
[Next section free]
[Next section Occupied]
On California
[Arrive at TBM]
Drive into gantry
[Loading & Unloading finished]
[Cargo Destination Matches train pos.]
Wait for loading / unloading
Disconnect Segment Cars
Load Muck
[excavation completed]
Reconnect Segment Cars
Drive out
[Next section free]
On California
[Next section Occupied]
[Arrival at Shaft]
Disconnect Cars

Appendix 5: Reference Data

The following table contains all reference data collected including its probability distributions. The corresponding histograms are plotted following the overview table.

Datasets Overview

Name	**Horizontal Movement Segment Crane**	**Horizontal Movement Segment Crane**	**Horizontal Movement Segment Crane**	**Horizontal Movement Segment Crane**
Description	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between
Data Series Nr.	101	102	103	104
Source Project	H	I	J	K
Resource	Segment Crane	Segment Crane	Segment Crane	Segment Crane
Load Type	Segments	Segments	Segments	Segments
Distance / Angle	14.8	11.1	16.1	22.9
Hooking Type	-	-	-	-
No. Of Datasets	73	42	156	108
Minimum	11	14	5	4
Maximum	295	142	166	60
Average	46	41	27	37
Median	32	38	26	36
Distribution	lognormal(3.032349, 1.031405, 9.628789)	lognormal(3.635255, 0.377701, 0.000000)	lognormal(3.189325, 0.484388, 0.000000)	erlang(1.635924, 21, 2.469664)

Name	shifting train position	Connect and Disconnect Train	Maneuvering MSV in Shaft	Couple / Uncouple Trailer	Maneuvering MSV at Backup	Tunnel Pipe Extension (2pipes)	Change Grease Barrel	Ventilation Duct Extension	HV Cable Extension	Unload Rails
Description	shifting the position of the train after unmounting hanger or shunting in the shaft	Connect and disconnect cars from rest of the train	Drive MSV between portal and different loading positions	Towing Vehicle and Trailer to couple and uncouple	Driving into our out of the loading position	Extend tunnel pipes such as water, air, grout	Change barrel for tailskin grease, lubrication grease or HBW	Lower empty cassette, lift duct from car, install new duct	Duration of interruptuion for cable laying, installation and connecting the new cable	Unload Rails in the bridge area with the segment crane
Data Series Nr.	1	2	3	4	5	6	7	8	9	10
Source Project	H	H	G	G	G	A,L,M	A,L,M, B,D	A,L,M, B,D	A,L,M, B,D, N	H
Resource	Train	Train	MSV	MSV	MSV	Manual	Grease Crane	Ventilation	Cable Reel	Segment Crane
Load Type	-	-	-	-	-	Tunnel Pipe	Grease Barrel	Ventilation	HV Cable	Rails
Distance / Angle	-	-	-	-	-	-	-	-	-	-
Hooking Type	-	-	-	-	-	-	Barrel Claw	Hooks	Reel	Lifting Rope
No. Of Datasets	15	10	27	10	43	13	17	13	20	10
Minimum	6	70	24	65	33	560	180	480	2700	84
Maximum	42	390	195	275	226	3300	780	3600	28800	260
Average	21	201	97	199	109	1090	484	1929	13545	173
Median	22	210	92	234	105	900	540	1800	12600	189
Distribution	weibull(2.527177, 22.732699, 0.747633)	weibull(2.244590, 201.156846, 22.835513)	beta(1.212375, 2.692118, 22.634198, 260.559938)	beta(1.359085, 0.527118, 5.853720, 275.352330)	weibull(2.482235, 119.394688, 2.975459)	lognormal(5.696384, 1.152929, 527.026770)	beta(1.042171, 1.019674, 169.756483, 788.868370)	weibull(2, 1949.923787, 179.432016)	beta(1.327248, 2.922625, 2002.637193, 38805.312894)	beta(1.649849, 1.319653, 51.849961, 270.133144)

Name	Build Rails	Transfer Invert Segment	Slurry Pipe Extension	Dismantle Invert Slab	Unload Foam Container	Walkway Extension	Lift / Lower Crane in Shaft	Horizontal Movement between Shaft and Storage	Hook and Unhook Segments	Hook and Unhook Segments
Description	Build rails for train or gantry in the bridge area	Tansfer Invert Segment from vehicle to invert	Extend slurry circuit pipes	Dismantle invert slab on which the gantries roll	unload foam tenside container from vehicle and place on gantry	extend walkway in the tunnel behind the machine manually	Lift or lower material vertically in the shaft	Horizontal Crane movement between shaft and storage area	Hook and unhook segments with lifting ropes on the crane hook	Hook and unhook segments with lifting ropes on the crane hook
Data Series Nr.	11	12	13	14	15	16	17	18	19	20
Source Project	A,C,D,F,L	A,C,G	A, D	G	L	L, M	G	G	G	H
Resource	Segment Crane	Segment Crane	Manual	Aux Crane	Tenside Crane	Manual	Gantry Crane	Gantry Crane	Gantry Crane	Gantry Crane
Load Type	Rails	Invert Segment	Slurry Pipes	Invert Slab	Tenside	Walkway	Segments	Segments	Segments	Segments
Distance / Angle	-	-	-	-	-	-	35.0 m	25.0 m	-	-
Hooking Type	Lifting Rope	Segment Fork	Manual	Lifting Rope	Hook	Manual	-	-	Lifting Ropes	Lifting Ropes
No. Of Datasets	14	17	10	10	3	10	15	12	11	52
Minimum	600	154	399	236	300	600	86	25	57	14
Maximum	1800	957	1667	372	600	2700	127	94	96	898
Average	1107	369	1211	313	400	1440	105	52	78	102
Median	900	267	1383	323	300	1200	101	47	81	90
Distribution	87.534443 + 1 / weibull(3.285283, 0.001232, 0)	lognormal(5.140652, 0.891737, 117.639649)	beta(2.032330, 0.792536, 13.725122, 1675.455448)	weibull(10.271354, 329.194612, 0.000000)		erlang(524.452990, 2, 391.094020)	beta(0.724223, 0.858504, 85.765170, 127.698130)	beta(0.703770, 1.272431, 24.640271, 100.339226)	beta(1.371577, 1.027078, 53.412122, 97.146138)	81.100233 * exp(log(1 / uniform_pos() - 1) / 3.125742)

Name	Hook and Unhook Segments	Hook / unhook Road Elements	Hook / Unhook Lifting Fork	Pump Grout from Silo to Car	Position / Unhook Segments on MSV	Position / Unhook Segments on MSV	Position / hook Segments in storage	Position / hook Segments in storage	Crane Rotation from Storage to Shaft	Crane Rotation from Storage to Shaft
Description	Hook and unhook segments with lifting ropes on the crane hook	Hook and unhook road elements using a lifting fork in storage or a vehicle	Hook and unhook the lifting fork from the surface crane	Pump from surface silo into the tank on a grout car	Hook and unhook segments with electrically operated tong on the crane hook	Hook and unhook segments with mechanically operated tong on the crane hook. Including precise	Hook and unhook segments with mechanically operated tong on the crane hook in the storage without	Hook and unhook segments with electrically operated tong on the crane hook in the storage without	Rotate tower crane between storage and shaft	Rotate tower crane between storage and shaft
Data Series Nr.	21	22	23	24	25	26	27	28	29	30
Source Project	I	G	G	G	K	J	J	K	J, K	J, K
Resource	Gantry Crane	Gantry Crane	Gantry Crane	Grout Pump	Tower Crane	Tower Crane	Tower Crane	Tower Crane	Tower Crane	Tower Crane
Load Type	Segments	Road Element	Lifting Fork	Grout	Segments	Segments	Segments	Segments	Segments	Segments
Distance / Angle	-	-	-	4.0 m³	-	-	-	-	90 °	110 °
Hooking Type	Lifting Ropes	Lifting Fork	-	-	electr. Tong	mech. Tong	mech. Tong	electr. Tong	-	-
No. Of Datasets	47	3	2	11	15	31	31	15	3	10
Minimum	15	129	79	265	46	152	62	38	42	37
Maximum	172	165	82	378	203	437	294	82	79	175
Average	85	143	80	323	97	241	128	56	63	106
Median	76	134	80	312	96	229	119	54	67	112
Distribution	lognormal(4.337320, 0.470982, 0.000000)	triangular(120,140,180)	triangular(70,80,140)	beta(2.287496, 3.018838, 248.182272, 421.634659)	92.513787 * exp(log(1 / uniform_pos() - 1) / 6.430596)	gamma(3.932085, 32.534888, 112.876515)	beta(1.400793, 8.106583, 60.604403, 521.429093)	17.440381 + 37.059340 * exp(log(1 / uniform_pos() - 1) / 7.020770)		beta(2.372455, 2.008269, 3.332118, 192.415178)

Name	Crane Rotation from Storage to Shaft	Crane Rotation from Storage to Shaft	Crane Rotation from Storage to Shaft	Crane Rotation from Storage to Shaft	Crane Rotation from Storage to Shaft	Crane Rotation from Storage to Shaft	Hook / Unhook Muck Container	Hook / Unhook Muck Container	Hook / Unhook Muck Container	Vertical Lift / Lower Muck Container
Description	Rotate tower crane between storage and shaft	Rotate tower crane between storage and shaft	Rotate tower crane between storage and shaft	Rotate tower crane between storage and shaft	Rotate tower crane between storage and shaft	Rotate tower crane between storage and shaft	Hook and Unhook Muck container manually from lifting bar on gantry crane	Hook and Unhook Muck container manually from lifting bar on gantry crane	Hook and Unhook Muck container manually from lifting bar on gantry crane	Vertically lift muck container from train. Start after finishing hooking or after horizontal movement stopped
Data Series Nr.	31	32	33	34	35	36	37	38	39	40
Source Project	J, K	J, K	J, K	J, K	J, K	J, K	K	H	I	K
Resource	Tower Crane	Tower Crane	Tower Crane	Tower Crane	Tower Crane	Tower Crane	Gantry Crane	Gantry Crane	Gantry Crane	Gantry Crane
Load Type	Segments	Segments	Segments	Segments	Segments	Segments	Muck	Muck	Muck	Muck
Distance / Angle	130 °	160 °	170 °	180 °	30 °	120 °	-	-	-	8.0 m
Hooking Type	-	-	-	-	-	-	Bar & Hooks	Bar & Hooks	Bar & Hooks	-
No. Of Datasets	11	22	11	23	11	10	38	233	26	38
Minimum	30	12	58	20	6	32	9	4	46	21
Maximum	135	172	229	207	91	141	78	142	258	392
Average	77	87	114	102	50	64	23	42	87	49
Median	77	80	112	96	43	49	22	40	72	33
Distribution	beta(0.949391, 1.268973, 27.654958, 142.401539)	81.390863 * exp(log(1 / uniform_pos() - 1) / 3.996295)	beta(0.832601, 3.223820, 56.694442, 334.970062)	weibull(2.233212, 115.556140, 0.000000)	beta(1.394228, 1.275521, 0.206393, 95.850638)	beta(0.421903, 1.376698, 31.957887, 166.907660)	20.823644 * exp(log(1 / uniform_pos() - 1) / 4.444798)	gamma(3.210614, 13.159141, 0.000000)	1 / weibull(3.371385, 0.015101, 0)	lognormal(2.685820, 0.985242, 20.080063)

Name	Empty Muck Container	Remove Sticky Muck from Container	Lift / Lower Crane in Shaft	Horizontal Movement between Shaft and Muckpit	Horizontal Movement between Shaft and Storage	Lift / Lower Crane to intermediate storage	Lift / Lower Crane in Shaft	Horizontal Movement between Shaft and Muckpit	Horizontal Movement between Shaft and Muckpit	Horizontal Movement between Shaft and Storage
Description	Empty muck container into muckpit	Use an excavator or forklift to scrape sticky muck from the containers	Vertically lift muck container from train. Start after finishing hooking or after horizontal movement stopped	Purely horizontal crane movement	Purely horizontal crane movement	Vertically lift material to storage. Start after finishing hooking or after horizontal movement stopped	Vertically lift muck container from train. Start after finishing hooking or after horizontal movement stopped	Purely horizontal crane movement	Purely horizontal crane movement	Purely horizontal crane movement
Data Series Nr.	41	42	43	44	45	46	47	48	49	50
Source Project	K	K	H	I	H	H	I	I	I	I
Resource	Gantry Crane	Excavator	Gantry Crane	Gantry Crane	Gantry Crane	Gantry Crane	Gantry Crane	Gantry Crane	Mobile Crane	Gantry Crane
Load Type	Muck	Muck	Muck /	Muck	Segments	Segments	Muck /	Muck	Muck	Segments
Distance / Angle	-	-	42.0 m	26.0 m	18.0 m	6.0 m	44.0 m	15.0 m	15.0 m	16.0 m
Hooking Type	-	-	-	-	-	-	-	-	-	-
No. Of Datasets	19	19	276	276	54	30	246	199	140	81
Minimum	109	40	11	4	14	6	30	34	14	10
Maximum	345	264	283	1337	70	66	493	390	160	82
Average	155	194	67	60	34	24	103	80	58	35
Median	144	202	64	50	33	19	92	74	50	32
Distribution	61.288278 + 1 / weibull(3.464262, 0.013719, 0)	weibull(5.095737, 209.591778, 0.000000)	64.224826 * exp(log(1 / uniform_pos() - 1) / 6.629405)	49.420938 * exp(log(1 / uniform_pos() - 1) / 3.997457)	beta(0.928820, 1.662719, 13.868814, 71.279529)	beta(0.686539, 1.837534, 5.973890, 71.492697)	96.382402 * exp(log(1 / uniform_pos() - 1) / 6.530740)	lognormal(3.803789, 0.570315, 26.972513)	gamma(2.420984, 18.357850, 13.148799)	gamma(5.525659, 6.307275, 0.000000)

Name	Lift / Lower Crane to intermediate storage	Hook Segments	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments
Description	Vertically lift material to storage. Start after finishing hooking or after horizontal movement stopped	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the transfer table	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the transfer table	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle
Data Series Nr.	51	52	53	54	55	56	57	58	59	60
Source Project	I	A	A	B	B	B	B	C	C	D
Resource	Gantry Crane	Segment Crane	Segment Crane	Front Segment	Front Segment	Rear Segment	Rear Segment	Segment Crane	Segment Crane	Segment Crane
Load Type	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments
Distance / Angle	6.0 m	-	-	-	-	-	-	-	-	-
Hooking Type	-	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Mech	Mech	Vacuum
No. Of Datasets	43	21	21	22	22	20	32	21	21	16
Minimum	5	8	18	9	10	35	4	8	3	9
Maximum	88	91	80	115	25	74	12	91	55	30
Average	28	24	38	43	14	62	6	24	12	22
Median	20	17	36	39	13	63	6	17	8	23
Distribution	lognormal(3.010212, 0.683250, 2.704963)	lognormal(2.524018, 0.867314, 5.835630)	beta(0.897882, 2.802129, 17.685164, 100.326751)	gamma(1.718295, 21.469537, 6.063556)	1 / weibull(6.571226, 0.081587, 0)	beta(1.465208, 0.499057, 24.756154, 74.167356)	gamma(4.510172, 0.750126, 3.023054)	lognormal(2.524018, 0.867314, 5.835630)	gamma(0.638993, 13.737695, 2.935994)	beta(1.153075, 0.647088, 7.677309, 30.043381)

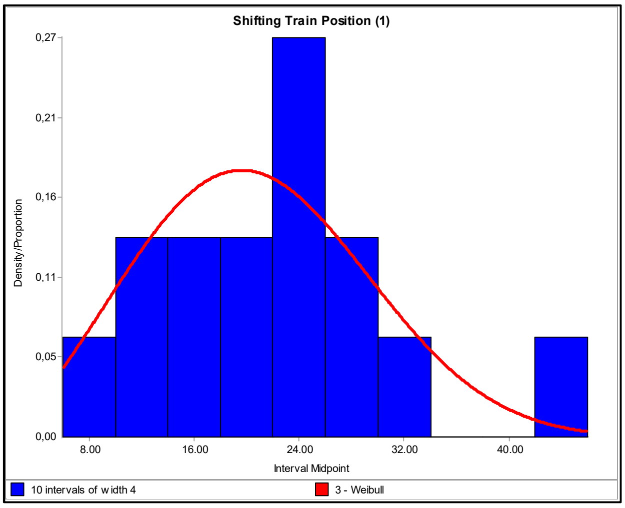
Name	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments	Unhook Segments	Hook Segments
Description	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle
Data Series Nr.	61	62	63	64	65	66	67	68	69	70
Source Project	D	E	E	F	F	G	G	H	H	J
Resource	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane
Load Type	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments
Distance / Angle	-	-	-	-	-	-	-	-	-	-
Hooking Type	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Mech	Mech	Vacuum
No. Of Datasets	16	28	28	35	35	16	20	33	29	33
Minimum	7	12	13	13	16	18	43	8	20	9
Maximum	98	48	45	65	399	54	107	508	278	31
Average	27	24	29	28	43	34	68	78	91	19
Median	24	22	28	27	26	32	64	54	66	19
Distribution	22.865375 * exp(log(1 / uniform_pos() - 1) / 3.675905)	lognormal(2.687645, 0.484733, 7.769022)	beta(0.901654, 0.969704, 12.707375, 45.477230)	erlang(2.757507, 10, 0.024927)	lognormal(2.468929, 1.102843, 15.379492)	lognormal(3.488283, 0.241262, 0.000000)	beta(1.269604, 2.701898, 42.032086, 122.242101)	lognormal(3.967250, 0.803515, 1.718168)	lognormal(4.158221, 0.707519, 9.705346)	beta(6.174476, 13.262396, 4.243912, 51.812732)

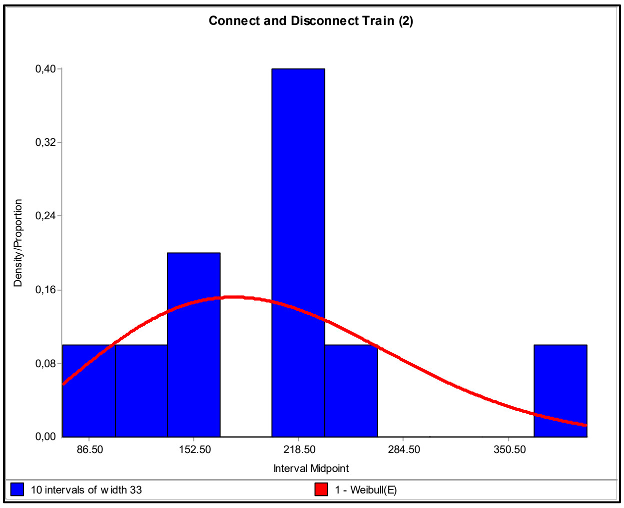
Name	Unhook Segments	Hook Segments	Unhook Segments	Lift Segments	Lower Segments	Lift Segments	Lower Segments	Lift Segments	Lower Segments	Lift Segments
Description	Positioning and place segments on the segment feeder	Positioning crane and hook segments with segment crane at the vehicle	Positioning and place segments on the segment feeder	Lift Segments from Vehicle	Lower Segments on Feeder and rotate	Lift Segments from Transfer Table	Lower Segments on Feeder and rotate	Lift Segments from Vehicle	Lower Segments on Transfer Table	Lift Segments from Vehicle
Data Series Nr.	71	72	73	74	75	76	77	78	79	80
Source Project	J	K	K	A	A	B	B	B	B	C
Resource	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane
Load Type	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments
Distance / Angle	-	-	-	0.8	1.6	1.2	2.0	4.5	5.3	0.7
Hooking Type	Vacuum	Vacuum	Vacuum	-	-	-	-	-	-	-
No. Of Datasets	33	54	54	21	42	20	45	20	56	21
Minimum	9	9	9	8	7	29	14	21	28	8
Maximum	66	49	74	51	44	416	45	55	51	51
Average	24	14	16	27	20	79	33	37	40	27
Median	18	14	14	23	18	37	30	41	45	23
Distribution	1 / weibull(2.625259, 0.059489, 0)	1.313017 + 12.184232 * exp(log(1 / uniform_pos() - 1) / 6.519043)	2.817600 + 1 / weibull(3.599753, 0.101617, 0)	beta(1.044904, 1.515431, 7.269542, 54.375366)	gamma(2.573378, 5.820184, 4.808183)	lognormal(2.153189, 1.840495, 28.860953)	beta(0.945888, 0.585837, 13.982147, 45.056734)	beta(0.656327, 0.757499, 20.527298, 55.093677)	beta(0.864160, 0.781496, 27.963480, 51.064109)	beta(1.044904, 1.515431, 7.269542, 54.375366)

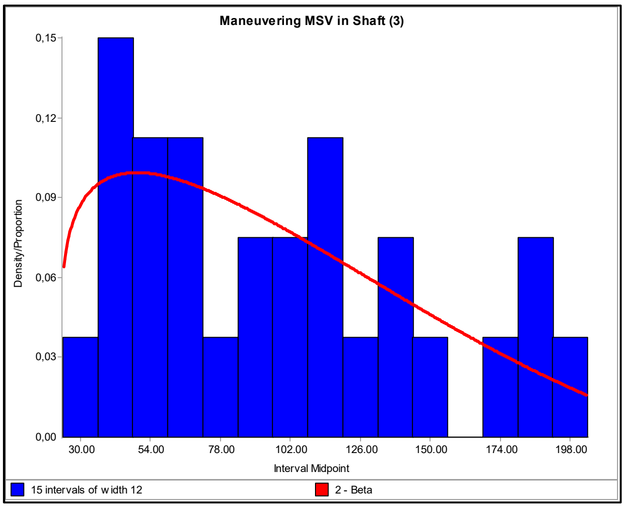
Name	Lower Segments	Lift Segments	Lower Segments	Lift Segments	Lower Segments	Lift Segments	Lower Segments	Lower Segments	Lift Segments	Lower Segments
Description	Lower Segments on Feeder and rotate	Lift Segments from Vehicle	Lower Segments on Feeder and rotate	Lift Segments from Vehicle	Lower Segments on Feeder and rotate	Lift Segments from Vehicle	Lower Segments on Feeder and rotate	Lower Segments on Feeder and rotate	Lift Segments from Vehicle	Lower Segments on Feeder and rotate
Data Series Nr.	81	82	83	84	85	86	87	88	89	90
Source Project	C	D	D	E	E	F	F	G	J	J
Resource	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane
Load Type	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments
Distance / Angle	2.1	0.6	1.6	0.8	2.2	0.9	2.2	2.2	1.2	2.2
Hooking Type	-	-	-	-	-	-	-	-	-	-
No. Of Datasets	42	16	32	28	52	35	71	18	33	66
Minimum	7	6	21	8	8	2	12	17	5	28
Maximum	44	41	60	45	38	34	62	24	46	198
Average	20	24	39	20	20	20	31	20	19	54
Median	18	22	39	19	16	19	31	20	18	50
Distribution	gamma(2.458389, 6.115194, 5.014091)	gamma(5.378632, 4.380761, 0.000000)	beta(0.610550, 0.710555, 20.868357, 60.079172)	gamma(3.904094, 4.081737, 3.671659)	beta(0.673099, 0.940746, 7.986380, 38.050709)	weibull(2.710794, 22.304649, 0.000000)	beta(1.621967, 2.912534, 11.729884, 66.585997)	weibull(2, 3.927413, 16.584509)	erlang(2.394590, 8, 0.025100)	lognormal(3.387330, 0.564515, 18.636749)

