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MAINTENANCE OF CUTTING TOOLS IN MECHANISED TUNNELLING - DEVELOPMENT OF A PROCESS SIMULATION MODEL FOR THE SCHEDULING AND EVALUATION OF MAINTENANCE STRATEGIES

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

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Maintenance of Cutting Tools in Mechanised Tunnelling - Development of a Process Simulation Model for the Scheduling and Evaluation of Maintenance Strategies

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List of Abbreviations

#REV	number of cutter head revolutions
AB	Agent-Based
ABI	Abrasiveness Index
AV	abrasion value
AVS	abrasion value steel
bdd	block-definition diagram
CA	Compressed Air
CAI	Cerchar Abrasivity Index
CLI	Cutter Life Index
CSM	Colorado School of Mines
Cu	Geotechnical Uniformity Index
CYCLONE	CYCLic Operations NEtwork
DES	Discrete-Event Simulation
DSM	Double-Shield Machines
EPB	Earth Pressure Balance
eQu	equivalent quartz content
GfT	Gesellschaft für Tribologie
HGB	homogeneous section
JTS	Japanese Tunneling Society
KSM	Combination Shield Machines
LAC	LCPC Abrasivity Coefficent
LCM	Colorado School of Mines a Linear Cutting Machine
LCPC	Laboratoire des Ponts et Chaussées
LF	linear feet
MCS	Monte Carlo Simulation
NDAT	Newly Developed Abrasion Test
NDD	Newly Developed Device
NTNU	Norwegian University of Science and Technology
PSAI	Penn State soil abrasion index

PVS	Parameter Variation Study
RNG	Random Number Generator
rpm	rounds per minute
RUB-TD	RUB-tunnelling device
RUL	Remaining Useful Life
SAT	Soil Abrasion Tester
SATC	Soil Abrasion Testing Chamber
SD	System-Dynamic
sd	sequenze diagrams
SGAT	Soft Ground Abrasion Tester
SGTL	Soft Ground Tool Life
SM	Shield Machines
sm^3/tool	solid-m^3 per tool
stm	state-machine diagrams
SysML	System Modelling Language
TBM	Tunnel Boring Machine
UCS	uniaxial compressive strength
UCS	Erklärung zur Abkürzung erst auf page 29
V&V	Verification and Validation
VNHR	Vicker’s hardness number of rock
VOB	German Contract Conditions

Abstract

In mechanised tunnelling, a high utilisation of the tunnelling machine is important to reach a sufficient productivity in construction. The maintenance of cutting tools is one of the processes, which significantly influences the performance of the project execution. A thorough scheduling of the maintenance processes is therefore necessary to ensure the economic success of the project. In slurry shield tunnelling, monitoring of the tool conditions simultaneous to the main production processes is hardly possible, so that a reliable prediction of the wear rate is required. However, the soil properties as well as the steering parameters, which are needed for the wear prediction, are subject to great uncertainties. These uncertainties must be considered in order to obtain a reliable maintenance schedule. Furthermore, additional boundary conditions influence the feasibility of an intervention at a certain position of the tunnel alignment.

In this thesis, a maintenance scheduling method is developed, which considers the uncertain wear prediction of the cutting tools as well as the project-specific boundary conditions. Process simulation is used to model and analyse the wear of cutting tools and to evaluate different maintenance schedules, since it has been proven useful for the evaluation of complex systems and processes. For the wear prediction, the empirical wear prediction model of Köppl (2014) is implemented. The model developed in this thesis evaluates all cutting tools individually and offers a comprehensible structure to analyse the overall system and dependencies. Furthermore, the model can be used to conduct a variety of analyses to increase the knowledge of the system behaviour and to evaluate different maintenance schedules. Input data can be easily adapted to analyse and compare different projects.

In particular, Monte Carlo Simulations are conducted to consider uncertain input data. The determined maintenance interval, which bases solely on the wear of cutting tools, has to be adapted to the boundary conditions of the project. By evaluating all cutting tools individually, preventive maintenance can be scheduled and adjusted using a correction factor in order to take the uncertainties into account and to adapt the schedule to the risk affinity of the scheduler. Sensitivity analyses are conducted in order to increase the knowledge of the system behaviour and dependencies. These results are further used for verification and validation of the model.