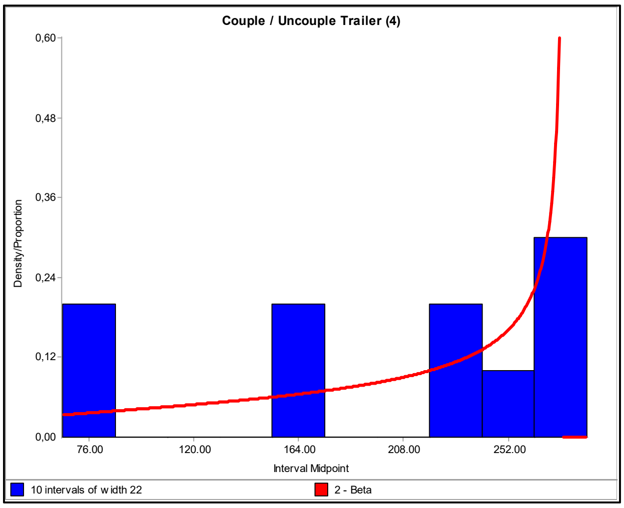
Name	Lift Segments	Lower Segments	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane	Horizontal Movement Segment Crane
Description	Lift Segments from Vehicle	Lower Segments on Feeder and rotate	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between	Horizontal movement of the segment crane including stopping in between
Data Series Nr.	91	92	93	94	95	96	97	98	99	100
Source Project	K	K	A	B	B	C	D	E	F	G
Resource	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane	Segment Crane
Load Type	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments	Segments
Distance / Angle	1.4	2.3	7.5	37.5	108.0	7.3	8.3	18.8	17.3	6.3
Hooking Type	-	-	-	-	-	-	-	-	-	-
No. Of Datasets	54	108	42	83	39	42	48	56	93	79
Minimum	4	25	8	10	65	8	4	8	10	17
Maximum	43	76	87	200	150	87	33	66	98	78
Average	14	40	29	45	99	29	17	31	35	40
Median	12	35	27	15	90	27	16	29	41	43
Distribution	2.780054 + 9.407328 * exp(log(1 / uniform_pos() - 1) / 2.859803)	20.508806 + 1 / weibull(2.344795, 0.072405, 0)	weibull(1.552182, 26.494077, 5.389827)	beta(0.428770, 1.678930, 9.987463, 200.614682)	beta(0.982864, 1.557524, 64.914458, 153.115058)	weibull(1.542337, 26.432220, 5.495067)	weibull(2.982916, 17.978460, 0.944225)	gamma(6.693364, 4.570092, 0.000000)	weibull(2, 39.674211, 0.000000)	weibull(3.588353, 44.263864, 0.000000)

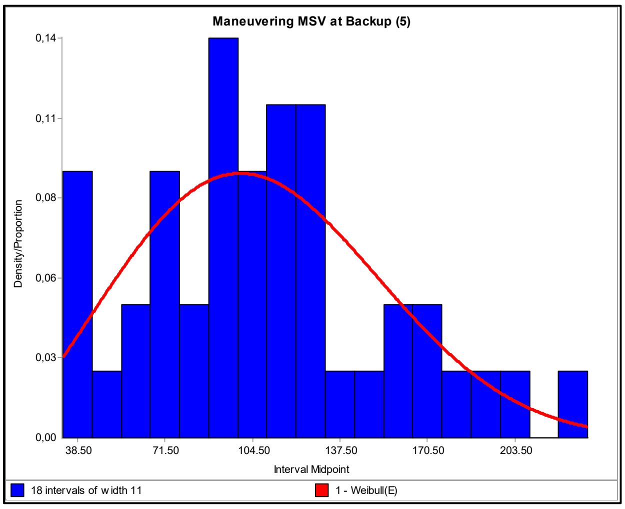
Histograms

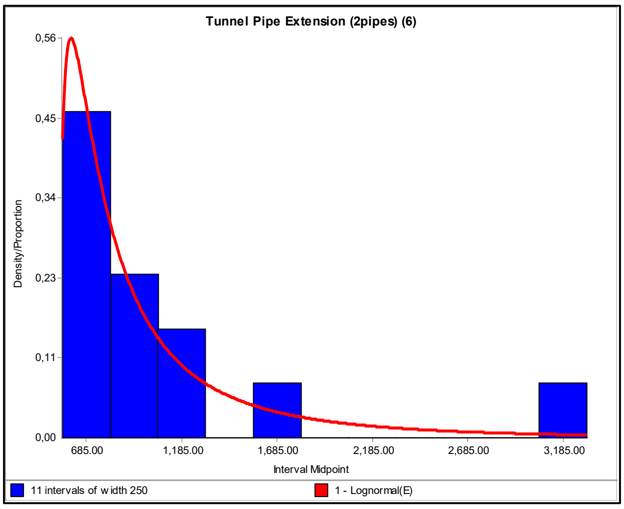

Shifting Train Position (1)
Density/Proportion
0,27
0,21
0,16
0,11
0,05
0,00
8.00
16.00
24.00
32.00
40.00
Interval Midpoint
10 intervals of width 4
3 - Weibull

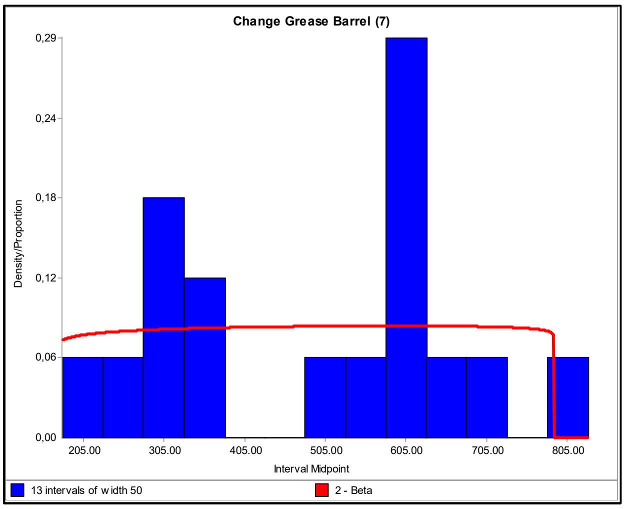

Connect and Disconnect Train (2)
Density/Proportion
0,40
0,32
0,24
0,16
0,08
0,00
86.50
152.50
218.50
284.50
350.50
Interval Midpoint
10 intervals of width 33
1 - Weibull(E)

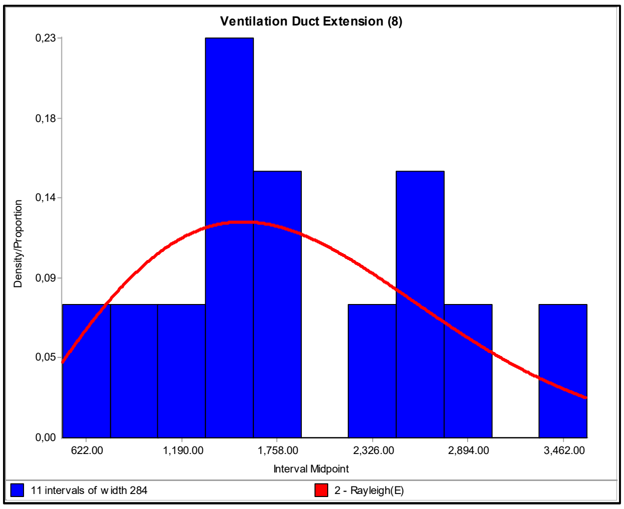

Maneuvering MSV in Shaft (3)
Density/Proportion
0,15
0,12
0,09
0,06
0,03
0,00
30.00
54.00
78.00
102.00
126.00
150.00
174.00
198.00
Interval Midpoint
15 intervals of width 12
2 - Beta

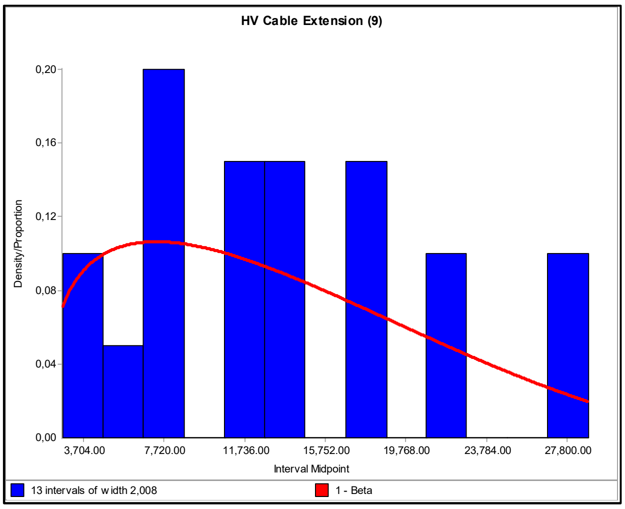

Couple / Uncouple Trailer (4)
Density/Proportion
0,60
0,48
0,36
0,24
0,12
0,00
76.00
120.00
164.00
208.00
252.00
Interval Midpoint
10 intervals of width 22
2 - Beta

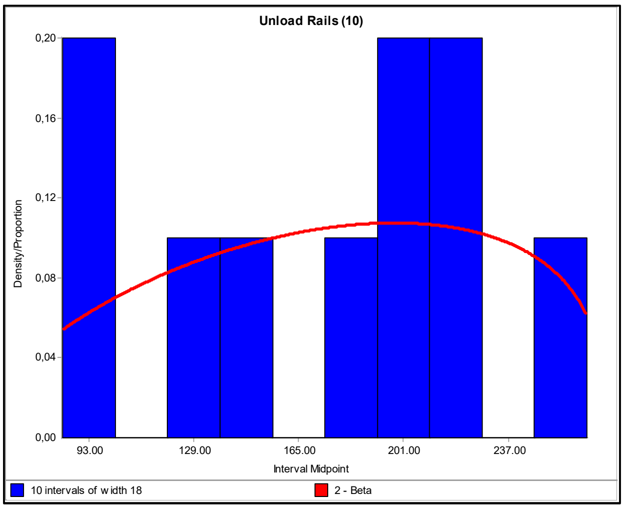

Maneuvering MSV at Backup (5)
Density/Proportion
0,14
0,11
0,08
0,06
0,03
0,00
38.50
71.50
104.50
137.50
170.50
203.50
Interval Midpoint
18 intervals of width 11
1 - Weibull(E)

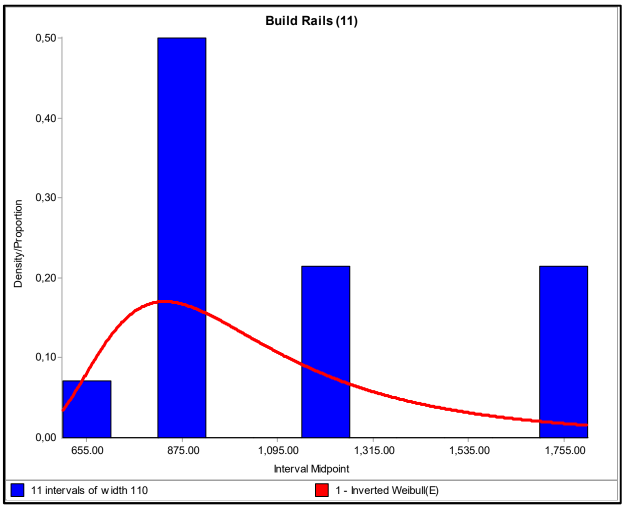

Tunnel Pipe Extension (2pipes) (6)
Density/Proportion
0,56
0,45
0,34
0,23
0,11
0,00
685.00
1,185.00
1,685.00
2,185.00
2,685.00
3,185.00
Interval Midpoint
11 intervals of width 250
1 - Lognormal(E)

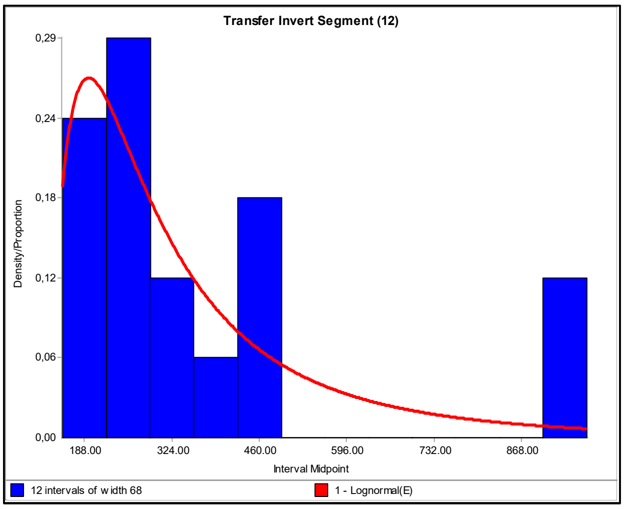

Change Grease Barrel (7)
0,29
0,24
0,18
0,12
0,06
0,00
Density/Proportion
205.00
305.00
405.00
505.00
605.00
705.00
805.00
Interval Midpoint
13 intervals of width 50
2 - Beta

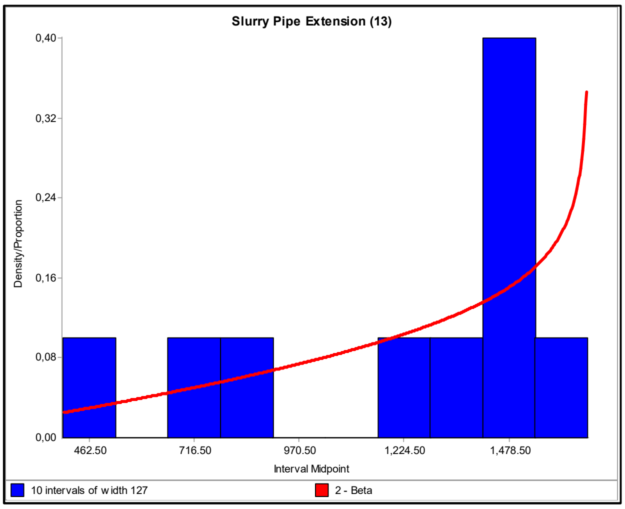

Ventilation Duct Extension (8)
0,23
0,18
0,14
0,09
0,05
0,00
Density/Proportion
622.00
1,190.00
1,758.00
2,326.00
2,894.00
3,462.00
Interval Midpoint
11 intervals of width 284
2 - Rayleigh(E)

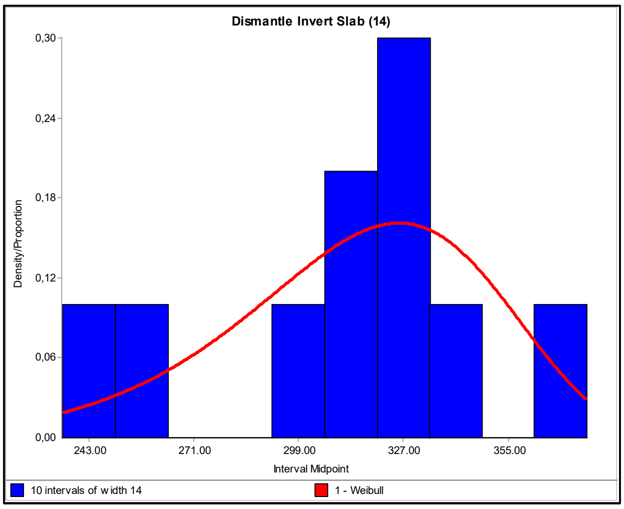

HV Cable Extension (9)
0,20
0,16
0,12
0,08
0,04
0,00
Density/Proportion
3,704.00
7,720.00
11,736.00
15,752.00
19,768.00
23,784.00
27,800.00
Interval Midpoint
13 intervals of width 2,008
1 - Beta

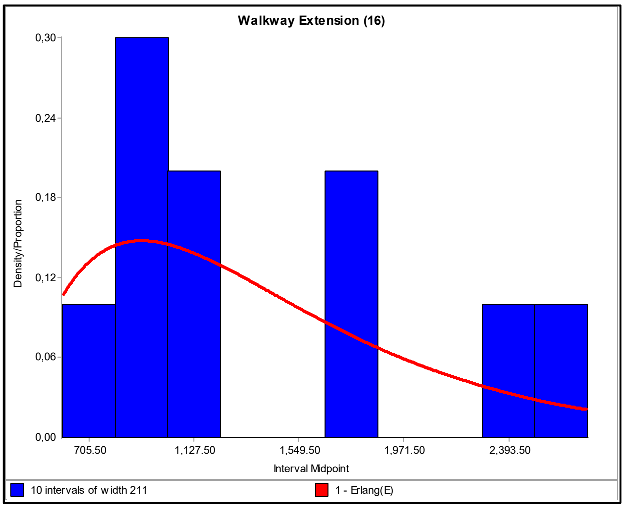

Unload Rails (10)
0,20
0,16
0,12
0,08
0,04
0,00
Density/Proportion
93.00
129.00
165.00
201.00
237.00
Interval Midpoint
10 intervals of width 18
2 - Beta

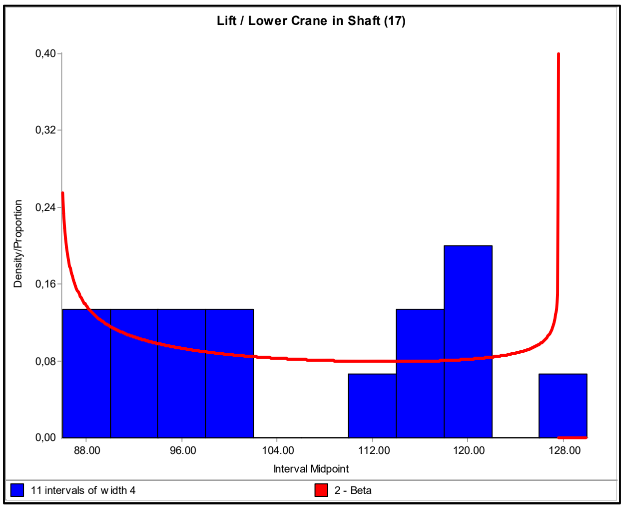

Build Rails (11)
0,50
0,40
0,30
0,20
0,10
0,00
Density/Proportion
655.00
875.00
1,095.00
1,315.00
1,535.00
1,755.00
Interval Midpoint
11 intervals of width 110
1 - Inverted Weibull(E)

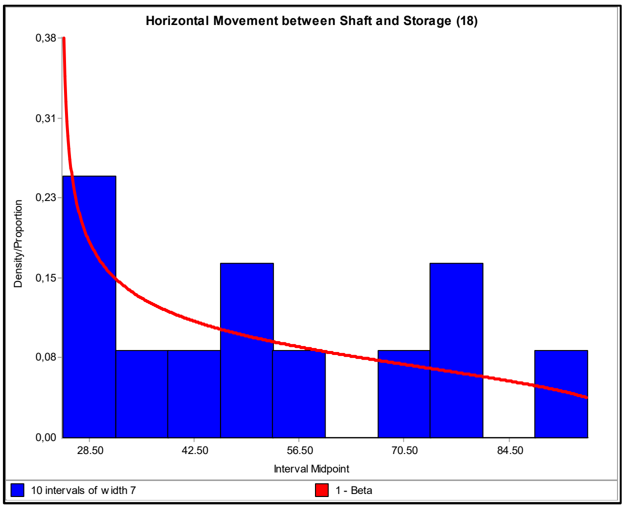

Transfer Invert Segment (12)
0,29
0,24
0,18
0,12
0,06
0,00
Density/Proportion
188.00
324.00
460.00
596.00
732.00
868.00
Interval Midpoint
12 intervals of width 68
1 - Lognormal(E)

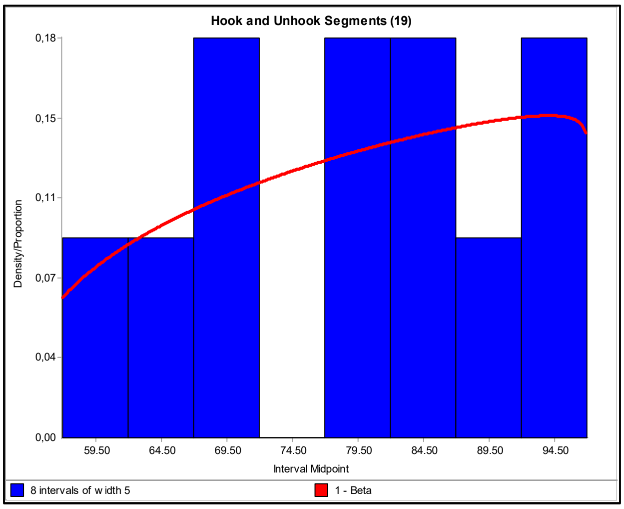

Slurry Pipe Extension (13)
Density/Proportion
0,40
0,32
0,24
0,16
0,08
0,00
462.50
716.50
970.50
1,224.50
1,478.50
Interval Midpoint
10 intervals of width 127
2 - Beta

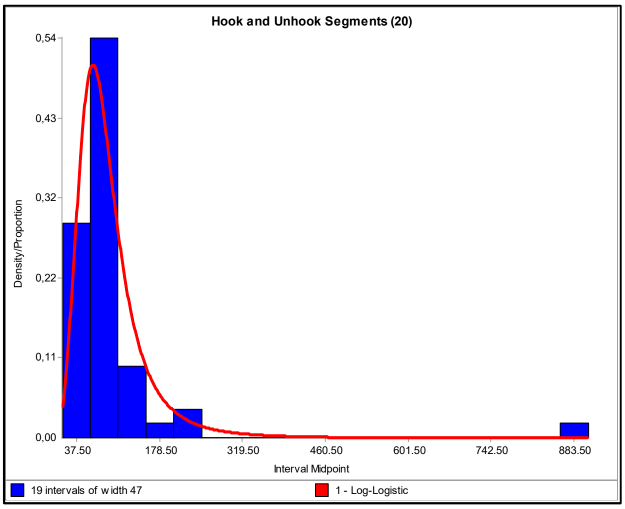

Dismantle Invert Slab (14)
Density/Proportion
0,30
0,24
0,18
0,12
0,06
0,00
243.00
271.00
299.00
327.00
355.00
Interval Midpoint
10 intervals of width 14
1 - Weibull

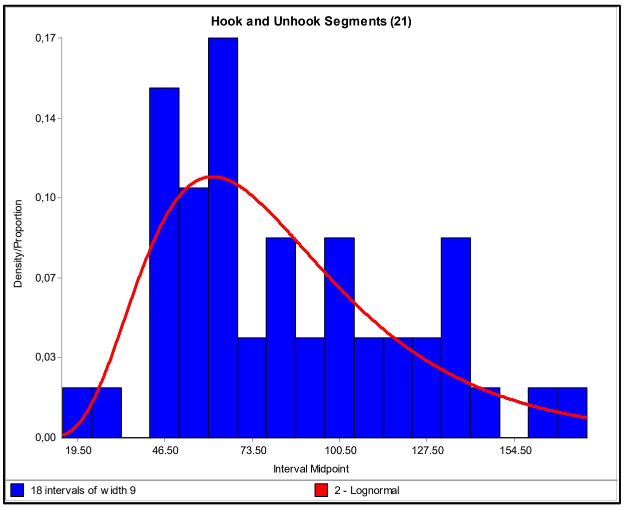

Walkway Extension (16)
Density/Proportion
0,30
0,24
0,18
0,12
0,06
0,00
705.50
1,127.50
1,549.50
1,971.50
2,393.50
Interval Midpoint
10 intervals of width 211
1 - Erlang(E)