Based on the conducted analyses, a procedure to schedule and improve the maintenance of cutting tools is recommended using the proposed model. In general, a detailed documentation of wear and maintenance will increase the reliability of future maintenance schedules, if the data is properly processed and added to the proposed model.

1 Introduction

1.1 Problem definition

Mechanised tunnelling is proven to be a useful method to construct long tunnels or tunnels in urban areas. However, the initial costs for a tunnel boring machine (TBM) are very high. Therefore, a high utilisation of the machine, hence a high performance, is mandatory in order to achieve an economic project execution.

The total performance of tunnelling projects is determined by the performance of all production processes and the amount of downtime due to disturbances. Figure 1-1 presents the classification of the durations of a sample project that has been evaluated. For this project downtimes account for approximately two thirds of the total project duration. Analysing the downtime in more detail shows that the cause of the downtime can be a variety of the system's elements. Furthermore, a distinction is made between scheduled and unscheduled downtime. Unscheduled downtime is caused by disturbances, e.g. technical failures or insufficient material supply. Scheduled downtime occurs when maintenance is conducted. Both cases have a significant influence on the total project duration.

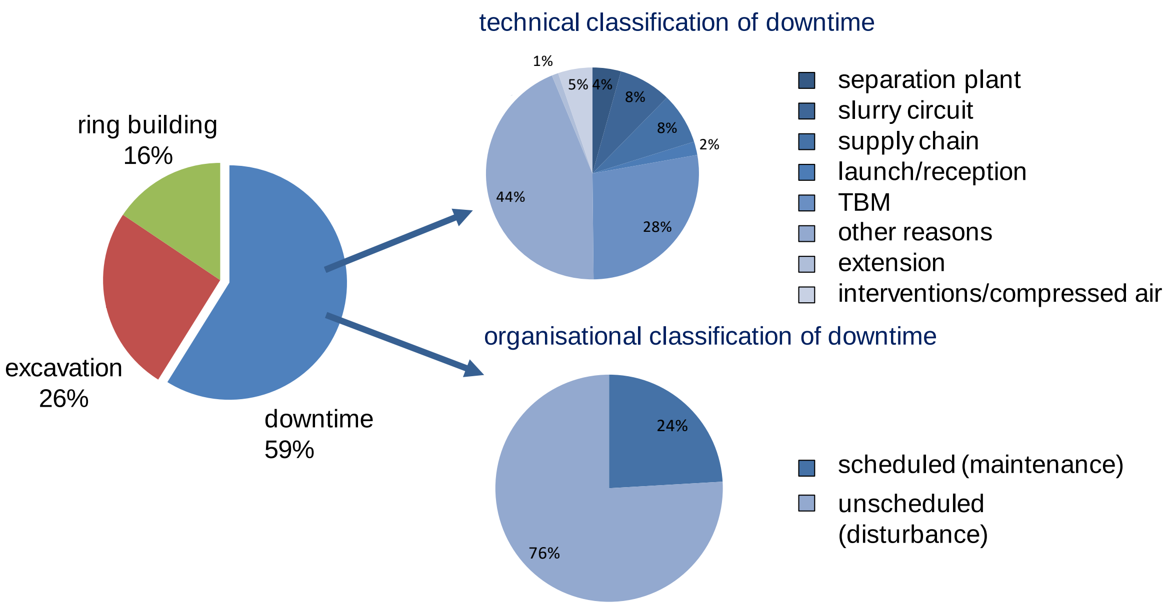


Figure 1-1: Evaluation and classification of the durations of a sample project with a focus on the downtime.

In order to improve the overall performance of the project, it is necessary to improve the productivity of all production processes and to reduce the scheduled and unscheduled downtime. During the planning phase of a project the production processes, in particular the production rate, have to be estimated. Furthermore, the disturbances and maintenance processes have to be predicted and evaluated.