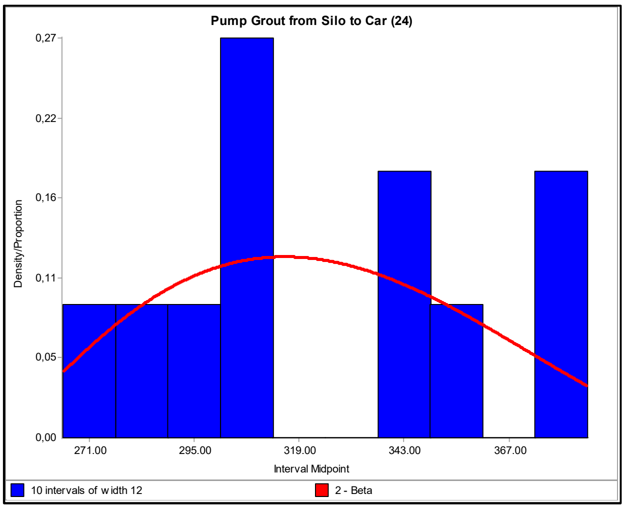

Lift / Lower Crane in Shaft (17)
Density/Proportion
0,40
0,32
0,24
0,16
0,08
0,00
88.00
96.00
104.00
112.00
120.00
128.00
Interval Midpoint
11 intervals of width 4
2 - Beta

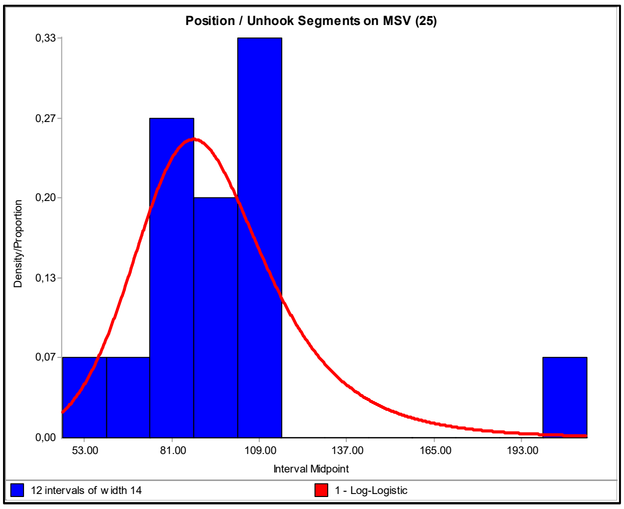

Horizontal Movement between Shaft and Storage (18)
Density/Proportion
0,38
0,31
0,23
0,15
0,08
0,00
28.50
42.50
56.50
70.50
84.50
Interval Midpoint
10 intervals of width 7
1 - Beta

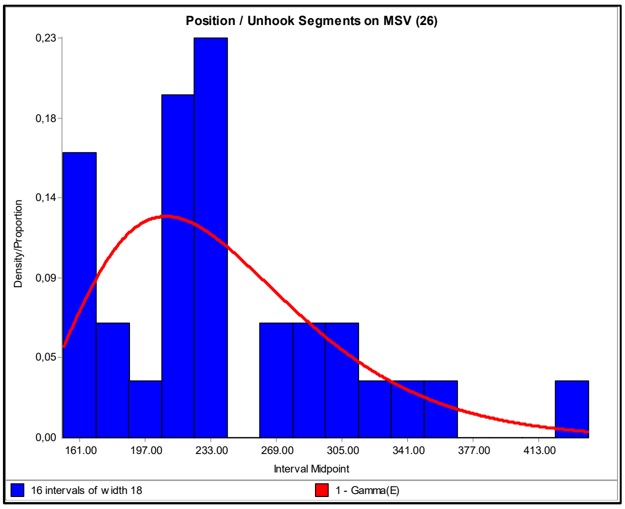

Hook and Unhook Segments (19)
Density/Proportion
0,18
0,15
0,11
0,07
0,04
0,00
59.50
64.50
69.50
74.50
79.50
84.50
89.50
94.50
Interval Midpoint
8 intervals of width 5
1 - Beta

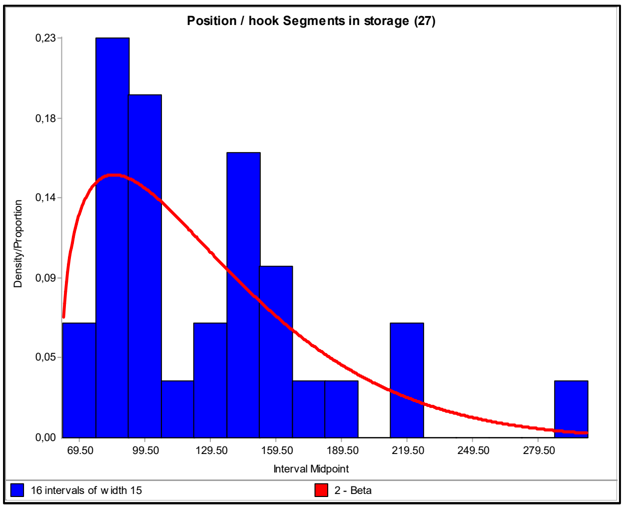

Hook and Unhook Segments (20)
Density/Proportion
0,54
0,43
0,32
0,22
0,11
0,00
37.50
178.50
319.50
460.50
601.50
742.50
883.50
Interval Midpoint
19 intervals of width 47
1 - Log-Logistic

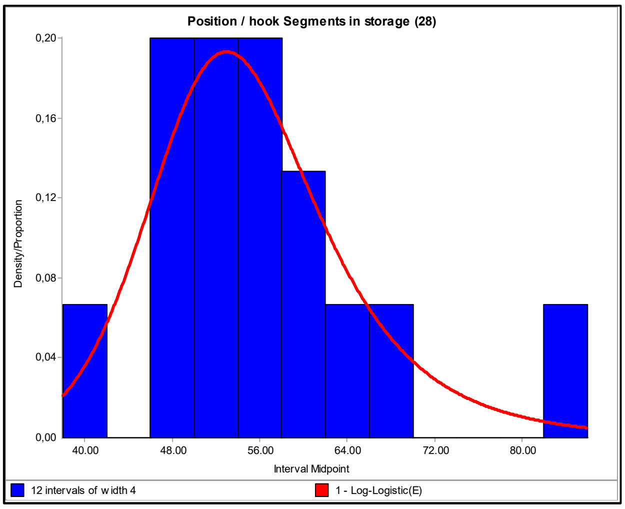

Hook and Unhook Segments (21)
Density/Proportion
0,17
0,14
0,10
0,07
0,03
0,00
19.50
46.50
73.50
100.50
127.50
154.50
Interval Midpoint
18 intervals of width 9
2 - Lognormal

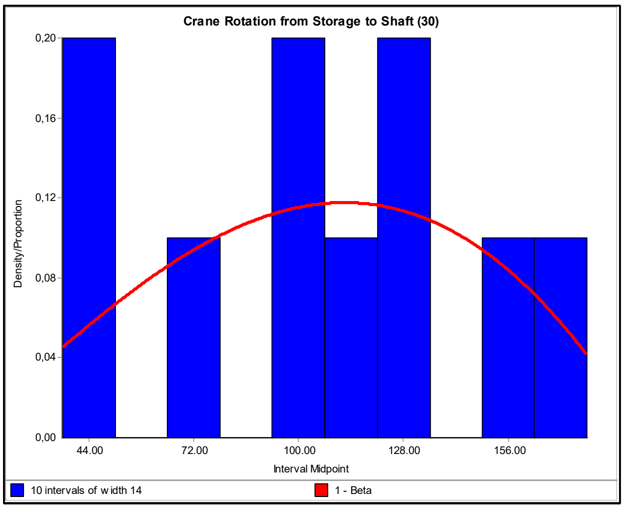

Pump Grout from Silo to Car (24)
Density/Proportion
0,27
0,22
0,16
0,11
0,05
0,00
271.00
295.00
319.00
343.00
367.00
Interval Midpoint
10 intervals of width 12
2 - Beta

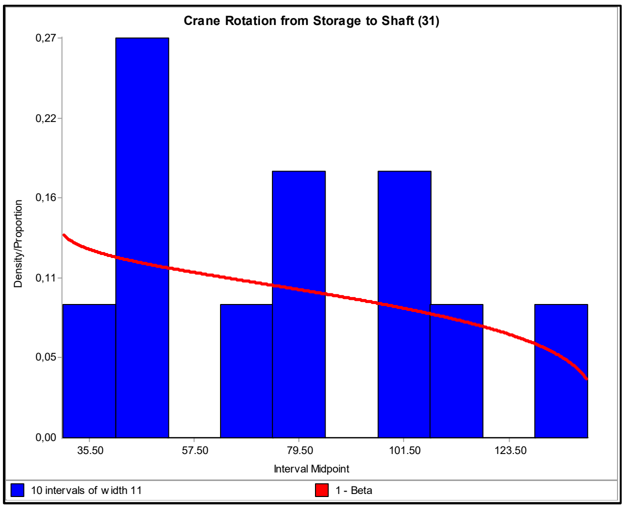

Position / Unhook Segments on MSV (25)
Density/Proportion
0,33
0,27
0,20
0,13
0,07
0,00
53.00
81.00
109.00
137.00
165.00
193.00
Interval Midpoint
12 intervals of width 14
1 - Log-Logistic

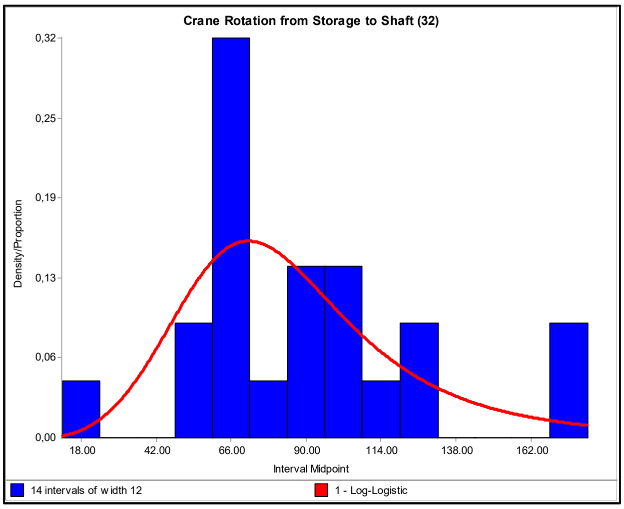

Position / Unhook Segments on MSV (26)
Density/Proportion
0,23
0,18
0,14
0,09
0,05
0,00
161.00
197.00
233.00
269.00
305.00
341.00
377.00
413.00
Interval Midpoint
16 intervals of width 18
1 - Gamma(E)

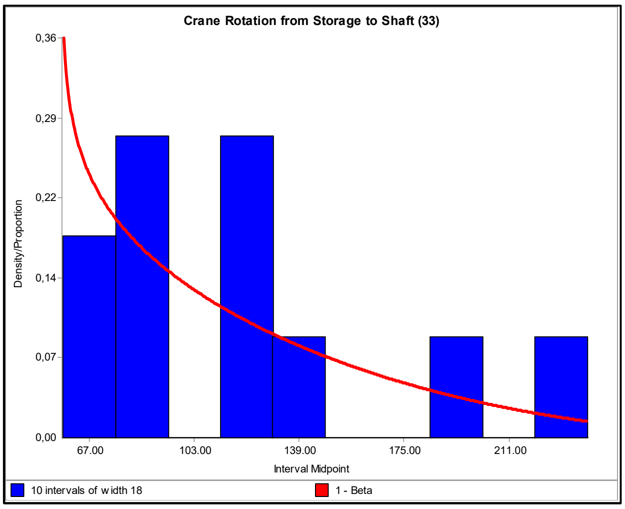

Position / hook Segments in storage (27)
Density/Proportion
0,23
0,18
0,14
0,09
0,05
0,00
69.50
99.50
129.50
159.50
189.50
219.50
249.50
279.50
Interval Midpoint
16 intervals of width 15
2 - Beta

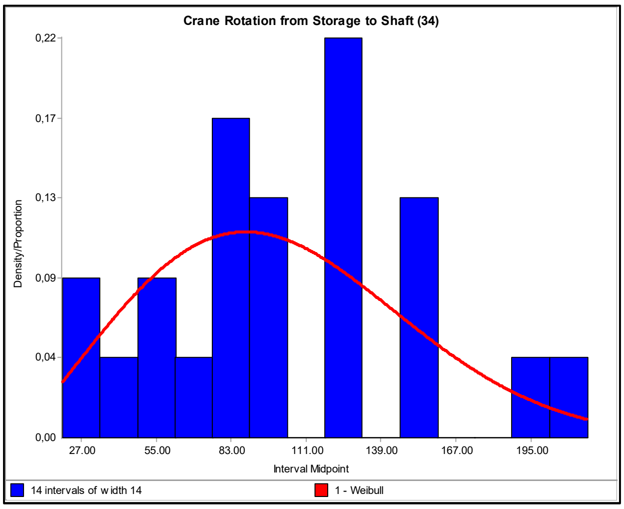

Position / hook Segments in storage (28)
0,20
0,16
0,12
0,08
0,04
0,00
Density/Proportion
40.00
48.00
56.00
64.00
72.00
80.00
Interval Midpoint
12 intervals of width 4
1 - Log-Logistic(E)

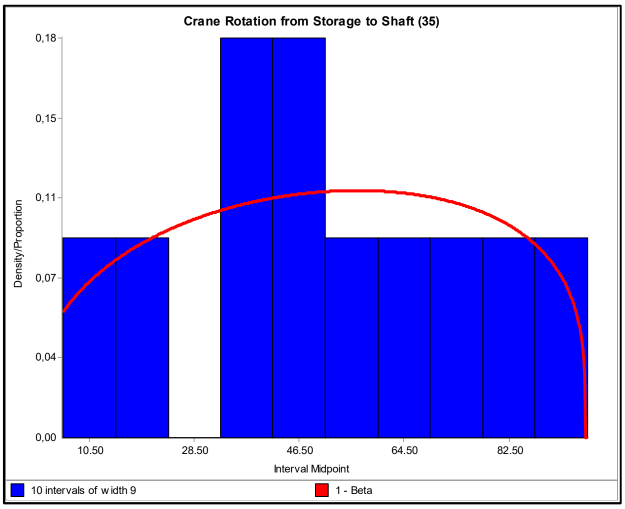

Crane Rotation from Storage to Shaft (30)
0,20
0,16
0,12
0,08
0,04
0,00
Density/Proportion
44.00
72.00
100.00
128.00
156.00
Interval Midpoint
10 intervals of width 14
1 - Beta

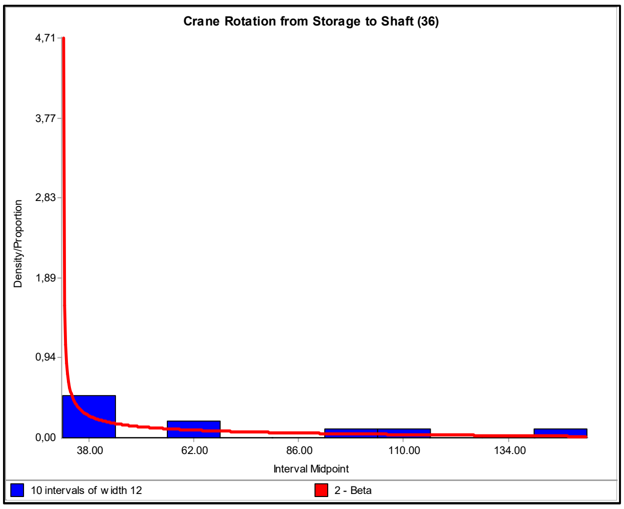

Crane Rotation from Storage to Shaft (31)
0,27
0,22
0,16
0,11
0,05
0,00
Density/Proportion
35.50
57.50
79.50
101.50
123.50
Interval Midpoint
10 intervals of width 11
1 - Beta

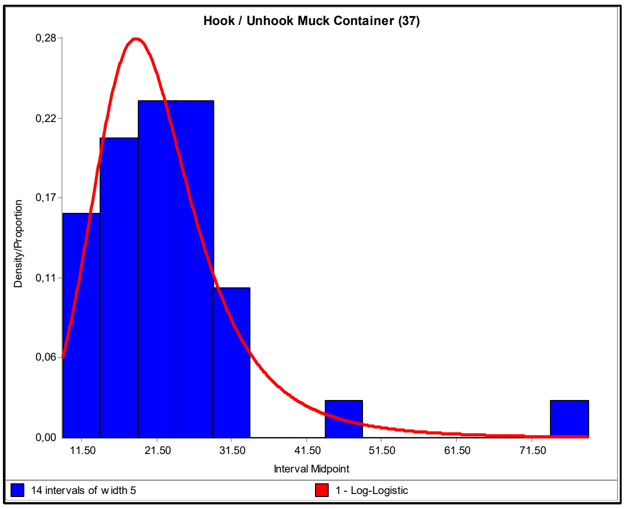

Crane Rotation from Storage to Shaft (32)
0,32
0,25
0,19
0,13
0,06
0,00
Density/Proportion
18.00
42.00
66.00
90.00
114.00
138.00
162.00
Interval Midpoint
14 intervals of width 12
1 - Log-Logistic

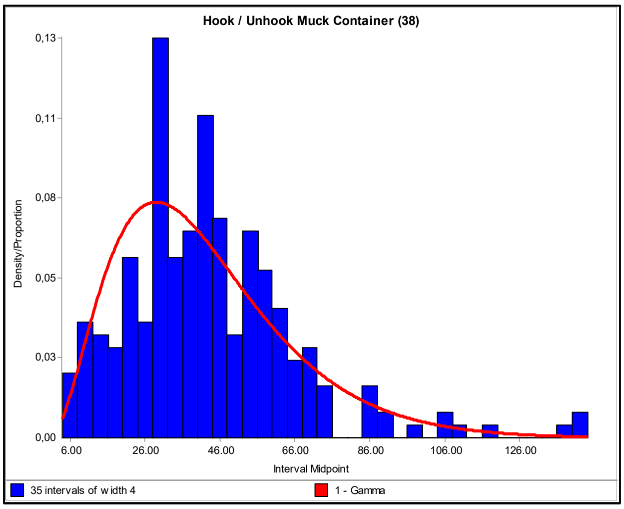

Crane Rotation from Storage to Shaft (33)
0,36
0,29
0,22
0,14
0,07
0,00
Density/Proportion
67.00
103.00
139.00
175.00
211.00
Interval Midpoint
10 intervals of width 18
1 - Beta

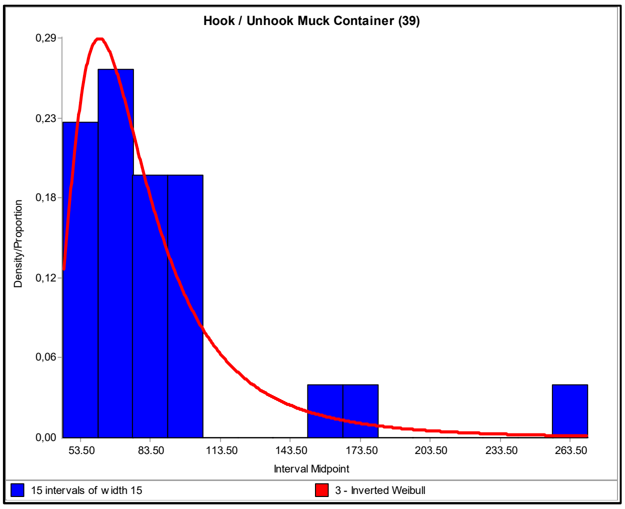

Crane Rotation from Storage to Shaft (34)
0,22
0,17
0,13
0,09
0,04
0,00
Density/Proportion
27.00
55.00
83.00
111.00
139.00
167.00
195.00
Interval Midpoint
14 intervals of width 14
1 - Weibull

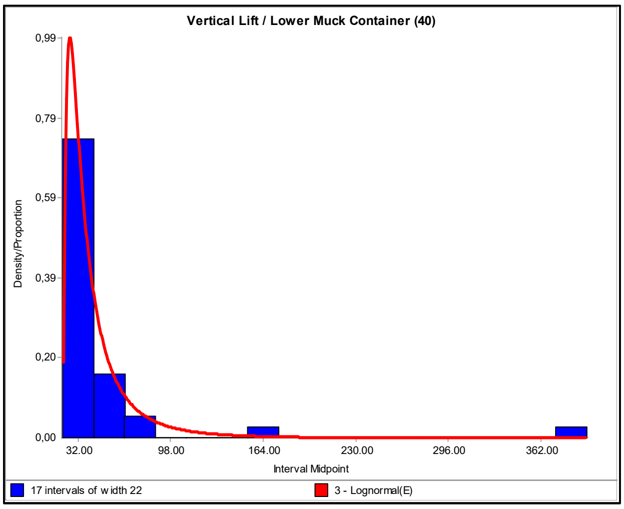

Crane Rotation from Storage to Shaft (35)
0,18
0,15
0,11
0,07
0,04
0,00
Density/Proportion
10.50
28.50
46.50
64.50
82.50
Interval Midpoint
10 intervals of width 9
1 - Beta

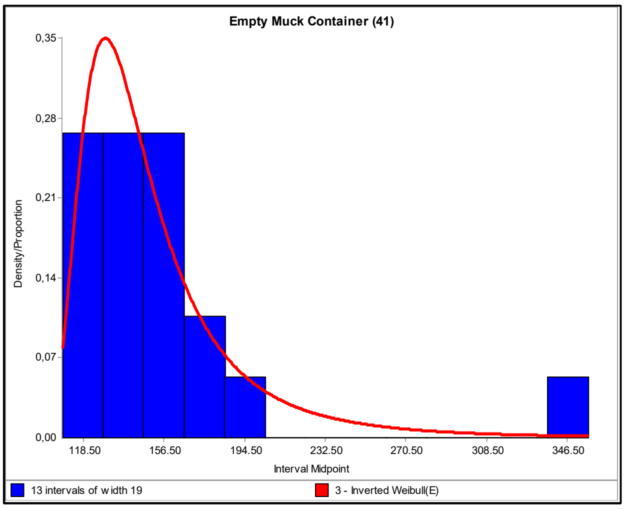

Crane Rotation from Storage to Shaft (36)
4,71
3,77
2,83
1,89
0,94
0,00
Density/Proportion
38.00
62.00
86.00
110.00
134.00
Interval Midpoint
10 intervals of width 12
2 - Beta

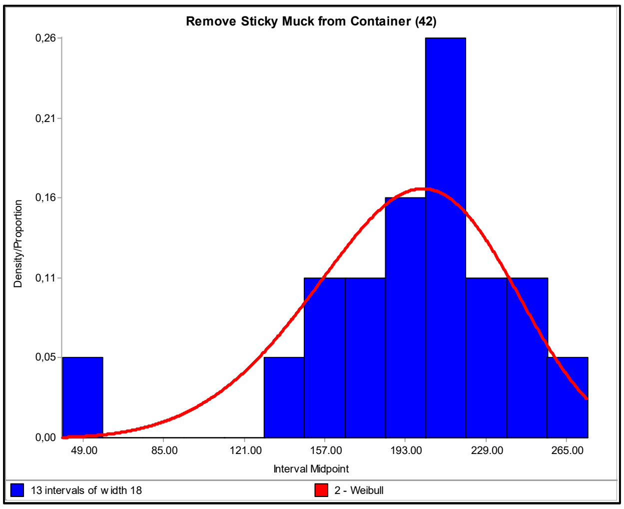

Hook / Unhook Muck Container (37)
0,28
0,22
0,17
0,11
0,06
0,00
Density/Proportion
11.50
21.50
31.50
41.50
51.50
61.50
71.50
Interval Midpoint
14 intervals of width 5
1 - Log-Logistic