The performance of the excavation process mainly depends on the prevailing ground conditions. For the planning of a project, especially for the excavation of hard rock, there are many prediction models to estimate the possible performance of a tunnel boring machine (TBM) (Gertsch et al. 2007; Hassanpour et al. 2011; Rostami and Ozdemir 2011; Rostami 2016; Schneider et al. 2012; Thuro et al. 2015; Galler et al. 2014). Most of the models determine the possible penetration, which, in combination with the chosen rotational speed, determines the advance rate of a TBM. In addition, some of the performance prediction models consider downtime for the maintenance of cutting tools to reduce the overall performance (Lislerud 1988). Maidl and Wingmann (2009) propose a first approach to estimate the performance of an earth pressure balance (EPB) shield for soft ground excavation. This approach considers not only the advancement speed of the machine but also the duration of ring building and disturbances. For the ring building, the degree of experience is taken into account.

In order to reduce the amount of unscheduled disturbances, Rahm (2017) analysed the disturbances and their cause with the help of process simulation. The developed model can be used to identify the bottleneck of the supply chain, which limits the overall performance. The implemented model also considers the influence of technical disturbances of the system elements. The benefit of planning the supply chain of a tunnelling project has been further investigated by Duhme (2018). He compared the conventional planning method with the simulation approach.

Since the production processes as well as the disturbance are widely discussed and a variety of methods already exist the focus of this thesis lies on the remaining scheduled downtime. Regarding the scheduled downtime, the maintenance of the cutting tools is the most time-consuming process. There is a great potential of decreasing the downtime by improving the maintenance schedule. Hard rock tunnelling machines need a high maintenance effort because of the high wear rate. However, the cutting tools are easily accessible, which enables a regular inspection and replacement of the cutting tools. In soft ground, the planning of maintenance stations for the replacement of cutting tools is more complex and characterised by many uncertainties. The maintenance stops are often planned based on empirical values and according to the project-specific boundary conditions for the accessibility of the excavation chamber. An exact prediction of the expected wear of the mining tools during the planning phase or the continuous monitoring of the wear condition during driving is not possible yet. Binary wear monitoring sensors, which are used on modern TBM, only send a signal, when the wear limits are exceeded. This leads to too many or too few maintenance stops at possibly unfavourable positions of the tunnel alignment.

Models for the empirical wear prognosis of the mining tools allow an initial, quantified estimation of the expected interventions. However, they are subject to great uncertainties, which leads to a large scattering of the prognosis result. Further investigations show that relatively small fluctuations of the soil parameters as well as of the steering parameters may have large effects on the achievable excavation distance until the wear limit is reached. In order to investigate these uncertainties and to take them into account in maintenance scheduling, the wear for each tool under fluctuating conditions must be determined. A purely deterministic planning of the maintenance work does not lead to reliable results.

1.2 Research goals and methodology

The objective of this thesis is to develop an approach for improving the maintenance schedule for soft ground TBM tunnelling. The method shall consider the uncertainties of the influencing parameters and the boundary conditions of individual projects. Furthermore, it has to offer an opportunity to evaluate different maintenance strategies. Therefore, a comprehensible and flexible model is required to conduct a variety of experiments. This way it shall support the decision-making process for maintenance scheduling.

Based on a literature review, suitable methodologies are identified, which can be adapted for the maintenance scheduling of cutting tools. Currently, the wear prediction model of Köppl (2014) is the most suitable method in slurry shield tunnelling for wear prediction of each individual cutting tool on the cutterhead. A simulation-based approach has been chosen to model the variety of elements and processes. Process simulation is a reliable tool to evaluate the productivity of single processes and of the whole system. Furthermore, it offers the opportunity to implement and evaluate uncertain data. The simulation framework AnyLogic is used, since it offers a multi-method implementation. This way, structured modelling is possible, which increases the comprehensibility of the system and the analyses. Parameter variation studies and Monte Carlo simulations are conducted to gain a better understanding of the system and to evaluate the maintenance schedule of a project. Cost factors are added to the model in order to estimate the maintenance costs. The maintenance costs combine both evaluation criteria, maintenance duration and number of replaced tools, hence the evaluation only bases on one value. This simplifies the evaluation of results and the optimisation of the maintenance strategy.

1.3 Structure of the thesis

In a first step, a review of the background and former research is conducted. Therefore, in chapter 2, the processes of mechanised tunnelling are analysed first. The difference between the main types of tunnelling machines are evaluated and classified. Afterwards, the basic principles of process simulation are reviewed in order to find a suitable method for the comprehensible evaluation of maintenance strategies. Process simulation offers the possibility to implement complex systems with uncertain parameters and to evaluate them in a comprehensible way. This way, it is not only possible to compare alternatives, but also to perform sensitivity analyses or optimisations. In order to develop a model for maintenance scheduling, input data is required. For this purpose, the data that result from project execution and methods for data processing are analysed.

For scheduling the maintenance work, a prediction of the wear of the cutting tools is required. The research on wear of cutting tools is reviewed in chapter 3, in order to find a suitable prediction method that can be used for the model generation. Furthermore, the different wear mechanisms that occur and the resulting wear pattern of the cutting tools are investigated. A great variety of different approaches to predict the wear of the cutting tools have been found and are discussed. The wear prediction, which shall be used for the developed model, needs to be quantitative and it has to offer the possibility to determine the wear state of each tool at each point in time individually.

At last, the background of maintenance is reviewed in chapter 4. The basic methods of maintenance in general are analysed in order to find suitable methods that can be adapted to the cutting tool replacement. The processes of the maintenance work have been identified and process durations are defined. Furthermore, the boundary conditions, which have to be considered for maintenance scheduling, are reviewed. At last, evaluation criteria and methods for the maintenance schedule are identified and evaluated.

Based on the background review, a simulation model is developed which stochastically depicts the wear of each tool on the cutting wheel. With this model, the maintenance schedule can be examined and evaluated according to the accuracy of the wear prognosis. In chapter 5, the input parameters and boundary conditions of the maintenance-scheduling model are identified. Afterwards, the implemented wear prognosis method is analysed with respect to the level of detail of the given input data. Subsequently, the development and implementation of the simulation model is provided. Therefore, the theoretical structure and build of the model, the implementation and the chosen simulation experiments are described.

The presented model is then used to perform a variety of analyses described in chapter 6. First sensitivity analyses of the wear prediction model alone and then of the evaluation of the maintenance model are conducted. This way, the behaviour of the system, as well as the model can be evaluated. Furthermore, the sensitivity analyses are used to verify the implemented model. Afterwards, the model is used for a case study, where two different project setups are compared and the robustness of the variants is evaluated. In order to verify and validate the proposed model, the verification and validation methods are reviewed and applied as far as possible based on the results of the previous investigations. The chapter closes with a discussion of the conducted analyses and gained results.

The overall findings of the modelling and analysis are summarised in chapter 7 and recommendations for the application in practice are given. In the concluding chapter 8 a summary and an outlook are given.

2 Processes and simulation in mechanised tunnelling

TBM tunnelling enables high performances due to the high degree of mechanisation. In particular, the repeating processes of excavation and ring building lead to a higher performance than conventional tunnelling methods. However, due to the high initial cost of the machine, a high degree of utilization is mandatory to ensure the economical success of the project. Therefore, an improvement of all relevant processes is necessary to reduce the downtime of the machine.

In order to identify the factors that determine the performance, the processes of mechanised tunnelling projects are reviewed. The performance of each process is quantified by evaluating former projects. Furthermore, process simulation, which is a tool to analyse the interaction of processes, i.e. the behaviour of a system, is introduced. Its application as a method to analyse the factors influencing the overall performance is reviewed. Furthermore, the processing of the different types of data derived from tunnelling projects is presented, which are needed for the simulation model to create valid results.

2.1 Processes in mechanised tunnelling

In mechanised tunnelling, there are four main types of tunnelling machines, which are used for different ground conditions (DAUB 2010). In hard rock, tunnel boring machines (TBM) or double-shield machines (DSM) are used, while in unstable ground conditions, i.e. soil, shield machines (SM) or combination shield machines (KSM) are required, which support the excavated cavity with the help of a cylindrical steel tube as well as the tunnel face using different support media. Furthermore, a segmental lining is mounted under the protection of the shield to ensure a permanent support of the tunnel cavity. (Maidl et al. 2013)

The performance of a tunnelling project mainly depends on the performance of the production processes. Here it is differentiated between production processes that are directly needed for the excavation and construction of the tunnel and support processes that only indirectly influence the productivity but are still mandatory for the execution of the production processes. However, disturbances caused by technical failure or insufficient support processes reduce the overall productivity significantly. Therefore, not only single processes have to be regarded, but also the interaction and dependencies of all processes.