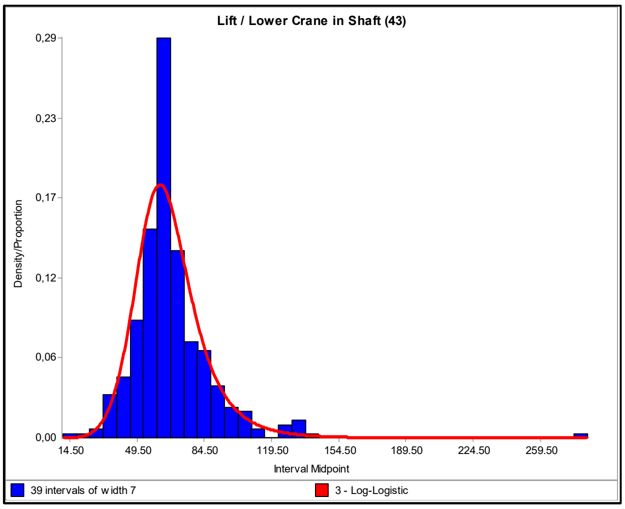

Hook / Unhook Muck Container (38)
0,13
0,11
0,08
0,05
0,03
0,00
Density/Proportion
6.00
26.00
46.00
66.00
86.00
106.00
126.00
Interval Midpoint
35 intervals of width 4
1 - Gamma

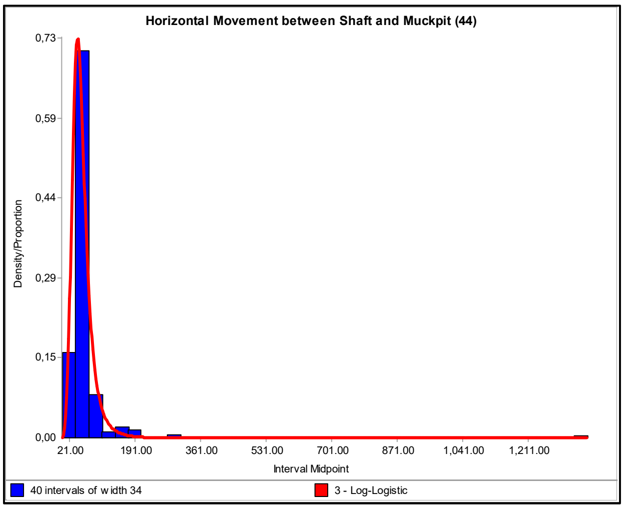

Hook / Unhook Muck Container (39)
0,29
0,23
0,18
0,12
0,06
0,00
Density/Proportion
53.50
83.50
113.50
143.50
173.50
203.50
233.50
263.50
Interval Midpoint
15 intervals of width 15
3 - Inverted Weibull

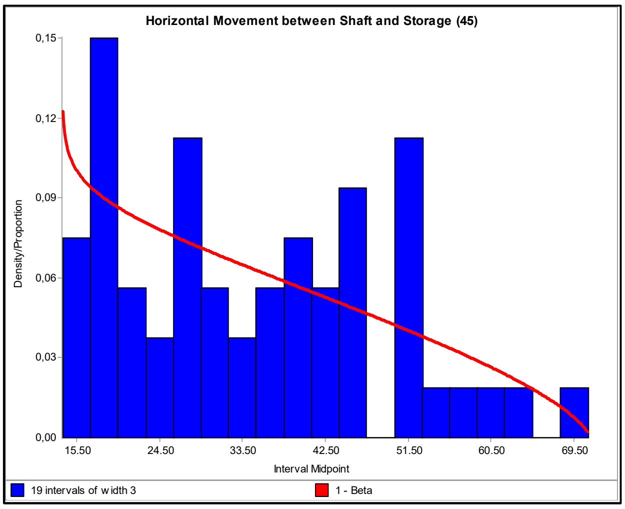

Vertical Lift / Lower Muck Container (40)
0,99
0,79
0,59
0,39
0,20
0,00
Density/Proportion
32.00
98.00
164.00
230.00
296.00
362.00
Interval Midpoint
17 intervals of width 22
3 - Lognormal(E)

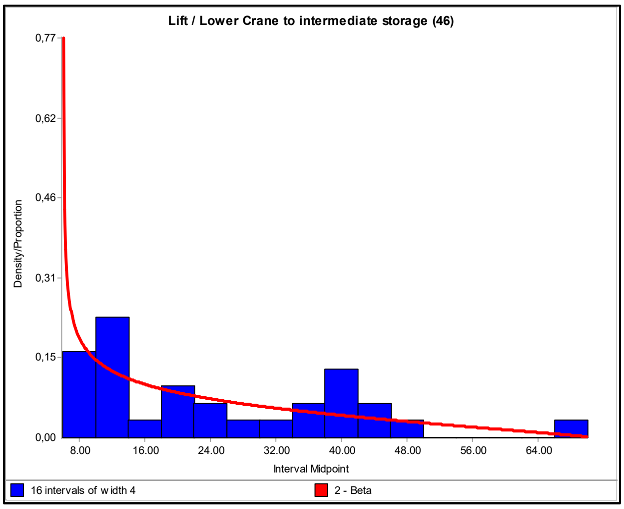

Empty Muck Container (41)
Density/Proportion
Interval Midpoint
13 intervals of width 19
3 - Inverted Weibull(E)

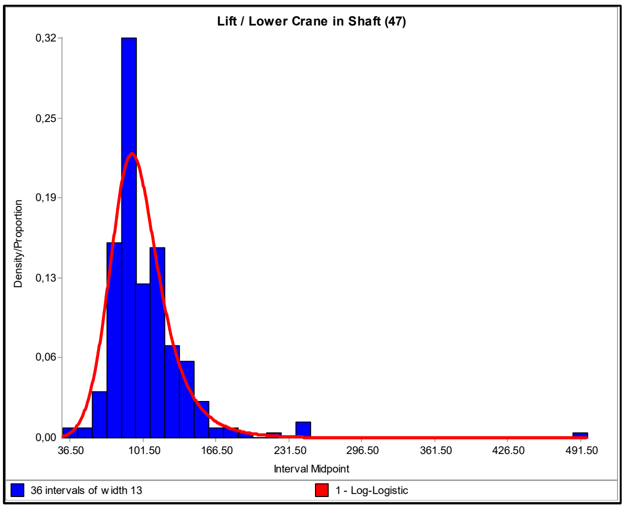

Remove Sticky Muck from Container (42)
Density/Proportion
Interval Midpoint
13 intervals of width 18
2 - Weibull

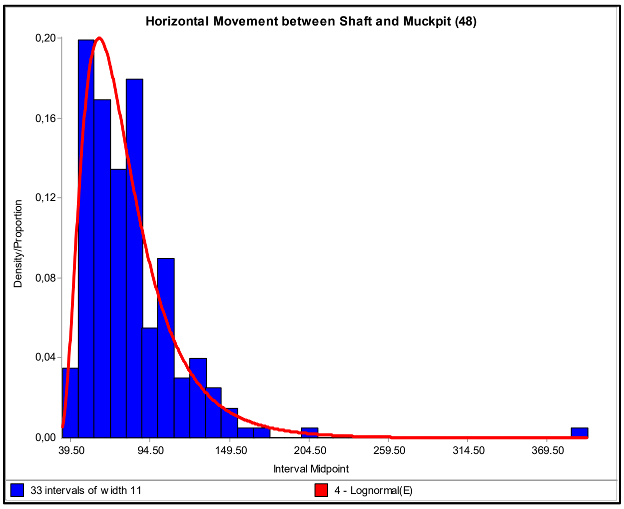

Lift / Lower Crane in Shaft (43)
Density/Proportion
Interval Midpoint
39 intervals of width 7
3 - Log-Logistic

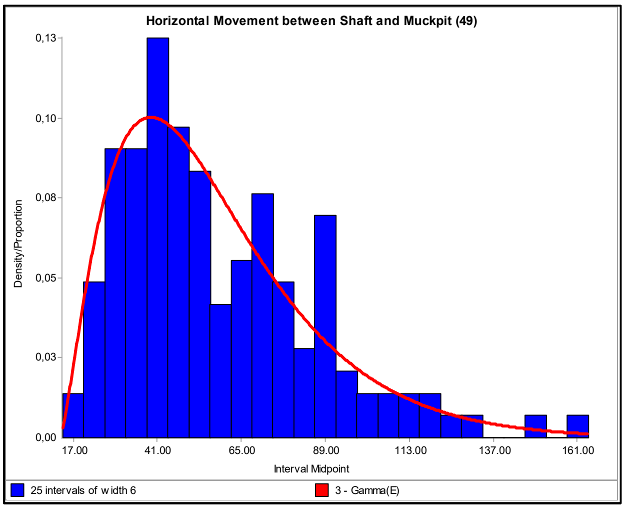

Horizontal Movement between Shaft and Muckpit (44)
Density/Proportion
Interval Midpoint
40 intervals of width 34
3 - Log-Logistic

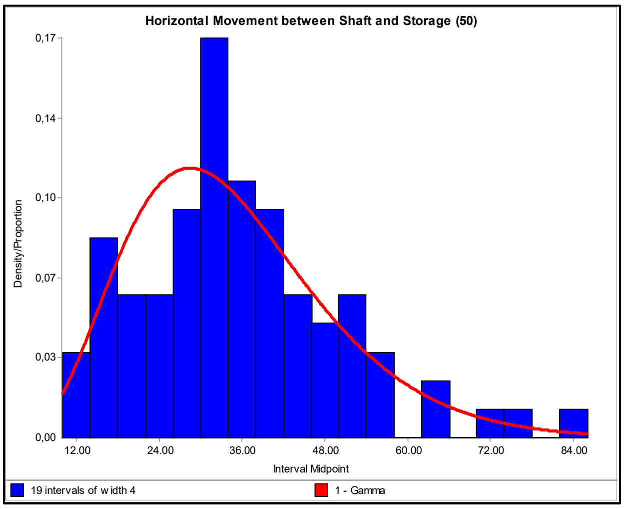

Horizontal Movement between Shaft and Storage (45)
Density/Proportion
Interval Midpoint
19 intervals of width 3
1 - Beta

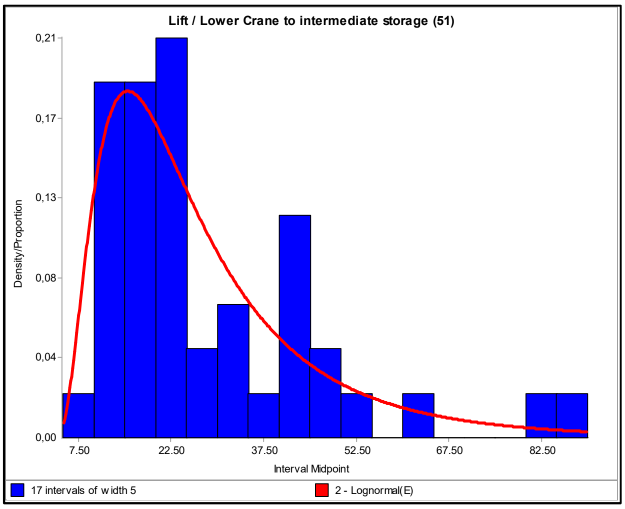

Lift / Lower Crane to intermediate storage (46)
Density/Proportion
Interval Midpoint
16 intervals of width 4
2 - Beta

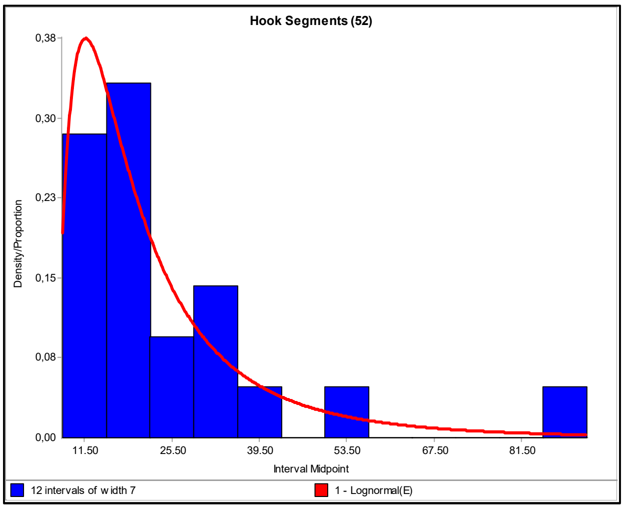

Lift / Lower Crane in Shaft (47)
Density/Proportion
0,32
0,25
0,19
0,13
0,06
0,00
36.50
101.50
166.50
231.50
296.50
361.50
426.50
491.50
Interval Midpoint
36 intervals of width 13
1 - Log-Logistic

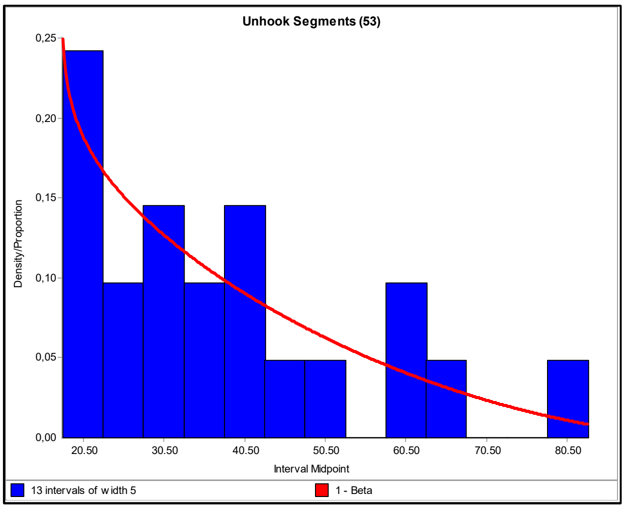

Horizontal Movement between Shaft and Muckpit (48)
Density/Proportion
0,20
0,16
0,12
0,08
0,04
0,00
39.50
94.50
149.50
204.50
259.50
314.50
369.50
Interval Midpoint
33 intervals of width 11
4 - Lognormal(E)

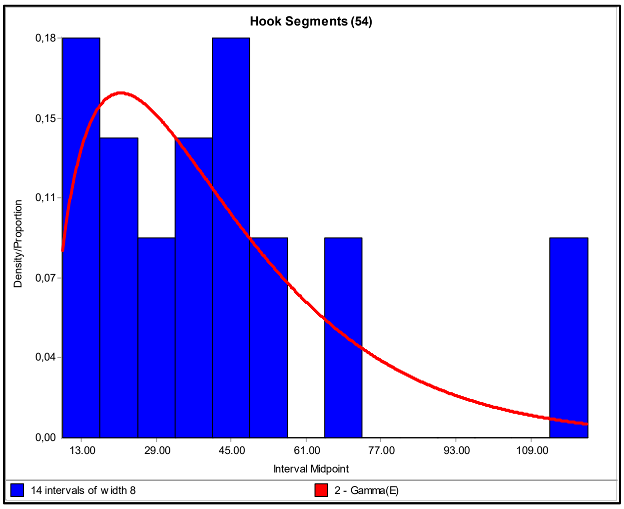

Horizontal Movement between Shaft and Muckpit (49)
Density/Proportion
0,13
0,10
0,08
0,05
0,03
0,00
17.00
41.00
65.00
89.00
113.00
137.00
161.00
Interval Midpoint
25 intervals of width 6
3 - Gamma(E)

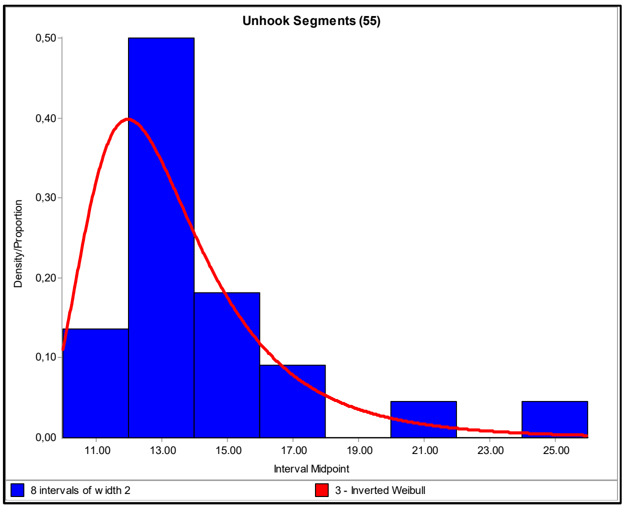

Horizontal Movement between Shaft and Storage (50)
Density/Proportion
0,17
0,14
0,10
0,07
0,03
0,00
12.00
24.00
36.00
48.00
60.00
72.00
84.00
Interval Midpoint
19 intervals of width 4
1 - Gamma

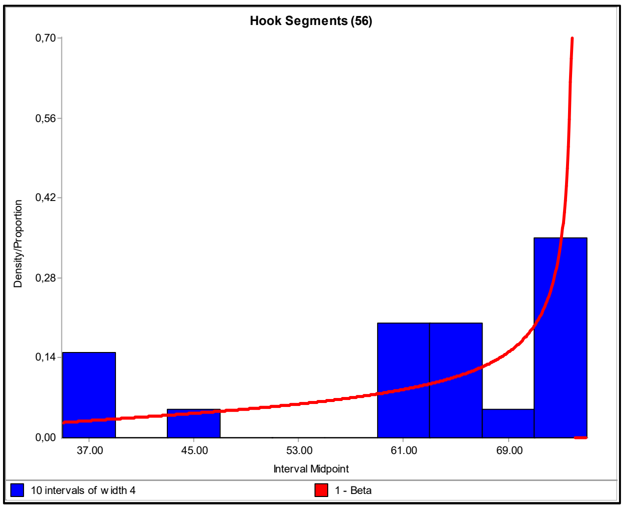

Lift / Lower Crane to intermediate storage (51)
Density/Proportion
0,21
0,17
0,13
0,08
0,04
0,00
7.50
22.50
37.50
52.50
67.50
82.50
Interval Midpoint
17 intervals of width 5
2 - Lognormal(E)

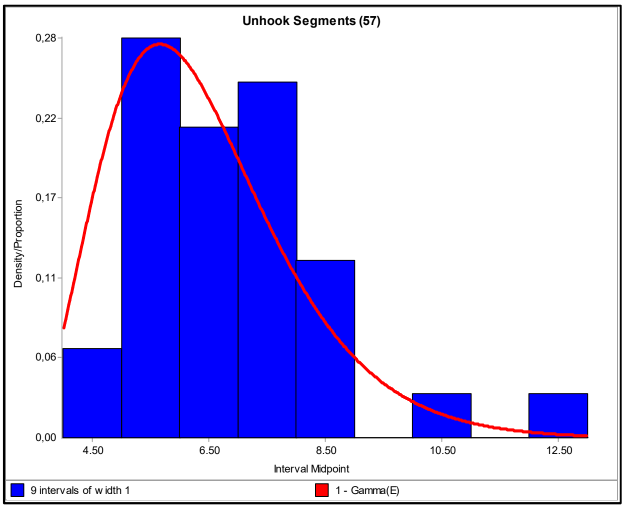

Hook Segments (52)
Density/Proportion
0,38
0,30
0,23
0,15
0,08
0,00
11.50
25.50
39.50
53.50
67.50
81.50
Interval Midpoint
12 intervals of width 7
1 - Lognormal(E)

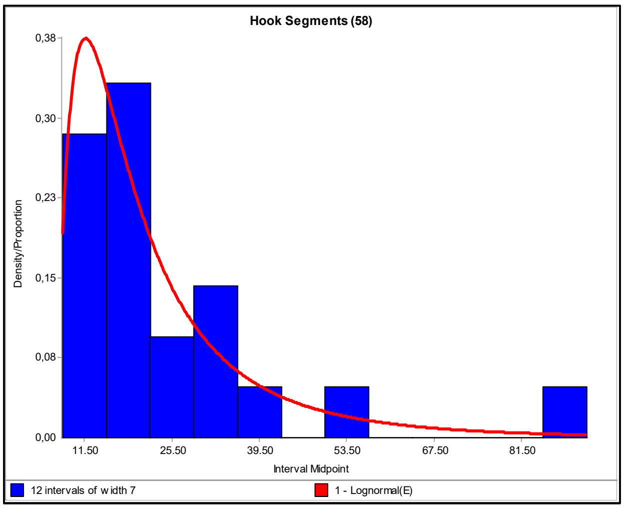

Unhook Segments (53)
Density/Proportion
Interval Midpoint
13 intervals of width 5
1 - Beta

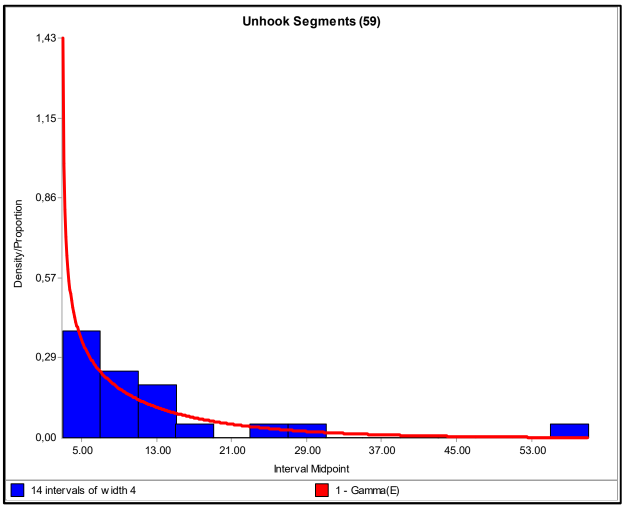

Hook Segments (54)
Density/Proportion
Interval Midpoint
14 intervals of width 8
2 - Gamma(E)

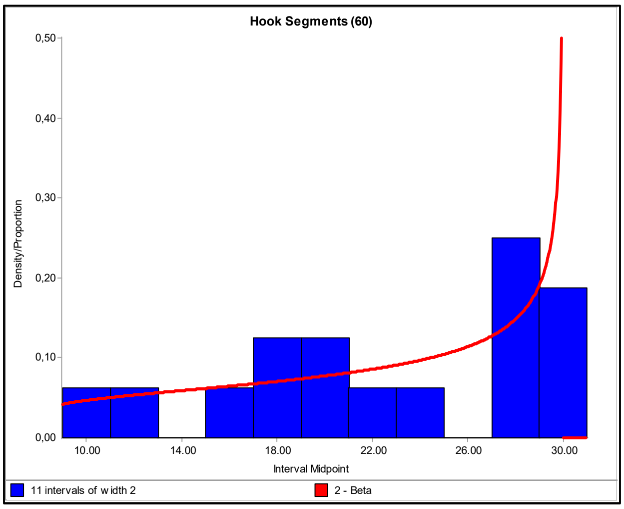

Unhook Segments (55)
Density/Proportion
Interval Midpoint
8 intervals of width 2
3 - Inverted Weibull

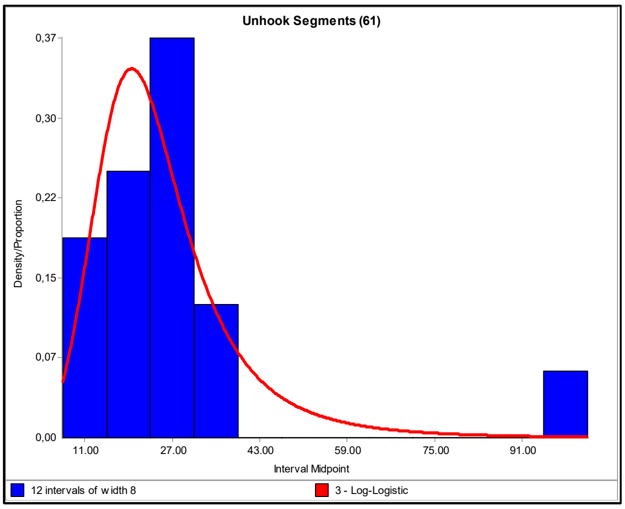

Hook Segments (56)
Density/Proportion
Interval Midpoint
10 intervals of width 4
1 - Beta