2.1.1 Production processes

The production processes can be divided into the two main processes excavation and ring building. These two processes are essential to build a tunnel structure. In addition, there are minor processes that have to be conducted as they are indispensable for the overall production. These processes are directly needed for the main processes excavation and ring building. Since they are planned interruptions of the main processes, they are regarded as individual, repetitive parts of the construction chain (Figure 2-1).

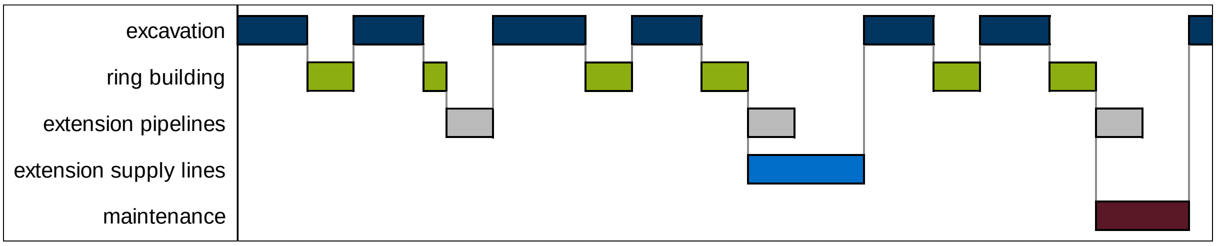


Figure 2-1: Gantt chart of repetitive construction processes.

Ring building

The tunnel lining consists of precast reinforced concrete segments. These segments form a ring, whose width defines the length of one excavation step L_{adv}. One excavation step and one mounted ring are one advance cycle. As shown in Figure 2-2, the ring is mounted under the protection of the shield tail (1) of the tunnelling machine. An erector (2) places the segments at their designed position, where they are temporarily fixated by the thrust cylinders (3). The last mounted ring (4) is then used as bearing for the thrust cylinders to push forward during excavation. The gap (5) between the ground and the tunnel lining is continuously filled with mortar or pea gravel during the advancing of the machine.

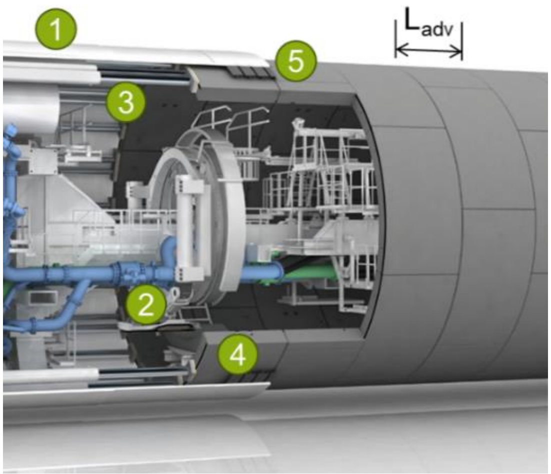


Figure 2-2: Shield tail elements of a tunnelling machine
(based on (Herrenknecht AG 2019c)).

Excavation

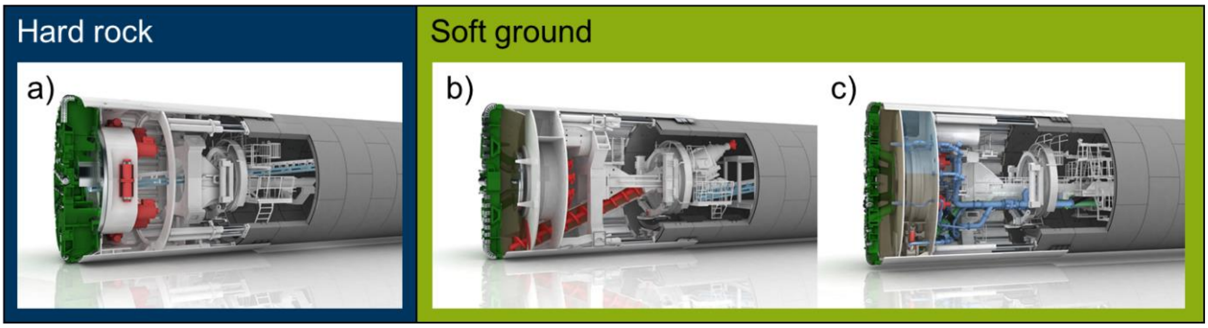


Figure 2-3: a) Single shield TBM; b) EPB shield; c) Hydro shield (pictures from (Herrenknecht AG 2019a, 2019b, 2019c))