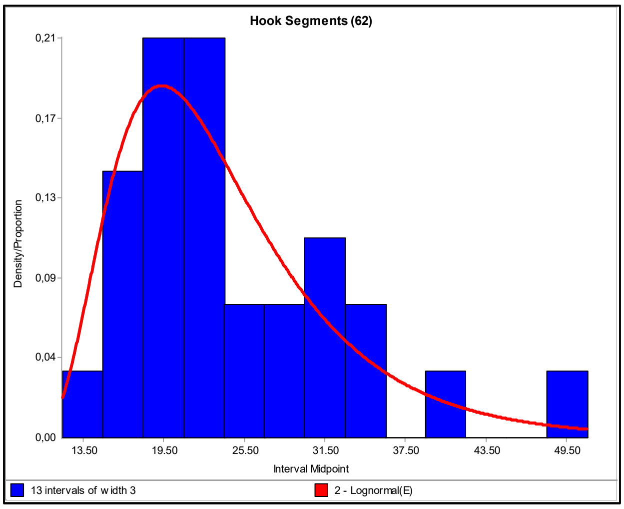

Unhook Segments (57)
Density/Proportion
Interval Midpoint
9 intervals of width 1
1 - Gamma(E)

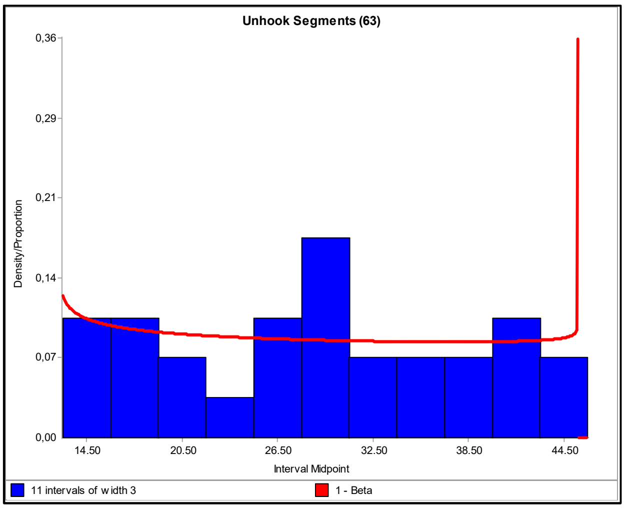

Hook Segments (58)
Density/Proportion
Interval Midpoint
12 intervals of width 7
1 - Lognormal(E)

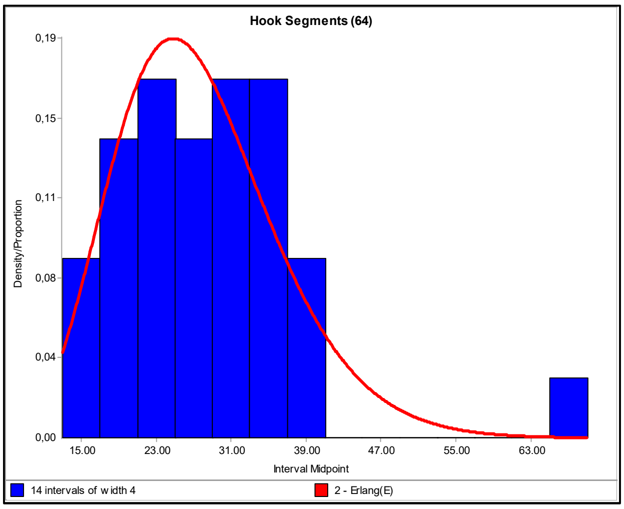

Unhook Segments (59)
Density/Proportion
1,43
1,15
0,86
0,57
0,29
0,00
5.00
13.00
21.00
29.00
37.00
45.00
53.00
Interval Midpoint
14 intervals of width 4
1 - Gamma(E)

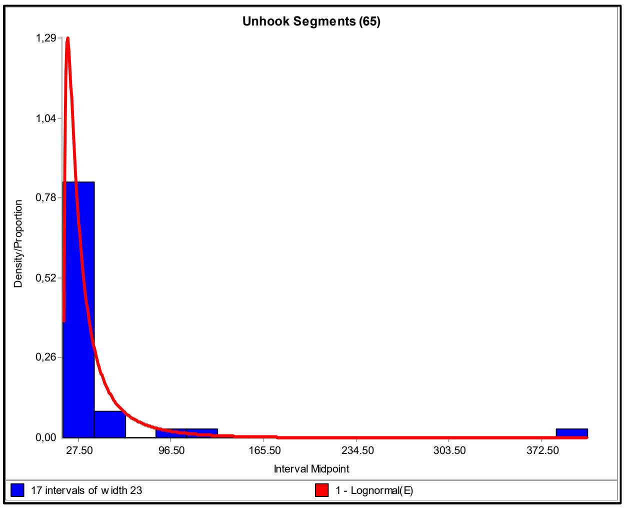

Hook Segments (60)
Density/Proportion
0,50
0,40
0,30
0,20
0,10
0,00
10.00
14.00
18.00
22.00
26.00
30.00
Interval Midpoint
11 intervals of width 2
2 - Beta

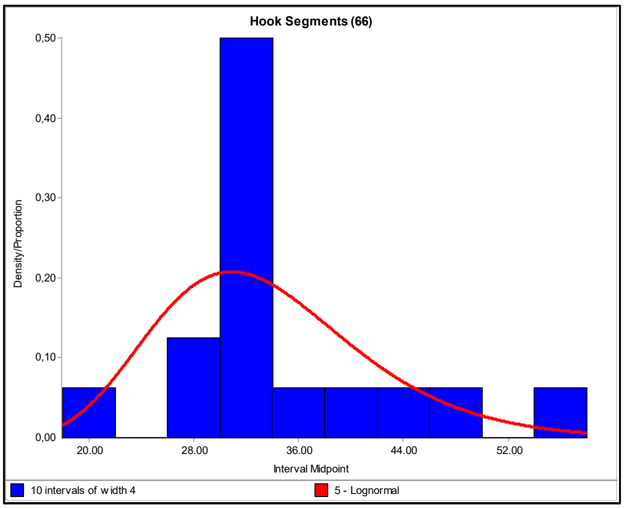

Unhook Segments (61)
Density/Proportion
0,37
0,30
0,22
0,15
0,07
0,00
11.00
27.00
43.00
59.00
75.00
91.00
Interval Midpoint
12 intervals of width 8
3 - Log-Logistic

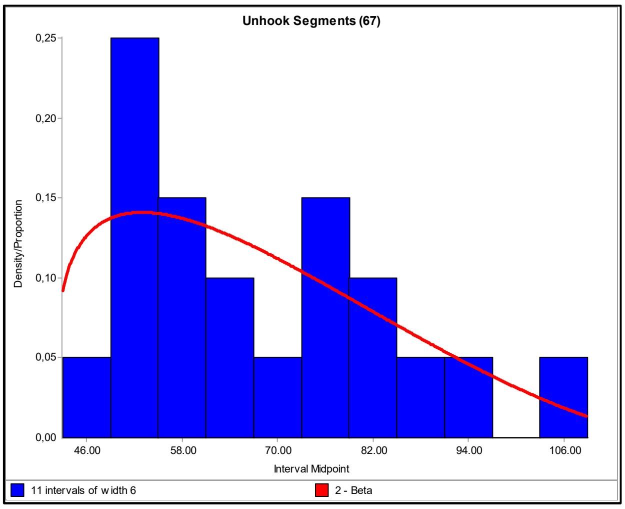

Hook Segments (62)
Density/Proportion
0,21
0,17
0,13
0,09
0,04
0,00
13.50
19.50
25.50
31.50
37.50
43.50
49.50
Interval Midpoint
13 intervals of width 3
2 - Lognormal(E)

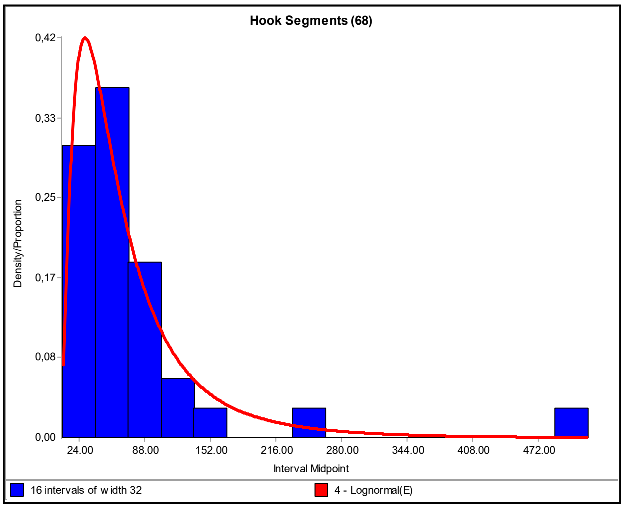

Unhook Segments (63)
Density/Proportion
0,36
0,29
0,21
0,14
0,07
0,00
14.50
20.50
26.50
32.50
38.50
44.50
Interval Midpoint
11 intervals of width 3
1 - Beta

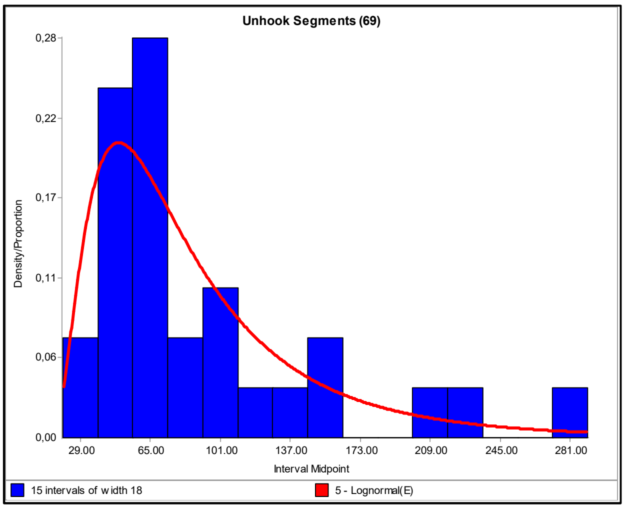

Hook Segments (64)
Density/Proportion
0,19
0,15
0,11
0,08
0,04
0,00
15.00
23.00
31.00
39.00
47.00
55.00
63.00
Interval Midpoint
14 intervals of width 4
2 - Erlang(E)

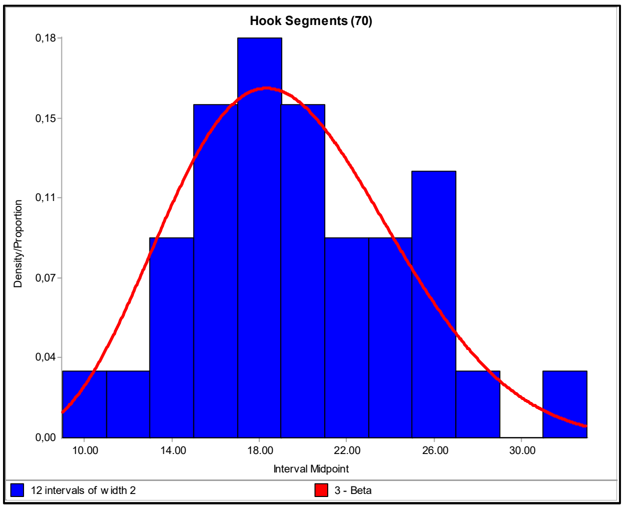

Unhook Segments (65)
1,29
1,04
0,78
0,52
0,26
0,00
Density/Proportion
27.50
96.50
165.50
234.50
303.50
372.50
Interval Midpoint
17 intervals of width 23
1 - Lognormal(E)

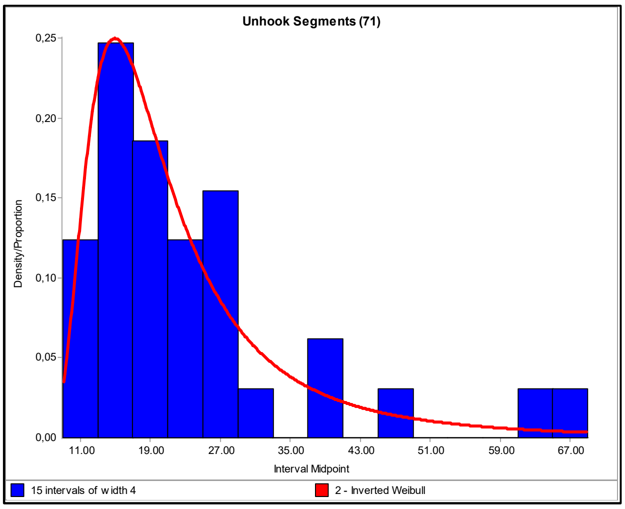

Hook Segments (66)
0,50
0,40
0,30
0,20
0,10
0,00
Density/Proportion
20.00
28.00
36.00
44.00
52.00
Interval Midpoint
10 intervals of width 4
5 - Lognormal

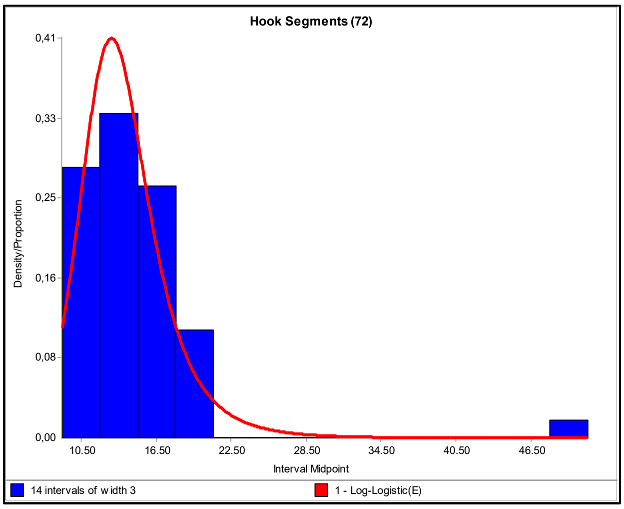

Unhook Segments (67)
0,25
0,20
0,15
0,10
0,05
0,00
Density/Proportion
46.00
58.00
70.00
82.00
94.00
106.00
Interval Midpoint
11 intervals of width 6
2 - Beta

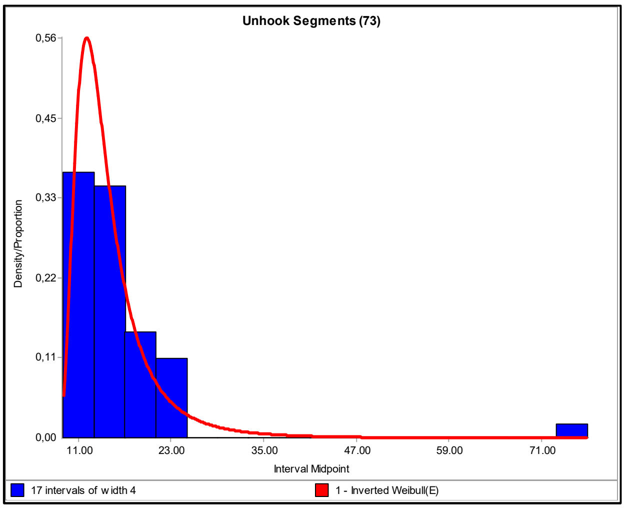

Hook Segments (68)
0,42
0,33
0,25
0,17
0,08
0,00
Density/Proportion
24.00
88.00
152.00
216.00
280.00
344.00
408.00
472.00
Interval Midpoint
16 intervals of width 32
4 - Lognormal(E)

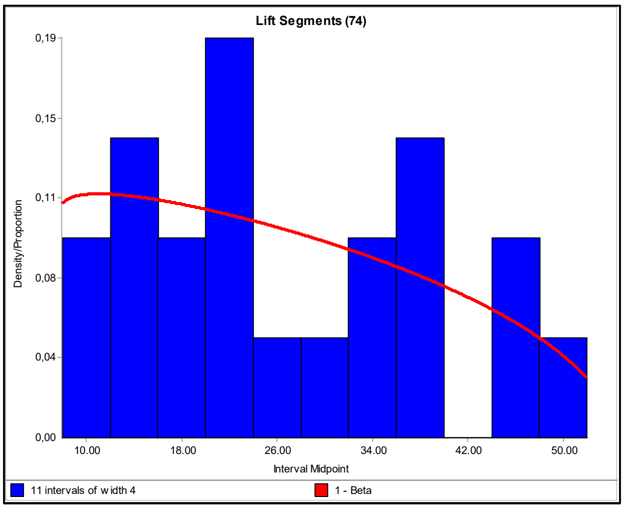

Unhook Segments (69)
0,28
0,22
0,17
0,11
0,06
0,00
Density/Proportion
29.00
65.00
101.00
137.00
173.00
209.00
245.00
281.00
Interval Midpoint
15 intervals of width 18
5 - Lognormal(E)

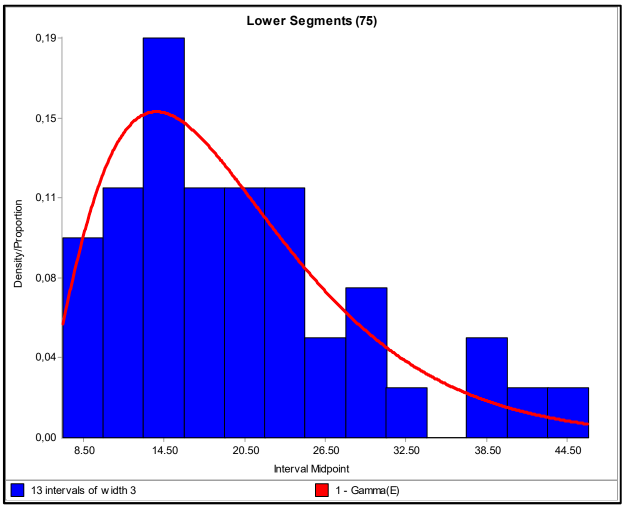

Hook Segments (70)
0,18
0,15
0,11
0,07
0,04
0,00
Density/Proportion
10.00
14.00
18.00
22.00
26.00
30.00
Interval Midpoint
12 intervals of width 2
3 - Beta

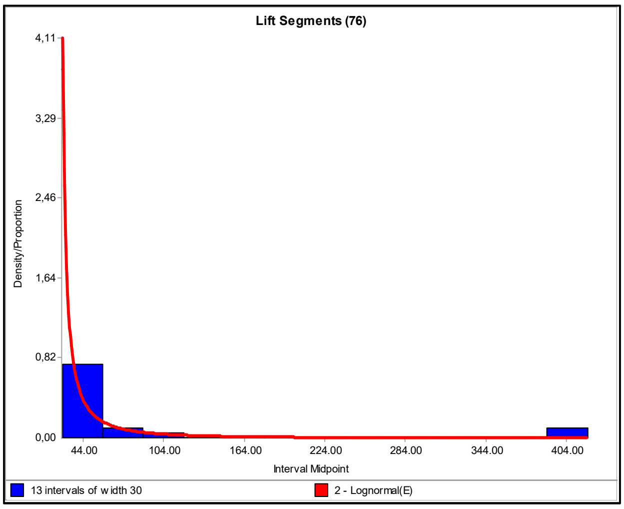

Unhook Segments (71)
Density/Proportion
Interval Midpoint
15 intervals of width 4
2 - Inverted Weibull

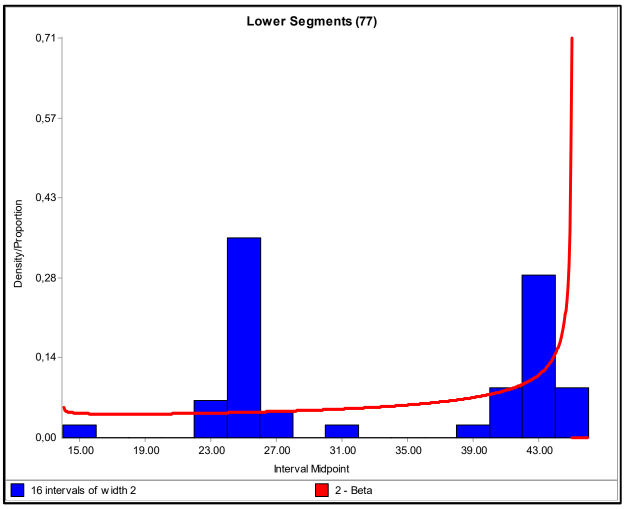

Hook Segments (72)
Density/Proportion
Interval Midpoint
14 intervals of width 3
1 - Log-Logistic(E)

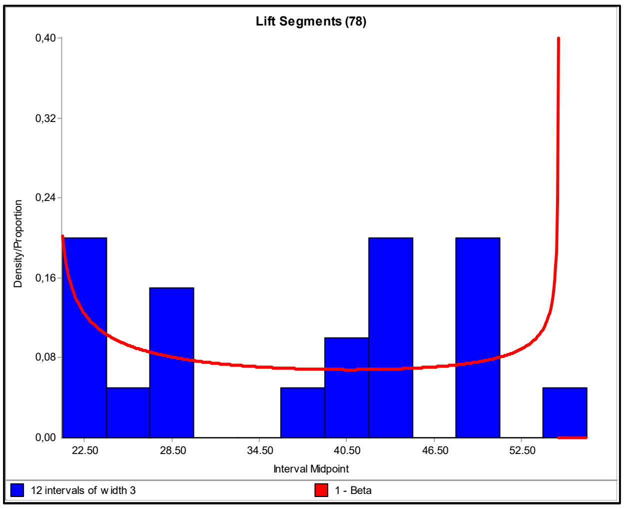

Unhook Segments (73)
Density/Proportion
Interval Midpoint
17 intervals of width 4
1 - Inverted Weibull(E)

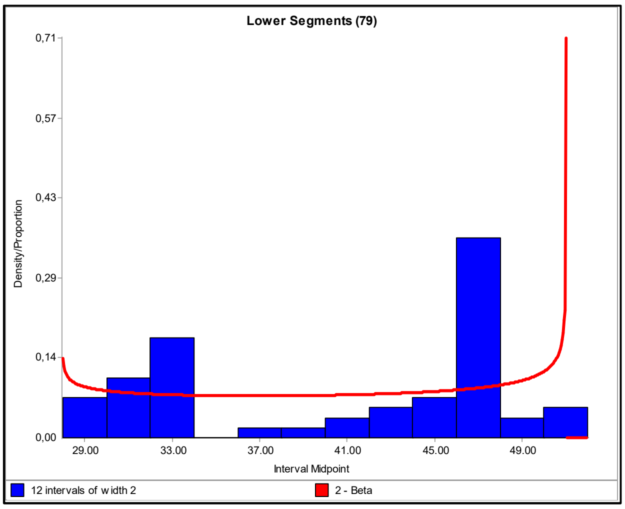

Lift Segments (74)
Density/Proportion
Interval Midpoint
11 intervals of width 4
1 - Beta