The advance rate of the tunnelling machine during the excavation process differs for each type of tunnelling machine and depends on various boundary conditions, e.g. ground conditions or operation parameters. The main machine types are shown in Figure 2-3. If the tunnel face is stable, no face support is needed. In hard rock, the cutting wheel of the TBM is mainly equipped with cutting discs, which excavate the rock by inducing high local pressure on the tunnel face causing cracks to propagate within the rock (Figure 2-4). If the cracks of two tool tracks meet, rock chips are formed and spall off the tunnel face. Buckets mounted on the outer tracks of the cutting wheel transport the excavated chips through the openings behind the cutting wheel, where they are loaded on a belt conveyor. The size of the cutting wheel openings restricts the maximum size of blocks that are able to pass the cutting wheel.

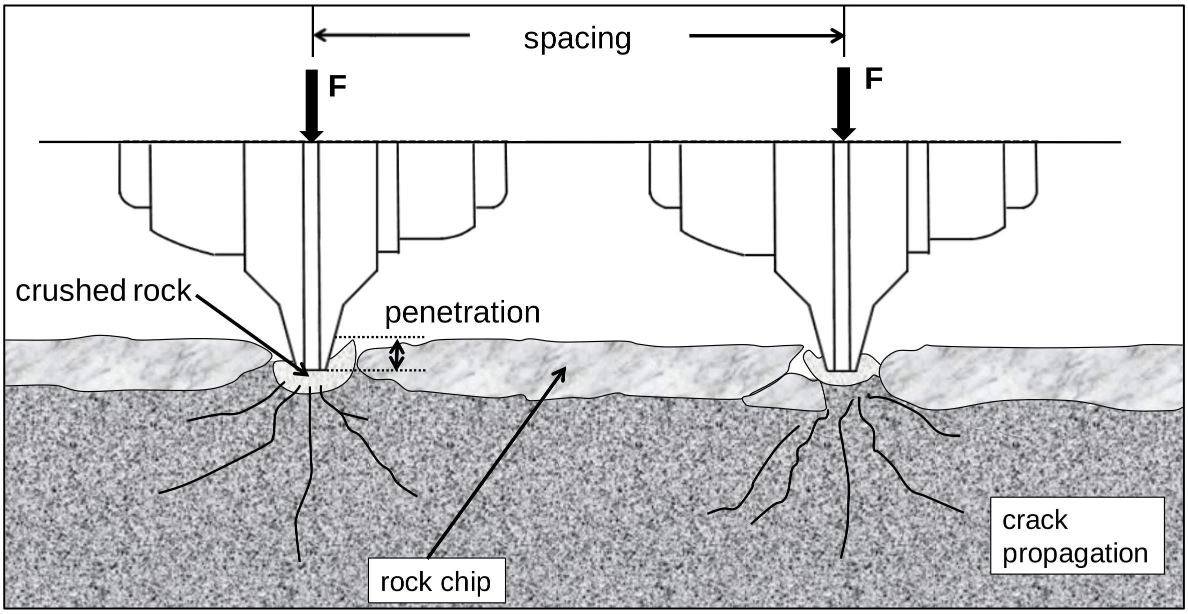


Figure 2-4: Crack propagation and rock chipping for hard rock excavation with disc cutters.

In soft ground, there are two main machine types: earth pressure balance (EPB) shields and hydro shields. The main difference is in the field of application according to the grain size distribution of the soil and the applied face support method. Sometimes, different hybrid machine types are required for special fields of application.

EPB-shields are mainly used in clay and silty soils with a high content of fine particles (< 0.06 mm). If the content of coarse particles increases or adhesion occurs, a conditioning of the soil, for instance with foam, becomes necessary (Budach 2011). The excavation chamber is partly or completely filled with the excavated earth muck, which is used as support medium to support the tunnel face. The support pressure is regulated by the ratio between the excavation speed, i.e. the quantity of material inflow, and the quantity of material outflow through the screw conveyor. Depending on the face stability, there are three different modes of the machine that can be used: open mode, transition mode and closed mode.

Open mode can be used, when the tunnel face does not require any support. The excavation chamber is not filled with earth muck, thus is accessible at all times. However, to avoid ground water inflow, compressed air is applied in the chamber. The transition mode is used if a partly support of the tunnel face is required. Half of the chamber is filled with earth muck. This way, the upper half of the excavation chamber is still accessible. In closed mode, the excavation chamber is completely filled with earth muck to support the unstable tunnel face and avoid settlements. A detailed explanation can be found in Herrenknecht et al. (2011).

Hydro shields are mainly applied in non-cohesive soils, i.e. sand and gravel. The excavation chamber is filled with a pressurized suspension that supports the unstable tunnel face. In most cases, this suspension consists of a bentonite slurry. Applying the support pressure on the tunnel face leads to a filtration of the bentonite particles at the tunnel face. This way, the particles form a filter cake or a penetration zone where the support pressure is transmitted to the soil matrix (Zizka 2019).The pressure is regulated with the help of a compressed air reservoir inside the pressure chamber (DAUB 2016).

Soft ground cutting tools, i.e. scrapers, buckets and ripper tools, excavate the soil. Cutting discs are only needed if boulders are expected, for partial encounter of hard rock layers or for the machine to pass through the concrete walls of shafts or similar obstacles along the tunnel alignment. Detailed explanations of the different kind of cutting tools and their application are given in Section 3.1.2.

Auxiliary production processes

The length of the tunnel increases with the progressing advance. Therefore, all pipelines and cables that are needed for the machine to operate have to be extended after several meters of advancement. An automatic extension of the supply pipes and cables simultaneous to the advance of the machine is limited to the length of extension pipes and cable reels. The main extension cannot take place at the same time as the advance or ring building, since the pipelines and cables are temporarily detached during the extension process. Since they interrupt the alternating cycle of the main processes, their duration must be added to the total project duration.

Further, technical machine parts need to be maintained to ensure their availability and to avoid a failure that leads to an interruption of the production processes. The maintenance of machine parts that are required directly for either excavation or ring building have a large influence on the overall productivity. In particular, the maintenance of the cutting tools is a very time-consuming process, since all other production processes have to be paused. Further details about the maintenance of cutting tools are given in Chapter 4.

2.1.2 Support processes

Support processes are the processes of the supply chain that provide the tunnelling machine with the materials needed and enable the disposal of excavated soil or rock. Hence, they are mainly logistical processes. As shown in Figure 2-5, the area of the actual production is relatively small; hence, the number of support processes is significantly larger than the production processes, which only take place at the TBM. The support processes are categorized as processes of either production logistics or external logistics. The production logistic are those processes of the supply chain that are conducted on the construction side, supplying the production processes. The external logistic consists of the processes for the supply of the construction side and is therefore influenced by the surrounding infrastructure. A more detailed overview of the support processes can be found in Duhme (2018, pp. 41–58).