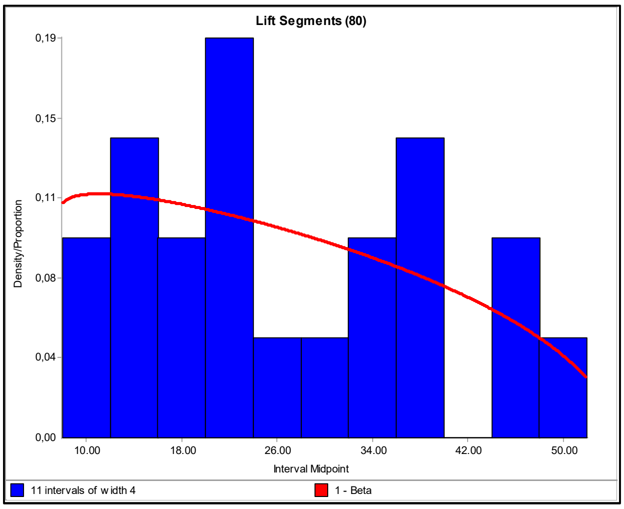

Lower Segments (75)
Density/Proportion
Interval Midpoint
13 intervals of width 3
1 - Gamma(E)

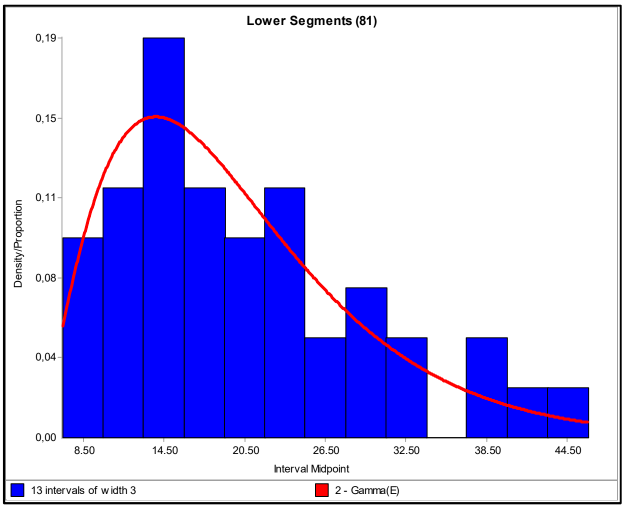

Lift Segments (76)
Density/Proportion
Interval Midpoint
13 intervals of width 30
2 - Lognormal(E)

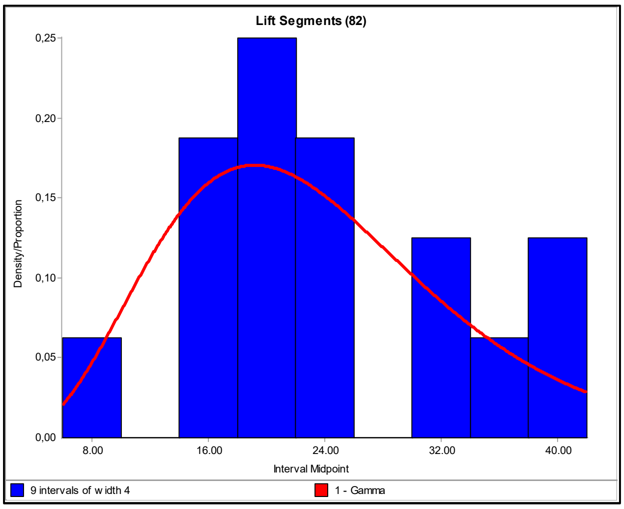

Lower Segments (77)
Density/Proportion
0,71
0,57
0,43
0,28
0,14
0,00
15.00
19.00
23.00
27.00
31.00
35.00
39.00
43.00
Interval Midpoint
16 intervals of width 2
2 - Beta

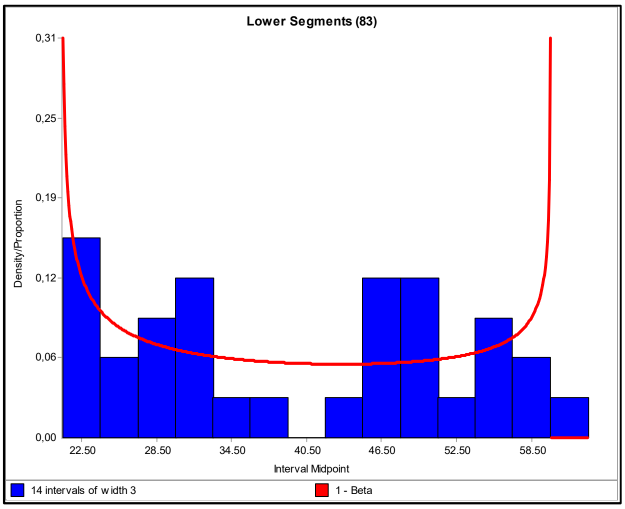

Lift Segments (78)
Density/Proportion
0,40
0,32
0,24
0,16
0,08
0,00
22.50
28.50
34.50
40.50
46.50
52.50
Interval Midpoint
12 intervals of width 3
1 - Beta

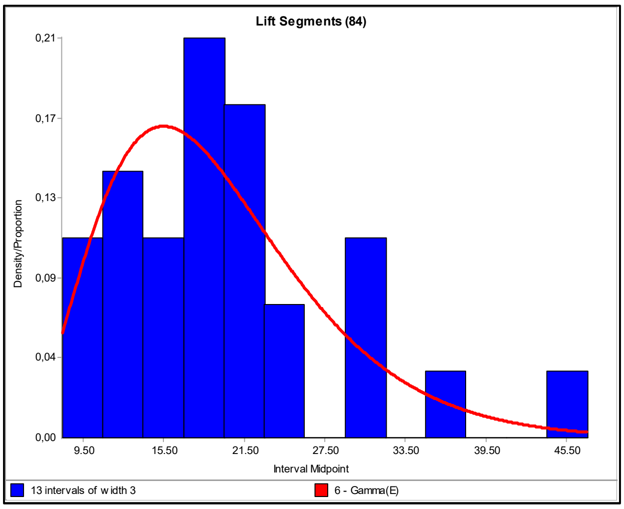

Lower Segments (79)
Density/Proportion
0,71
0,57
0,43
0,29
0,14
0,00
29.00
33.00
37.00
41.00
45.00
49.00
Interval Midpoint
12 intervals of width 2
2 - Beta

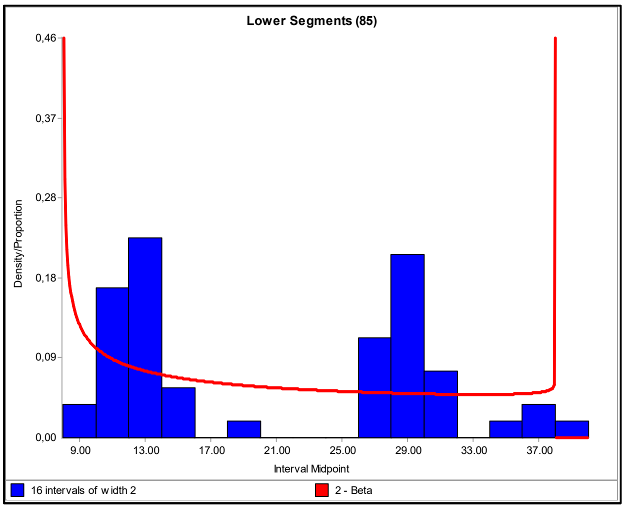

Lift Segments (80)
Density/Proportion
0,19
0,15
0,11
0,08
0,04
0,00
10.00
18.00
26.00
34.00
42.00
50.00
Interval Midpoint
11 intervals of width 4
1 - Beta

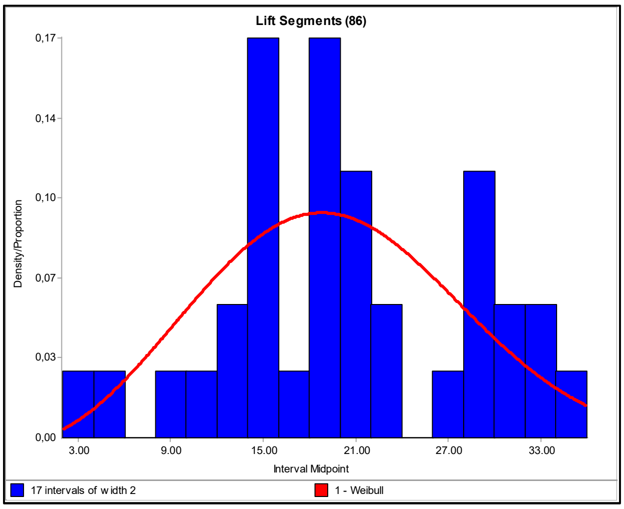

Lower Segments (81)
Density/Proportion
0,19
0,15
0,11
0,08
0,04
0,00
8.50
14.50
20.50
26.50
32.50
38.50
44.50
Interval Midpoint
13 intervals of width 3
2 - Gamma(E)

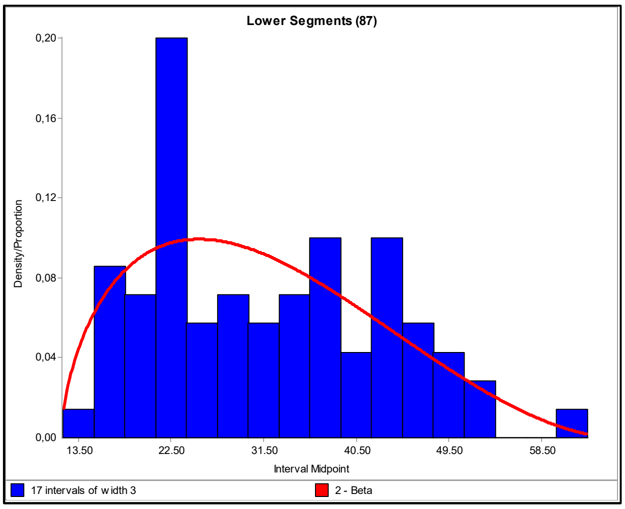

Lift Segments (82)
Density/Proportion
0,25
0,20
0,15
0,10
0,05
0,00
8.00
16.00
24.00
32.00
40.00
Interval Midpoint
9 intervals of width 4
1 - Gamma

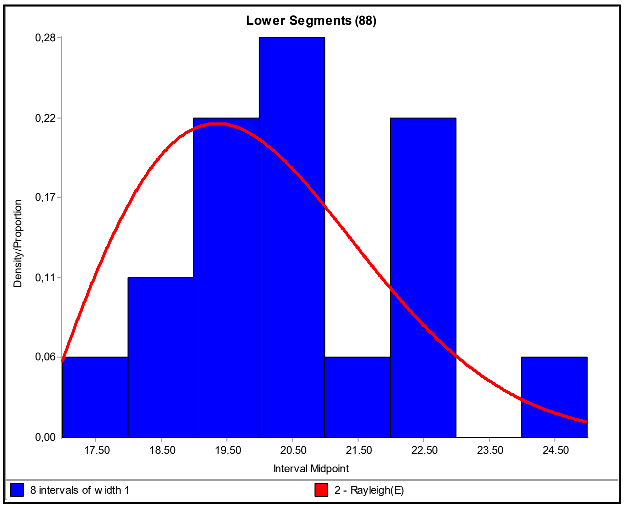

Lower Segments (83)
Density/Proportion
0,31
0,25
0,19
0,12
0,06
0,00
22.50 28.50 34.50 40.50 46.50 52.50 58.50
Interval Midpoint
14 intervals of width 3
1 - Beta

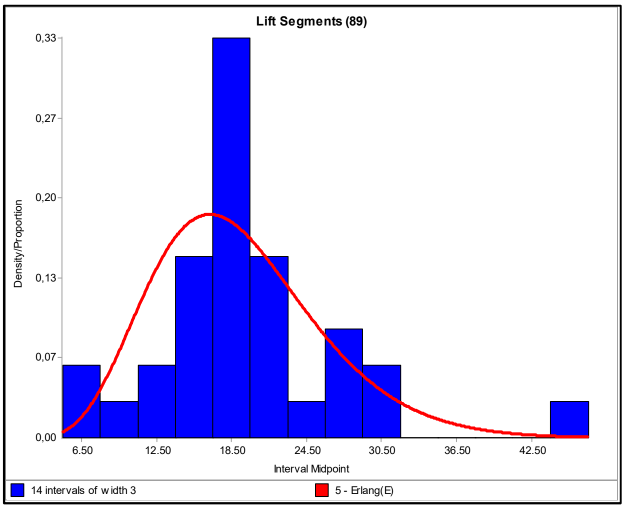

Lift Segments (84)
Density/Proportion
0,21
0,17
0,13
0,09
0,04
0,00
9.50 15.50 21.50 27.50 33.50 39.50 45.50
Interval Midpoint
13 intervals of width 3
6 - Gamma(E)

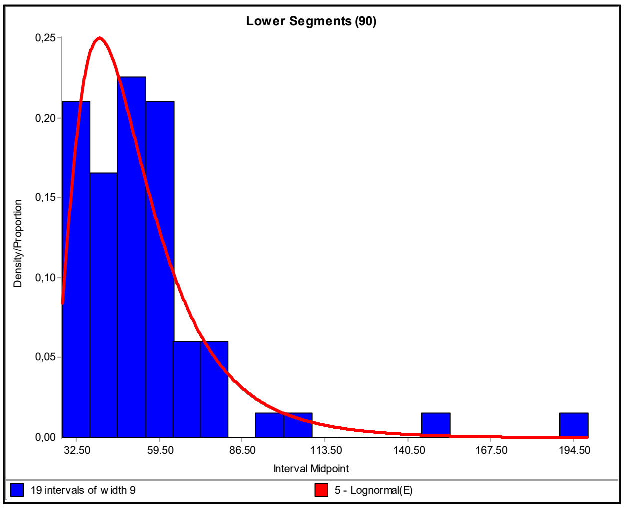

Lower Segments (85)
Density/Proportion
0,46
0,37
0,28
0,18
0,09
0,00
9.00 13.00 17.00 21.00 25.00 29.00 33.00 37.00
Interval Midpoint
16 intervals of width 2
2 - Beta

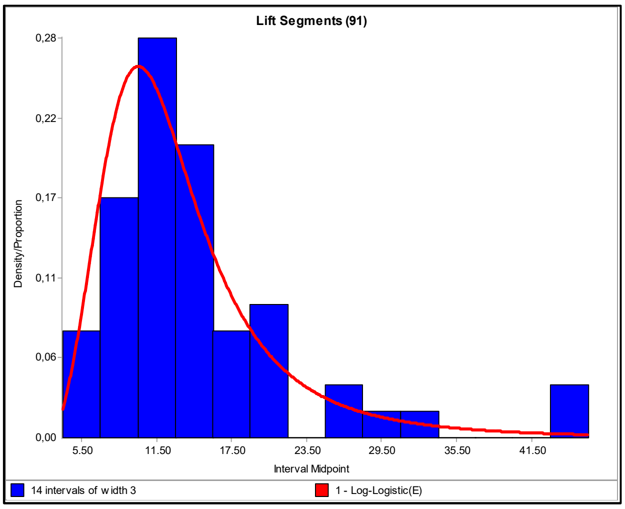

Lift Segments (86)
Density/Proportion
0,17
0,14
0,10
0,07
0,03
0,00
3.00 9.00 15.00 21.00 27.00 33.00
Interval Midpoint
17 intervals of width 2
1 - Weibull

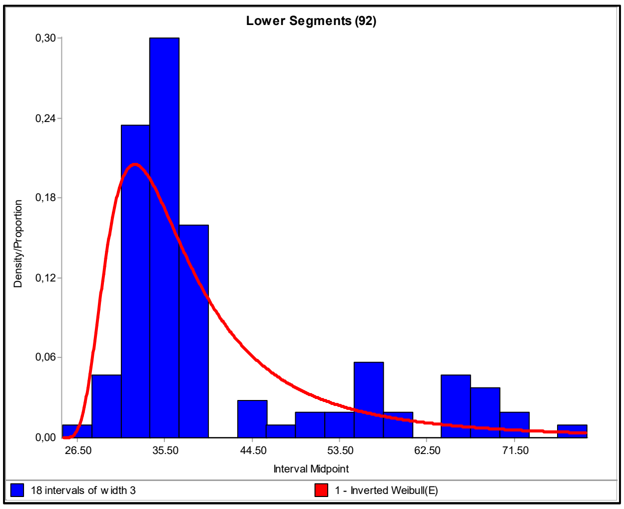

Lower Segments (87)
Density/Proportion
0,20
0,16
0,12
0,08
0,04
0,00
13.50 22.50 31.50 40.50 49.50 58.50
Interval Midpoint
17 intervals of width 3
2 - Beta

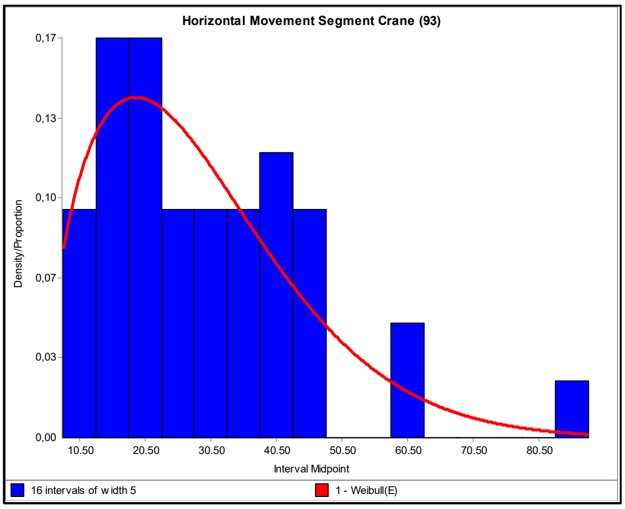

Lower Segments (88)
Density/Proportion
0,28
0,22
0,17
0,11
0,06
0,00
17.50 18.50 19.50 20.50 21.50 22.50 23.50 24.50
Interval Midpoint
8 intervals of width 1
2 - Rayleigh(E)

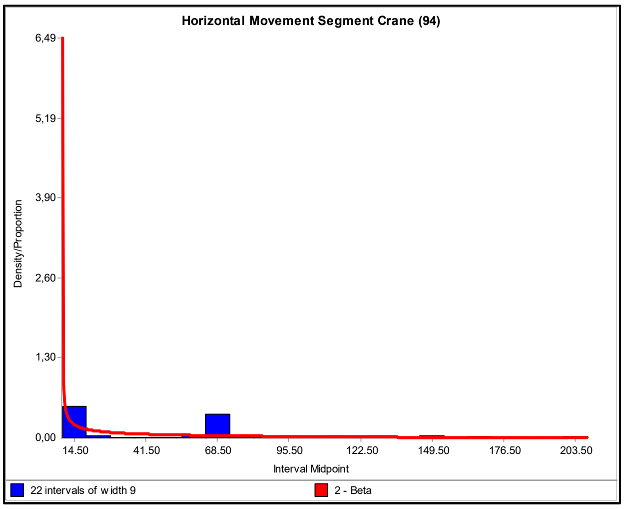

Lift Segments (89)
Density/Proportion
0,33
0,27
0,20
0,13
0,07
0,00
6.50 12.50 18.50 24.50 30.50 36.50 42.50
Interval Midpoint
14 intervals of width 3
5 - Erlang(E)

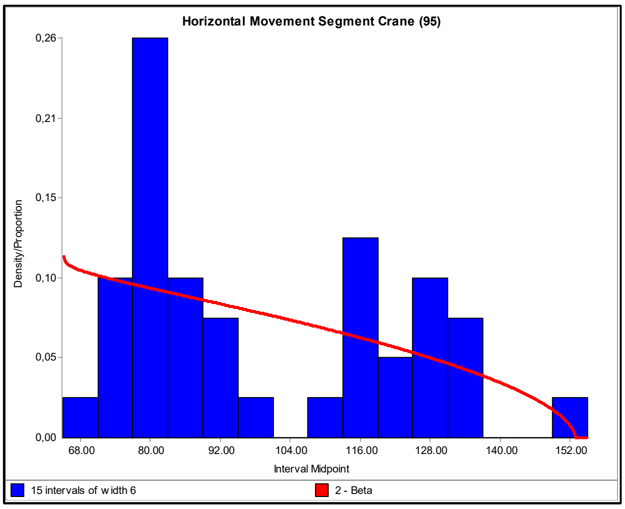

Lower Segments (90)
Density/Proportion
0,25
0,20
0,15
0,10
0,05
0,00
32.50 59.50 86.50 113.50 140.50 167.50 194.50
Interval Midpoint
19 intervals of width 9
5 - Lognormal(E)

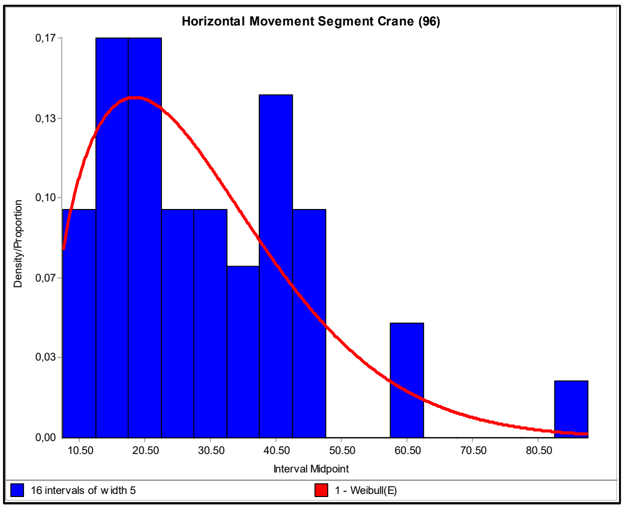

Lift Segments (91)
Density/Proportion
0,28
0,22
0,17
0,11
0,06
0,00
5.50 11.50 17.50 23.50 29.50 35.50 41.50
Interval Midpoint
14 intervals of width 3
1 - Log-Logistic(E)

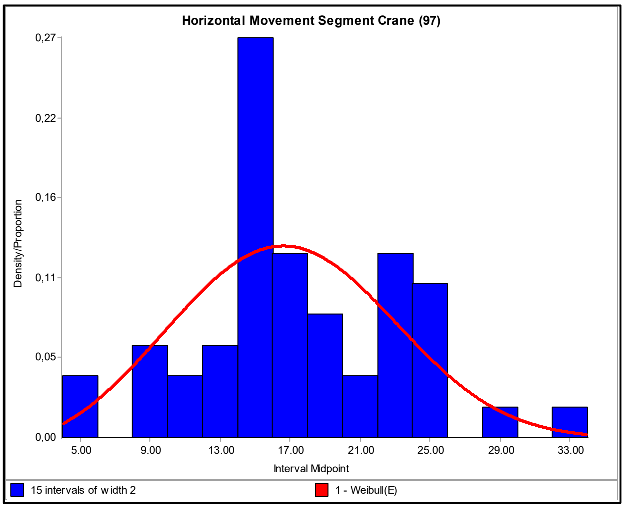

Lower Segments (92)
Density/Proportion
0,30
0,24
0,18
0,12
0,06
0,00
26.50 35.50 44.50 53.50 62.50 71.50
Interval Midpoint
18 intervals of width 3
1 - Inverted Weibull(E)

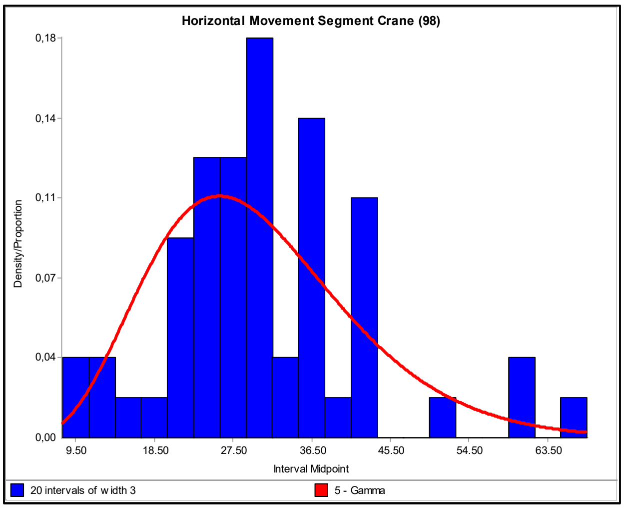

Horizontal Movement Segment Crane (93)
Density/Proportion
0,17
0,13
0,10
0,07
0,03
0,00
10.50 20.50 30.50 40.50 50.50 60.50 70.50 80.50
Interval Midpoint
16 intervals of width 5
1 - Weibull(E)

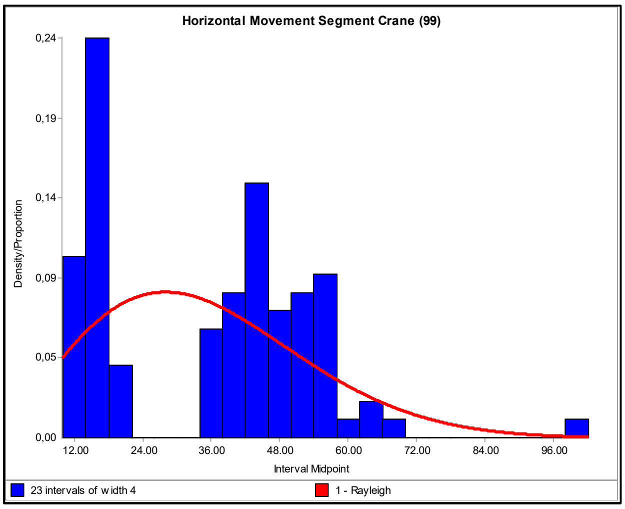

Horizontal Movement Segment Crane (94)
Density/Proportion
6,49
5,19
3,90
2,60
1,30
0,00
14.50 41.50 68.50 95.50 122.50 149.50 176.50 203.50
Interval Midpoint
22 intervals of width 9
2 - Beta

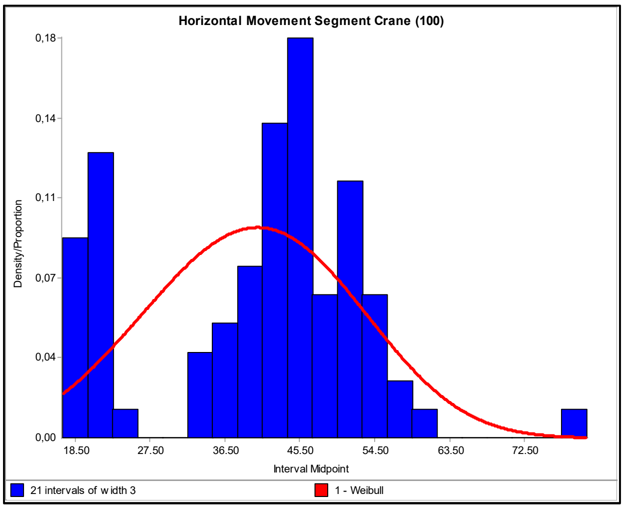

Horizontal Movement Segment Crane (95)
Density/Proportion
Interval Midpoint
15 intervals of width 6
2 - Beta

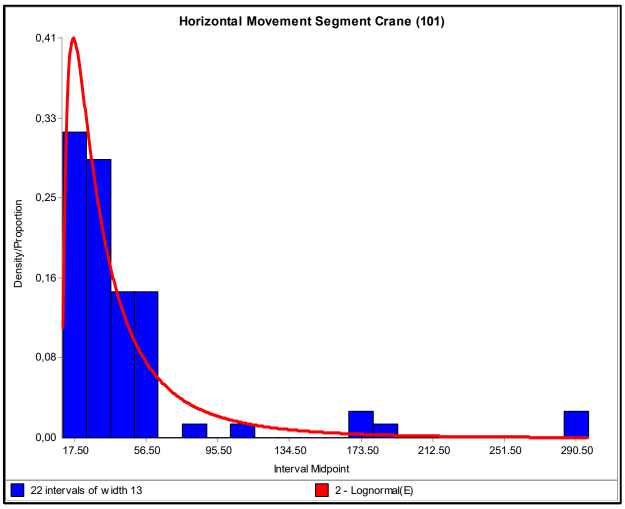

Horizontal Movement Segment Crane (96)
Density/Proportion
Interval Midpoint
16 intervals of width 5
1 - Weibull(E)

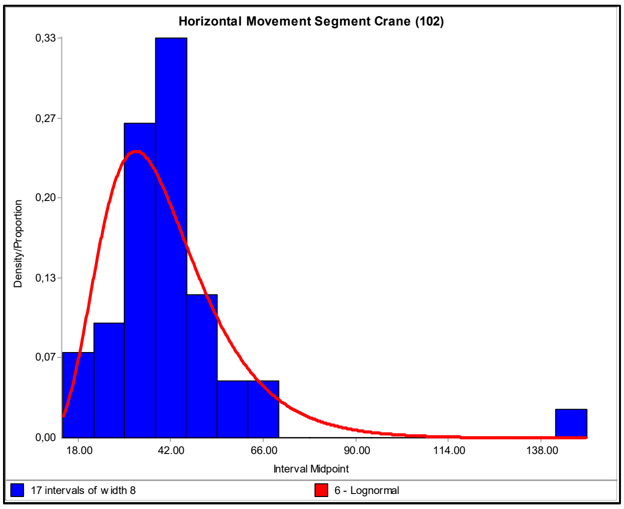

Horizontal Movement Segment Crane (97)
Density/Proportion
Interval Midpoint
15 intervals of width 2
1 - Weibull(E)

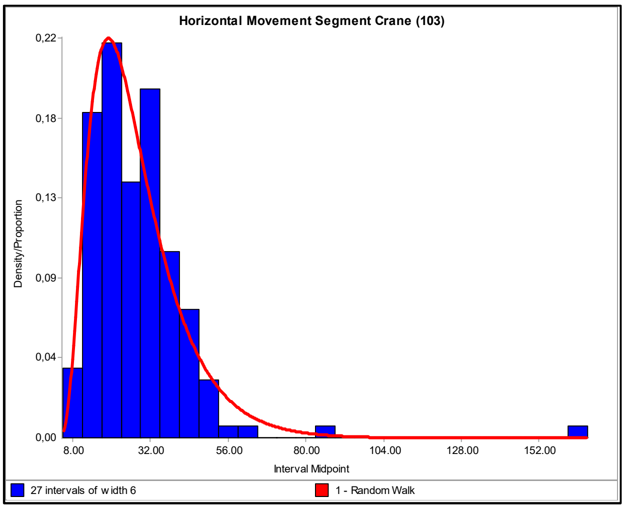

Horizontal Movement Segment Crane (98)
Density/Proportion
Interval Midpoint
20 intervals of width 3
5 - Gamma

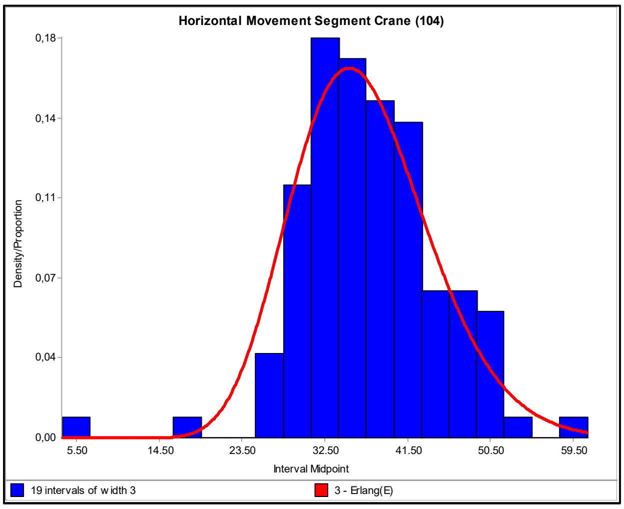

Horizontal Movement Segment Crane (99)
Density/Proportion
Interval Midpoint
23 intervals of width 4
1 - Rayleigh


Horizontal Movement Segment Crane (100)
Density/Proportion
Interval Midpoint
21 intervals of width 3
1 - Weibull


Horizontal Movement Segment Crane (101)
Density/Proportion
0,41
0,33
0,25
0,16
0,08
0,00
17.50
56.50
95.50
134.50
173.50
212.50
251.50
290.50
Interval Midpoint
22 intervals of width 13
2 - Lognormal(E)


Horizontal Movement Segment Crane (102)
Density/Proportion
0,33
0,27
0,20
0,13
0,07
0,00
18.00
42.00
66.00
90.00
114.00
138.00
Interval Midpoint
17 intervals of width 8
6 - Lognormal


Horizontal Movement Segment Crane (103)
Density/Proportion
0,22
0,18
0,13
0,09
0,04
0,00
8.00
32.00
56.00
80.00
104.00
128.00
152.00
Interval Midpoint
27 intervals of width 6
1 - Random Walk


Horizontal Movement Segment Crane (104)
Density/Proportion
0,18
0,14
0,11
0,07
0,04
0,00
5.50
14.50
23.50
32.50
41.50
50.50
59.50
Interval Midpoint
19 intervals of width 3
3 - Erlang(E)

Appendix 6: Analytic Planning Tools

Advance Rate Estimation North Tunnel

Track Chainage From	To	Length [m]	Soil/ Rock Discription	Remarks	Advance Rate [mm/min]	Ringbuild [min]	Exc. Time [min]
10,321.40	10,687.10	365.70	Soil (Residual)	Full Face soil in G VI	15	90	93
10,687.10	10,900.49	213.39	Soil (Residual + Marine	Full face mixed soil (residual +	20	72	70
10,900.49	10,984.01	83.52	Mixed	Mixed face (G V + G III)	10	63	140
10,984.01	11,614.94	630.93	Soil	Full Face soil in G VI	20	54	70
11,614.94	11,667.50	52.56	Mixed	Mixed face (G V + G III)	10	54	140
11,667.50	12,239.66	572.16	Rock	Full face Rock (G II / G III)	25	54	56
12,239.66	12,264.20	24.54	Mixed	Mixed face (G V + G III)	10	54	140
12,264.20	12,425.24	161.04	Soil	Full Face soil in G VI	35	54	40
12,425.24	12,533.48	108.24	Mixed	Mixed face (G V + G III)	10	45	140
12,533.48	12,616.97	83.49	Soil	Full Face soil in G VI	40	45	35
12,616.97	12,790.01	173.04	Mixed	Mixed face (G V + G III)	15	45	93
12,790.01	13,118.00	327.99	Soil	Full Face soil in G VI	40	45	35
13,118.00	13,198.43	80.43	Mixed	Mixed face (G V + G III)	15	45	93
13,198.43	13,340.69	142.26	Rock	Full face Rock (G II / G III)	25	45	56
13,340.69	13,370.31	29.62	Mixed	Mixed face (G V + G III)	15	45	93
Total Length		**3,048.91**					
Ring Length		1.40					
Number of Rings:		2178					

Cycle time [min]	Util. Rate [%]	work time [h]	Raw util rat [%]	Maintenance / day [min]	Downtime / day [min]	Rings / day [-]	advance/ day [m]	section duration [days]
183	40%	9.6	48%	240	1194.24	3.1	4.40	83.1
142	50%	12	60%	240	1192.8	5.1	7.10	30.1
203	50%	12	60%	240	1192.8	3.5	4.97	16.8
124	55%	13.2	66%	240	1192.08	6.4	8.94	70.6
194	50%	12	60%	240	1192.8	3.7	5.20	10.1
110	50%	12	60%	240	1192.8	6.5	9.16	62.4
194	65%	15.6	78%	240	1190.64	4.8	6.75	3.6
94	65%	15.6	78%	240	1190.64	10.0	13.94	11.6
185	65%	15.6	78%	240	1190.64	5.1	7.08	15.3
80	70%	16.8	84%	240	1189.92	12.6	17.64	4.7
138	75%	18	90%	240	1189.2	7.8	10.93	15.8
80	70%	16.8	84%	240	1189.92	12.6	17.64	18.6
138	65%	15.6	78%	240	1190.64	6.8	9.47	8.5
101	70%	16.8	84%	240	1189.92	10.0	13.97	10.2
138	70%	16.8	84%	240	1189.92	7.3	10.20	2.9
						Total Duration		12.1 months

	Adv. Rate [mm/min]	Ringbuild [min]	Exc. Time [min]	Cycle time [min]	Util. Rate [%]	Work [h]	Raw ut. rate [%]	Maint. / d [min]	Downt. / d [min]	Rings / d [-]	advance/ d [m]
min	10.00	45.00	35.00	80.00	0.40	9.60	48%	240	1189.20	3.14	4.40
max	40.00	90.00	140.00	203.00	0.75	18.00	90%	240	1194.24	12.60	17.64
avg	22.72	57.03	71.55	128.6	0.57	13.66	68%	240	1191.80	7.05	9.86

Advance Rate Estimation South Tunnel

Track Chainage		Length [m]	Soil/ Rock Discription	Remarks	Advance Rate	Ringbuild	Exc. Time
From	To				[mm/min]	[min]	[min]
10,323.22	10,671.07	347.84	Soil (Residual)	Full Face soil in G VI	15	90	93
10,671.07	10,915.42	244.35	Soil (Marine Clay +	Full face Mixed soil in GVI +	20	72	70
10,915.42	10,958.56	43.14	Mixed	Mixed face (G V + G III)	10	63	140
10,958.56	11,623.66	665.10	Soil	Full face soil (G V/ VI)	20	54	70
11,623.66	11,670.04	46.38	Mixed	Mixed face (G V + G III)	10	54	140
11,670.04	11,790.67	120.63	Rock	Rock (Granite)	25	54	56
11,790.67	11,883.46	92.79	Mixed	Mixed face (G V + G III)	10	54	140
11,883.46	12,208.21	324.75	Rock	Rock (Granite)	35	54	40
12,208.21	12,229.84	21.63	Mixed	Mixed face (G V + G III)	10	45	140
12,229.84	12,378.28	148.44	Soil	Full face soil (G V/ VI)	40	45	35
12,378.28	12,740.14	361.86	Mixed	Mixed face (G V + G III)	15	45	93
12,740.14	13,089.64	349.50	Soil	Full face soil (G V/ VI)	40	45	35
13,089.64	13,160.56	70.92	Mixed	Mixed face (G V + G III)	15	45	93
13,160.56	13,330.87	170.31	Rock (Granite)	Rock (Granite)	25	45	56
13,330.87	13,382.66	51.79	mixed face (Soil +rock)	Mixed face (G V + G III)	15	45	93
Total Length		**3,059.44**					
Ring Length		1.40					
Number of Rings:		2185					

Cycle time	Util. Rate	work time	Raw util rat	Maintenance / day	Downtime / day	Rings / day	advance/ day	section duration
[min]	[%]	[h]	[%]	[min]	[min]	[-]	[m]	[days]
183	40%	9.6	48%	240	1194.24	3.1	4.40	79.1
142	50%	12	60%	240	1192.8	5.1	7.10	34.4
203	50%	12	60%	240	1192.8	3.5	4.97	8.7
124	55%	13.2	66%	240	1192.08	6.4	8.94	74.4
194	50%	12	60%	240	1192.8	3.7	5.20	8.9
110	50%	12	60%	240	1192.8	6.5	9.16	13.2
194	65%	15.6	78%	240	1190.64	4.8	6.75	13.7
94	65%	15.6	78%	240	1190.64	10.0	13.94	23.3
185	65%	15.6	78%	240	1190.64	5.1	7.08	3.1
80	70%	16.8	84%	240	1189.92	12.6	17.64	8.4
138	75%	18	90%	240	1189.2	7.8	10.93	33.1
80	70%	16.8	84%	240	1189.92	12.6	17.64	19.8
138	65%	15.6	78%	240	1190.64	6.8	9.47	7.5
101	70%	16.8	84%	240	1189.92	10.0	13.97	12.2
138	70%	16.8	84%	240	1189.92	7.3	10.20	5.1
						Total Duration		11.5 months

	Adv. Rate	Ringbuild	Exc. Time	Cycle time	Util. Rate	Work	Raw ut. rate	Maint. / d	Downt. / d	Rings / d	advance/ d
	[mm/min]	[min]	[min]	[min]	[%]	[h]	[%]	[min]	[min]	[-]	[m]
min	10.00	45.00	35.00	80.00	0.40	9.60	48%	240	1189.20	3.14	4.40
max	40.00	90.00	140.00	203.00	0.75	18.00	90%	240	1194.24	12.60	17.64
avg	23.38	56.40	71.05	127.4	0.60	14.48	72%	241	1195.46	7.59	10.63

Transport Volume Calculation

Transport Volume Calculation **Example Project**

PROJECT

LOGISTICS - INPUT DATA

Input data

Bulk muck volume / ring	=	72.9 m³

Average Performance

Advance Speed	v_a	=	23 mm/min
Ringbuilding time	t_r	=	57 min
Excavation time	t_e	=	71 min
Cycle time	t_z	=	128 min
Gross tunnelling time	t_v	=	20 h
Maintenance/day	t_m	=	4 h
Other operations influence	HF	=	68%
No. of rings / day	N_r	=	6.4 rings

Maximum Performance

Advance Speed	v_a	=	40 mm/min
Ringbuilding time	t_r	=	45 min
Excavation time	t_e	=	35 min
Cycle time	t_z	=	80 min
Gross tunnelling time	t_v	=	20 h
Maintenance/day	t_m	=	4 h
Other operations influence	HF	=	90%
No. of rings / day	N_r	=	13.5 rings

TBM BELT CONVEYOR

Input data

Average muck flow	Q_e	=	62 m³/h	*at 3300mm/min, average advance speed*
Maximum muck flow	Q_{emax}	=	125 m³/h	*at REFmm/min, maximum advance speed*
Muck volume / ring		=	72.9 m³	
Bulk material density	ρ_e	=	1.8 t/m³	

Belt conveyor calculation

Belt width	=	800 mm
Belt speed*	=	2.5 m/s
Belt capacity	=	810 t/h
	=	450 m³/h

TRAIN CONFIGURATION

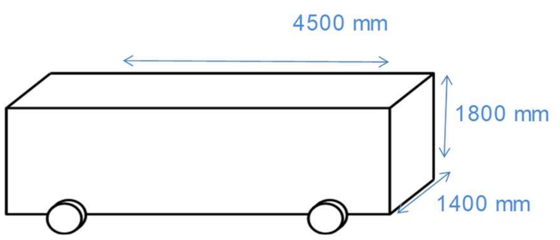
Train Patterns

Number of train / ring	=	2 No.				
Train A	=	1 Train	4 No.	Muck Cars	every	1 Ring(s)
			1 No.	Locomotive		
Both			1 No.	Segment Car		
-			1 No.	Grout Car		
Train B	=	1 Train	4 No.	Muck Cars		1 Ring(s)
			1 No.	Locomotive		
			1 No.	Segment Car		
			1 No.	Flat Car		

TRAIN LOGISTIC - MUCKING OUT

Input data

Bulk muck volume / ring	=	72.9 m³



Muck cars dimension

Width	=	1400 mm
Height	=	1800 mm
Length	=	4500 mm
Muck car max volume	=	11.3 m³
Filling rate	=	90%
Muck car capacity at 90 %	=	10.2 m³

Requirement

Required number of muck car	=	8 No.
Number of muck car / train	=	4 No.

TRAIN LOGISTIC - SEGMENT DELIVERY

Data

Segment OD	$Ø_{SOD}$	=	6.35 m	Segment weight	M_S	=	3.44 t
Segment ID	$Ø_{SID}$	=	5.80 m	Keystone weight	M_{KS}	=	1.15 t
Segment length	L_S	=	1.40 m	Segments per Stack	$n_{S,stack}$	=	3 No.
Segment configuration		=	5 + 1	Number of segment cars	n_{cars}	=	2
Number of Segments	n_S	=	6				

TUNNEL INFRASTRUCTURE

Data	Length	Amount	Type	Weight
Train Rail	6 m	2 No.	S49, 6m	35kg/m
Gantry Rail (circulated)	6 m	2 No.	S49, 6m	35kg/m
Ventilation Duct	100 m	1 No.	D800	300kg
HV Cable	150 m	1 No.	D50	900kg
Tunnel Pipe	6 m	4 No.	ø 100 mm	10kg/m
Walkway Material	4 m	1 No.	path, handrail, bolts	

TAIL VOID GROUTING

Grout Requirtements				Grout Transfer Pump		
Annular volume / ring	V_A	=	4.29 m³	Pump type	=	KSP 25
Safety coefficient	s_{f1}	=	1.2	Max pressure	=	30 bar
Tail Void Grout	$V_{MTreq.}$	=	5.1 m³	Pump capacity	=	24 m³/h
Mortar tank provided	V_{MT}	=	6 m³	Number of pump	=	1 No.
				Total pumping capacity	=	24 m³/h
				Transfer pumping duration	=	13 min

CONSUMABLES & WEAR PARTS

Consumables per ring			Wear Parts per ring		
Tenside	=	0.109 m³	Disc Cutters	=	0.4 No
Lub. Grease	=	4.8 L	SG Tools	=	0.2 No
Tailskin Grease	=	72.66 kg	*(from CSM model estimation)*		

STORAGE VOLUMES ON TBM & TRANSPORT BATCH SIZES

Material	Type	Batch Size		Storage Vol on TBM		
Muck	Bulk	Muck C	of 10.2 m³	0 Muck Car	of	10.2 m³
Segments	6	Stacks	of 3 pcs	2 Stacks	of	3 pcs
Train Rail	S49, 6m	Bundle:	of 6 pcs	2 Bundles	of	6 pcs
Gantry Rail (circulated)	S49, 6m	Bundle:	of 2 pcs	3 Bundles	of	2 pcs
Ventilation Duct	D800	Casset	of 1 pcs	0 Cassettes	of	1 pcs
HV Cable	D50	Drums	of 1 pcs	0 Drums	of	1 pcs
Tunnel Pipe	ø 100 mm	Bundle:	of 6 pcs	2 Bundles	of	6 pcs
Walkway Material	path, handrail, bolts	Sets	of 1 pcs	3 Sets	of	1 pcs
Tenside	foam agent	Contai	of 1000 l	1 Containers	of	1000 l
Lub. Grease	div	Barrels	of 200 l	2 Barrels	of	200 l
Tailskin Grease	div	Barrels	of 200 kg	3 Barrels	of	200 kg
Tail Void Grout	single component	Tanks	of 6 m³	1 Tanks	of	6 m³

TRAIN LOGISTIC - GOODS ARRIVAL / DEPARTURE FREQUENCY ESTIMATION

Material	Per Ring	Bring	Unit		Size		Frequency		Train
Muck	73 m³	4	Muck Car	of	10.2 m³	every	0.5 rings	on	Both
Segments	6 pcs	1	Stacks	of	3 pcs	every	0.5 rings	on	Both
Train Rail	0.47 pcs	1	Bundles	of	6 pcs	every	13 rings	on	Train A
Gantry Rail (circulated)	0.47 pcs	1	Bundles	of	2 pcs	every	4 rings	on	Both
Ventilation Duct	0.014 pcs	1	Cassettes	of	1 pcs	every	71 rings	on	Train A
HV Cable	0.01 pcs	1	Drums	of	1 pcs	every	107 rings	on	Train A
Tunnel Pipe	0.93 pcs	2	Bundles	of	6 pcs	every	13 rings	on	Train A
Walkway Material	0.35 pcs	2	Sets	of	1 pcs	every	6 rings	on	Train A
Tenside	0.11 cont.	1	Containers	of	1000 l	every	9 rings	on	Train A
Lub. Grease	0.02 barrels	1	Barrels	of	200 l	every	42 rings	on	Train A
Tailskin Grease	0.36 barrels	2	Barrels	of	200 l	every	6 rings	on	Train A
Tail Void Grout	5.1 m³	1	Tanks	of	6 m³	every	1 rings	on	Train B

SITE CONSUMPTION ESTIMATE

No. Of TBMs on site:	2

Material	Per Ring	Daily Avg/TBM	Daily Maximum/TBM	Daily Maximum/Site
Muck	73 m³	465 m³	985 m³	1969 m³
Segments	6 pcs	38 pcs	81 pcs	162 pcs
Train Rail	0.47 pcs	2.98 pcs	6.30 pcs	12.60 pcs
Gantry Rail (circulated)	0.47 pcs	-	-	-
Tenside	0.11 cont.	0.70 cont.	1.48 cont.	2.95 cont.
Lub. Grease	0.02 barrels	0.15 barrels	0.32 barrels	0.65 barrels
Tailskin Grease	0.36 barrels	2.32 barrels	4.90 barrels	9.81 barrels
Tail Void Grout	5.1 m³	32.8 m³	69.5 m³	138.9 m³
Ventilation Duct	0.014 pcs	0.1 m³	0.2 m³	0.4 pcs
HV Cable	0.01 pcs	0.1 m³	0.1 m³	0.3 pcs
Tunnel Pipe	0.93 pcs	6.0 m³	12.6 m³	25.2 pcs
Walkway Material	0.35 pcs	2.2 m³	4.7 m³	9.5 pcs

SITE DELIVERY & STORAGE

Material	Capacity	Comments	per Truck	Trucks		Frequency
Muck	800 m³	Muckpit 20mx8mx5m	14 m³	141	every	1 day(s)
Segments	240 pcs	400m² storage area	6 pcs	27	every	1 day(s)
Train Rail	600 pcs	in general storage area	36 pcs	2	every	7 day(s)
Gantry Rail (circulated)	-	rotating in TBM Backup Area	-	0	every	-
Tenside	50.00 cont.	Barrel & Container storage area	12.00 cont.	2	every	8 day(s)
Lub. Grease	30 barrels	Barrel & Container storage area	20 barrels	1	every	30 day(s)
Tailskin Grease	60 barrels	Barrel & Container storage area	20 barrels	2	every	4 day(s)
Tail Void Grout	300 m³	Grout Silo in Batching Plant	10 m³	14	every	1 day(s)
Ventilation Duct	10 pcs	in general storage area	6 pcs	1	every	16 day(s)
HV Cable	10 pcs	in general storage area	4 pcs	1	every	16 day(s)
Tunnel Pipe	1000 pcs	in general storage area	500 pcs	2	every	40 day(s)
Walkway Material	400 pcs	in general storage area	200 pcs	1	every	21 day(s)

Processes Durations in Average Performance TBM Cycle

TBM AVG PERFORMANCE										
			Cycle n		Cycle n+1		Cycle n+2		Cycle n+3	
Resource	Resource	Duration	Start	End	Start	End	Start	End	Start	End
Excavation	TBM	35.5	10	46	53	89	146	181	188	224
Ringbuilding	ER	57	0	0	89	146	0	0	224	281
Transfer Segment 1	SC	4.5	10	15	0	0	146	150	0	0
Transfer Segment 2	SC	4.5	15	19	0	0	150	155	0	0
Transfer Segment 3	SC	4.5	19	24	0	0	155	159	0	0
Transfer Segment 4	SC	4.5	0	0	53	58	0	0	188	193
Transfer Segment 5	SC	4.5	0	0	58	62	0	0	193	197
Transfer Segment 6	SC	4.5	0	0	62	67	0	0	197	202
Unload TrainRails	SC	2.9	24	27	0	0	0	0	0	0
Unload Gantry Rails	SC	2.9	27	30	0	0	0	0	0	0
Build Rails	SC	18.5	0	0	89	107	0	0	0	0
Unload Walkway Material	RC	2.9	1	4	0	0	0	0	0	0
Build Walkway	MAN	24.0	0	0	89	113	0	0	0	0
Unload Tunnel Pipes	RC	2.9	4	7	0	0	0	0	0	0
Extend Tunnel Pipes	MAN	18.2	0	0	113	131	0	0	0	0
Unload Tailskin Grease	GC	8.1	10	18	0	0	0	0	0	0
Change Tailskin Grease Barrel	GC	8.1	0	0	89	97	0	0	0	0
Unload Lubrication Grease	GC	8.1	18	27	0	0	0	0	0	0
Change Lubrication grease Barrel	GC	8.1	0	0	97	105	0	0	0	0
Unload Tenside	TC	6.7	10	17	0	0	0	0	0	0
Change tenside Container	TC	6.7	0	0	89	95	0	0	0	0
Transfer Grout	GTP	12.8	0	0	53	66	0	0	188	201
Change Train	TRA	3.6	46	49	0	0	181	185	0	0
TrainA drives into Backup System	TRA	3.6	7	10	0	0	142	146	0	0
TrainB drives into Backup System	TRA	3.6	0	0	49	53	0	0	185	188
Train A in TBM	TRA	35.5	10	46	0	0	146	181	0	0
Train B in TBM	TRA	35.5	0	0	53	89	0	0	188	224

Cycle n+4		Cycle n+5		Cycle n+6		Cycle n+7		Cycle n+8		Cycle n+9	
Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
281	316	323	359	416	451	459	494	551	587	594	629
0	0	359	416	0	0	494	551	0	0	629	686
281	285	0	0	416	420	0	0	551	556	0	0
285	290	0	0	420	425	0	0	556	560	0	0
290	294	0	0	425	429	0	0	560	565	0	0
0	0	323	328	0	0	459	463	0	0	594	598
0	0	328	332	0	0	463	468	0	0	598	603
0	0	332	337	0	0	468	472	0	0	603	607
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	607	610	0	0
0	0	0	0	0	0	0	0	0	0	629	648
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	494	518	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	629	648
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	494	502	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	323	336	0	0	459	471	0	0	594	607
316	320	0	0	451	455	0	0	587	590	0	0
277	281	0	0	412	416	0	0	548	551	0	0
0	0	320	323	0	0	455	459	0	0	590	594
281	316	0	0	416	451	0	0	551	587	0	0
0	0	323	359	0	0	459	494	0	0	594	629

Processes Durations in Best Performance TBM Cycle

TBM BEST PERFORMANCE																						
			Cycle n		Cycle n+1		Cycle n+2		Cycle n+3		Cycle n+4		Cycle n+5		Cycle n+6		Cycle n+7		Cycle n+8		Cycle n+9	
Resource	**Resource**	**Duration**	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
Excavation	TBM	17.5	10	28	35	53	98	115	122	140	185	202	209	227	272	289	297	314	359	377	384	401
Ringbuilding	ER	45.0	0	0	53	98	0	0	140	185	0	0	227	272	0	0	314	359	0	0	401	446
Transfer Segment 1	SC	4.5	10	15	0	0	98	102	0	0	185	189	0	0	272	276	0	0	359	364	0	0
Transfer Segment 2	SC	4.5	15	19	0	0	102	107	0	0	189	194	0	0	276	281	0	0	364	368	0	0
Transfer Segment 3	SC	4.5	19	24	0	0	107	111	0	0	194	198	0	0	281	285	0	0	368	373	0	0
Transfer Segment 4	SC	4.5	0	0	35	40	0	0	122	127	0	0	209	214	0	0	297	301	0	0	384	388
Transfer Segment 5	SC	4.5	0	0	40	44	0	0	127	131	0	0	214	218	0	0	301	306	0	0	388	393
Transfer Segment 6	SC	4.5	0	0	44	49	0	0	131	136	0	0	218	223	0	0	306	310	0	0	393	397
Unload TrainRails	SC	2.9	24	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unload Gantry Rails	SC	2.9	27	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	397	400	0	0
Build Rails	SC	18.5	0	0	53	71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	401	420
Unload Walkway Material	RC	2.9	1	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Build Walkway	MAN	24.0	0	0	53	77	0	0	0	0	0	0	0	0	0	0	314	338	0	0	0	0
Unload Tunnel Pipes	RC	2.9	4	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extend Tunnel Pipes	MAN	18.2	0	0	77	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	401	420
Unload Tailskin Grease	GC	8.1	10	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Change Tailskin Grease Barrel	GC	8.1	0	0	53	61	0	0	0	0	0	0	0	0	0	0	314	322	0	0	0	0
Unload Lubrication Grease	GC	8.1	18	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Change Lubrication grease Barrel	GC	8.1	0	0	61	69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unload Tenside	TC	6.7	10	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Change tenside Container	TC	6.7	0	0	53	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Transfer Grout	GTP	12.8	0	0	35	48	0	0	122	135	0	0	209	222	0	0	297	309	0	0	384	397
Change Train	TRA	3.6	28	31	0	0	115	119	0	0	202	206	0	0	289	293	0	0	377	380	0	0
TrainA drives into Backup System	TRA	3.6	7	10	0	0	94	98	0	0	181	185	0	0	268	272	0	0	356	359	0	0
TrainB drives into Backup System	TRA	3.6	0	0	31	35	0	0	119	122	0	0	206	209	0	0	293	297	0	0	380	384
Train A in TBM	TRA	17.5	10	28	0	0	98	115	0	0	185	202	0	0	272	289	0	0	359	377	0	0
Train B in TBM	TRA	17.5	0	0	35	53	0	0	122	140	0	0	209	227	0	0	297	314	0	0	384	401

Shaft Cycle Durations for one Ring of Both TBMs

SHAFT CYCLE										
			Cycle n		Cycle n+1		Cycle n+2		Cycle n+3	
Resource	**Resource**	**Duration**	Start	End	Start	End	Start	End	Start	End
TBM1 Train A Shunting	Train	11.1	0	11	44	55	154	165	198	209
TBM1 Train A Mucking	Gantry Crane	32.9	11	44	0	0	165	198	0	0
TBM1 Train A Loading	Mobile Crane	25.1	11	36	0	0	165	190	0	0
TBM2 Train A Shunting	Train	11.1	0	11	77	88	154	165	231	242
TBM2 Train A Mucking	Gantry Crane	32.9	44	77	0	0	198	231	0	0
TBM2 Train A Loading	Mobile Crane	25.1	36	61	0	0	190	215	0	0
TBM1 Train B Shunting	Train	11.1	55	66	110	121	209	220	264	275
TBM1 Train B Mucking	Gantry Crane	32.9	77	110	0	0	231	264	0	0
TBM1 Train B Loading	Mobile Crane	8.4	66	75	0	0	220	229	0	0
TBM2 Train B Shunting	Train	11.1	99	110	143	154	242	253	297	308
TBM2 Train B Mucking	Gantry Crane	32.9	110	143	0	0	264	297	0	0
TBM2 Train B Loading	Mobile Crane	8.4	110	118	0	0	253	261	0	0

Actually Achievable TBM Advance Rates

		Cycle n		Cycle n+1		Cycle n+2		Cycle n+3	
Resource	**Duration**	Start	End	Start	End	Start	End	Start	End
Excavation	17.5	0	18	29	46	132	150	161	178
Ringbuilding	45.0	0	0	46	91	0	0	178	223
Waiting for Train	(secondary)	18	29	91	132	150	161	223	264

Cycle n+4		Cycle n+5		Cycle n+6		Cycle n+7		Cycle n+8		Cycle n+9	
Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
264	282	293	310	0	0	0	0	0	0	0	0
0	0	310	355	0	0	0	0	0	0	0	0
282	293	355	396	0	0	0	0	0	0	0	0

Appendix 7: Simulation Model Parameters

Module	Parameter	Type	Fixed Value	Distribution Parameters
Backup	Storage Capacity Tailskin	parameter	3 pcs	-
Backup	Storage Capacity Lubrication Grease Barrels	parameter	2 pcs	-
Backup	Storage Capacity Tenside	parameter	1 pcs	-
Backup	Storage Capacity Rails	parameter	18 pcs	-
Backup	Storage Capacity Tunnel Pipes	parameter	12 pcs	-
Backup	Storage Capacity Walkways	parameter	4 pcs	-
Backup	Storage Capacity HV Cable	parameter	1 pcs	-
Backup	Storage Capacity Ventilation	parameter	1 pcs	-
Conditioning	Foam Injection Rate	parameter	60%	-
Conditioning	Foam Expansion Rate	parameter	14%	-
Conditioning	Tenside Concentration	parameter	4%	-
Conditioning	Tenside Container Volume	parameter	1000 l	-
Delivery Truck	Driving Speed on Site	parameter	10 km/h	-
Delivery Truck	Storage Capacity Segments	parameter	6 pcs	-
Delivery Truck	Storage Capacity Tailskin	parameter	20 pcs	-
Delivery Truck	Storage Capacity Lubrication Grease Barrels	parameter	20 pcs	-
Delivery Truck	Storage Capacity Tenside	parameter	12 pcs	-
Delivery Truck	Storage Capacity Rails	parameter	120 pcs	-
Delivery Truck	Storage Capacity Tunnel Pipes	parameter	200 pcs	-
Delivery Truck	Storage Capacity Walkways	parameter	100 pcs	-
Delivery Truck	Storage Capacity HV Cable	parameter	2 pcs	-
Delivery Truck	Storage Capacity Ventilation	parameter	6 pcs	-
Delivery Truck	Storage Capacity Grout	parameter	9 m^3	-

Module	Parameter	Type	Fixed Value	Distribution Parameters
Dumptruck	Driving Speed on Site	parameter	10 km/h	-
Dumptruck	Storage Capacity Muck	parameter	12 m^3	-
Erector	Daily Maintenance Duration	duration	4 h	-
Erector	Weekly TBM Downtime	duration	-	-
Erector	Segment Installation Duration	duration	7.5min - 15min	-
Excavator	Advance Speed	parameter	10 - 40mm/min	-
Excavator	Excavation Diameter	parameter	6650 mm	-
Excavator	Bulk Factor	parameter	1.5 [-]	-
Gantry Crane	Hook / Unhook Muck	duration	42 sec	gamma (3.21, 13.16, 0)
Gantry Crane	Vertical Movement Shaft	duration	67 sec	log-logistic [64.224826 * exp(log(1 / uniform_pos() - 1) / 6.629405)]
Gantry Crane	Horizontal Movement to Muckpit	duration	60 sec	log-logistic [49.420938 * exp(log(1 / uniform_pos() - 1) / 3.997457)]
Gantry Crane	Empty Muck Container	duration	155 sec	61.288278 + 1 / weibull(3.464262, 0.013719, 0)
Greasecrane	Unload Grease Barrel	duration	484 sec	beta (1.04, 1.01, 169.75, 788.86)
Greasecrane	Change Grease Barrel	duration	484 sec	beta (1.04, 1.01, 169.75, 788.86)
Grout Loading Pump	Transfer Grout to Train	parameter	24 m^3/h	-
Grout Transfer Pump	Transfer Grout to TBM	parameter	24 m^3/h	-
Infrastructure Building	tunnelpipe extension	duration	1090 sec	lognormal (5.7, 1.15, 527)
Infrastructure Building	walkway extension	duration	1440 sec	erlang(524, 2, 391)
Infrastructure Building	HV cable extension	duration	13545 sec	beta (1.33, 2.92, 2002.63, 38805.31)
Infrastructure Building	Vduct Extension	duration	1929 sec	weibull (2, 1949,92, 179,43)
Infrastructure Building	Unload Vduct	duration	included in ext.	included in extension
Infrastructure Building	Unload HV Cable	duration	included in ext.	included in extension
Infrastructure Building	Batch Size Pipe Extension	parameter	2 pcs	-

Module	Parameter	Type	Fixed Value	Distribution Parameters
Infrastructure Building	Batch Size Walkway Extension	parameter	1 pcs	-
Infrastructure Building	Bazch Size HV Cable Extension	parameter	1 pcs	-
Infrastructure Building	Batch Size Ventilation	parameter	1 pcs	-
Infrastructure Building	Batch Size Unload HV Cable	parameter	1 pcs	-
Infrastructure Building	Batch Size Unload Ventilation	parameter	1 pcs	-
Loading Excavator	Bucket Volume	parameter	1.5 m^3	-
Loading Excavator	Filling Bucket	duration	6 sec	-
Loading Excavator	Move and Empty	duration	9 sec	-
Loading Excavator	Reverse	duration	5 sec	-
Lubrication Greasing	Grease Volume Per Hour	parameter	4 l/h	-
Lubrication Greasing	Grease Barrel Volume	parameter	200 l	-
Mobile Crane	Lift / Lower at Storage	duration	28 sec	lognormal (3.01, 0.68, 2.70)
Mobile Crane	Horizontal Movement to/from	duration	35 sec	gamma (5.26, 6.31, 0)
Mobile Crane	Vertical Movement in Shaft	duration	103 sec	log-logistic[61.288278 + 1 / weibull(3.464262, 0.013719, 0)]
Mobile Crane	Hook / Unhook Goods	duration	85 sec	lognormal (4.33, 0.47, 0)
Mobile Crane	Batch Size Segments	parameter	6 pcs	-
Mobile Crane	Batch Size Unload Tailskin	parameter	6 pcs	-
Mobile Crane	Batch Size Unload Lubrication Grease Barrels	parameter	6 pcs	-
Mobile Crane	Batch Size Unload Tenside	parameter	1 pcs	-
Mobile Crane	Batch Size Unload Rails	parameter	30 pcs	-
Mobile Crane	Batch Size Unload Tunnel	parameter	30 pcs	-
Mobile Crane	Batch Size Unload Walkways	parameter	30 pcs	-
Mobile Crane	Batch Size HV Unload Cable	parameter	1 pcs	-
Mobile Crane	Batch Size Unload Ventilation	parameter	1 pcs	-

Module	Parameter	Type	Fixed Value	Distribution Parameters
Railcrane	Batch Size HV Unload Tunnel	parameter	2 pcs	-
Railcrane	Batch Size Unload Walkway	parameter	1 pcs	-
Railcrane	Unload Walkway	duration	173 sec	beta (1.65, 1.32, 51.85, 270.13)
Railcrane	Unload Tunnelpipe	duration	173 sec	beta (1.65, 1.32, 51.85, 270.13)
Rail Network	Length Switch	parameter	60 m	-
Rail Network	Length TBM Track	parameter	60 m	-
Segment Crane	Hook Segment	duration	78 sec	lognormal (3.97, 0.80, 1.72)
Segment Crane	Horizontal Movement	duration	46 sec	lognormal (3.03, 1.03, 9.63)
Segment Crane	Lift / Lower	duration	24 sec	gamma (5.38, 4.38, 0)
Segment Crane	Unhook Segment	duration	91 sec	lognormal (4.16, 0.71, 9.70)
Segment Crane	Lower and Rotate	duration	20 sec	weibull (2,3.93, 16.58)
Segment Crane	Batch Size Unload Rails	parameter	6 pcs	-
Segment Crane	Batch Size Build Gantry Rails	parameter	2 pcs	-
Segment Crane	Batch Size Build Train Rails	parameter	2 pcs	-
Segment Crane	Unload Rails	duration	173 sec	beta (1.65, 1.32, 51.85, 270.13)
Segment Crane	Build Rails	duration	1107 sec	weibull(1.5, 400, 600)
Segment Feeder	Feeding Duration	duration	60 sec	-
Shunting Platform	Shunting Duration	duration	60 sec	-
Surface	Storage Capacity Segments	parameter	240 pcs	-
Surface	Storage Capacity Tailskin	parameter	60 pcs	-
Surface	Storage Capacity Lubrication Grease Barrels	parameter	30 pcs	-
Surface	Storage Capacity Tenside	parameter	50 pcs	-
Surface	Storage Capacity Rails	parameter	600 pcs	-
Surface	Storage Capacity Tunnel Pipes	parameter	1000 pcs	-
Surface	Storage Capacity Walkways	parameter	400 pcs	-
Surface	Storage Capacity HV Cable	parameter	10 pcs	-

Module	Parameter	Type	Fixed Value	Distribution Parameters
Surface	Storage Capacity Ventilation	parameter	10 pcs	-
Surface	Storage Capacity Grout	parameter	800 m^3	-
Surface	Storage Capacity Muck	parameter	300 m^3	-
Surface	Distance Entry Gate to	parameter	80 m	-
Surface	Distance Loading to Exit Gate	parameter	60 m	-
Surface	Queue Size Dump Trucks on	parameter	5 pcs	-
Surface	Queue Size Delivery Trucks on	parameter	5 pcs	-
Tenside Crane	Refill Tenside	duration	400 sec	triangular (300, 600, 400)
Tenside Crane	Unload Tenside	duration	400 sec	triangular (300, 600, 400)
Train	Speed on Switch	parameter	3 km/h	-
Train	Speed on Track Inwards	parameter	10 km/h	-
Train	Speed on track Outwards	parameter	7 km/h	-
Train	Storage Capacity Segments	parameter	3 pcs	-
Train	Storage Capacity Tailskin	parameter	3 pcs	-
Train	Storage Capacity Lubrication Grease Barrels	parameter	2 pcs	-
Train	Storage Capacity Tenside	parameter	1 pcs	-
Train	Storage Capacity Rails	parameter	20 pcs	-
Train	Storage Capacity Tunnel Pipes	parameter	12 pcs	-
Train	Storage Capacity Walkways	parameter	4 pcs	-
Train	Storage Capacity HV Cable	parameter	1 pcs	-
Train	Storage Capacity Ventilation	parameter	1 pcs	-
Train	Storage Capacity Grout	parameter	6 m^3	-
Train	Storage Capacity Muck	parameter	37 m^3	-
Train	Maneuver in Shaft	duration	21 sec	weibull (2.53, 22.73, 0.75)
Train	Couple / Uncouple Cars	duration	201 sec	weibull (2.24, 201.16, 22.84)

Module	Parameter	Type	Fixed Value	Distribution Parameters
Tailskin Greasing	Grease Layer Thickness	parameter	2 mm	-
Tailskin Greasing	Grease Barrel Volume	parameter	200 l	-
Tunnel	Total Number of Rings	parameter	2185 pcs	-
Tunnel	Segment Length	parameter	1400 mm	-
Tunnel	Tunnel Diameter	parameter	6350 mm	-
Tunnel	Length Walkway Section	parameter	4000 mm	-
Tunnel	Length Tunnel Pipe Section	parameter	6000 mm	-
Tunnel	Length Rail Section	parameter	6000 mm	-
Tunnel	Length HV Cable Section	parameter	150000 mm	-
Tunnel	Length Ventilation Duct	parameter	100000 mm	-

Appendix 8: Curiculum Vitae

Family Name:	Duhme
First Name:	Jerome Ruben Maria
Date of Birth:	5. September 1984
Place of Birth:	Hamburg, Germany
Nationality:	German

Education:

2012 – 2017	Doctoral Student – Ruhr-University Bochum, Institute for Tunnelling and Construction Management, Bochum, Germany
2004 – 2010	Master of Mechanical Engineering – Technical University Munich, Germany

Career History:

Jan. 2017 – now	General Manager Engineering - Herrenknecht Asia Headquarters Pte. Ltd., Singapore
Apr. 2014 – Dec. 2017	Head of R&D Asia - Herrenknecht Tunneling Equipment Co. Ltd., Guangzhou, China
Nov. 2015 – Apr. 2016	Technical Manager - Herrenknecht Asia Headquarters Pte. Ltd., Singapore
Dez. 2010 - Apr. 2014	Research Engineer - Herrenknecht Asia Headquarters Pte. Ltd., Singapore