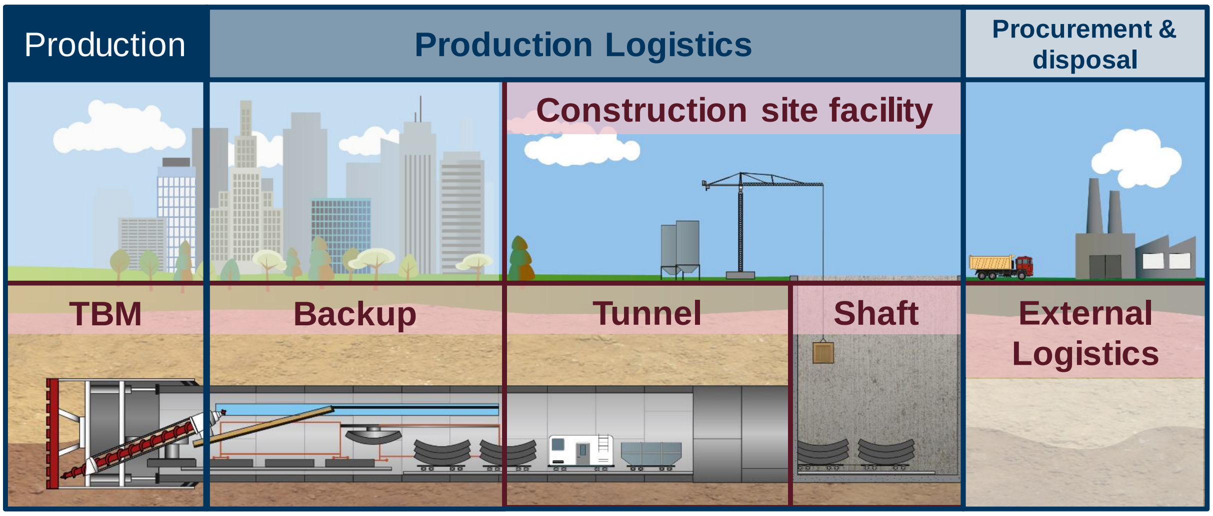


Figure 2-5: Local division of the production and support processes.

In most cases, the support processes have only an indirect influence on the production processes. A disturbance of a support process does not always lead to a disturbance of the production processes. There may be buffers within the supply chain that can compensate a delay of a support process. An evaluation of the supply chain and their disturbances can be found in Rahm et al. (2016) or Rahm (2017).

2.2 Process simulation

Process simulation is a tool to facilitate the analysis of complex systems. A simulation model is a digital representation of a system, which is used to analyse and evaluate a setup or schedule before the execution of a project. It is applied in particular when examinations or experiments of the real system are not possible or too expensive. Digital simulation enables a transparent modelling of the complex interactions and dependencies of the system elements, while considering the system's uncertainties (AbouRizk and Halpin 1992). Furthermore, a variety of experiments can be conducted to understand the system behaviour, identify bottlenecks and to support the decision making process (AbouRizk 2010).

Mechanised tunnelling is a complex system, consisting of a variety of elements, processes and interdependencies and is well suited for the analysis with process simulation. The maintenance process being a part of this complex system and being subject to many uncertainties as well can also be evaluated by using a simulation model. Therefore, the different methods to implement a simulation model are reviewed and the general procedure is presented.

2.2.1 Background

Process simulation has proven useful for scheduling of processes and their optimisation as well as to evaluate different system layouts, e.g. positions of transport routes or storages. It can be used to analyse complex systems with a wide range of system components and processes. Uncertainties of the system parameters can be taken into account while evaluating a system. Several different simulation methods can be used depending on the purpose and the system to be analysed. The main simulation methods that are used for the model development in Chapter 5 are shortly introduced in this section. The procedure to model and analyse a system with the help of process simulation is presented. Depending on the problem statement, different simulation experiments can be conducted to support the decision making process, hence, the types of experiments and their fields of application are discussed.

Simulation methods

Several different simulation methods exist for the evaluation of complex systems. Sometimes a combination of different methods, a hybrid or multi-method model, becomes useful to model a complex system properly. The approach that is presented in this thesis combines an agent-based (AB) approach with discrete-event simulation (DES). Furthermore, system-dynamic (SD) modelling has been proven useful to model the material flow or deterioration processes, in particular wear, of a tunnelling jobsite.

The AB simulation is an object-oriented approach that is very fitting for modelling of construction systems. Each component of the system is modelled as a specific agent so that attributes and processes can be set separately. Putting the components into the same environment, they are able to interact with each other and the environment. This way, the behaviour of the global system results from the individual behaviour of all agents placed into the system. Furthermore, this approach offers the possibility to define the level of detail by defining the boundaries and attributes of the agents, which are hierarchically ordered. The global system is structured by the combination of the defined agents (Borshchev and Filippov 2004).

In DES, possible states of the system or system components are defined. A transition between two states is triggered by a certain event. This event can be the lapse of a time span or the change of a parameter caused by other system components. If no event occurs, the state of the elements remains the same. This is a useful method to model interaction between system components, but also to analyse a project schedule, using this process oriented approach. (Rahm 2017)

The SD approach considers a continuous change in the state of the system. Therefore, the parameters of the system are recalculated after a predefined time step (Borshchev and Filippov 2004). This approach can be used to simulate the dynamical behaviour of a system, e.g. material flow or deterioration processes, where the system state changes even without certain events to occur. As shown in Figure 2-6, it consists of stocks and flows. This way, capturing the actual state at each point in time becomes possible. However, this method causes high computing efforts resulting in long durations for the calculation of the simulation results.

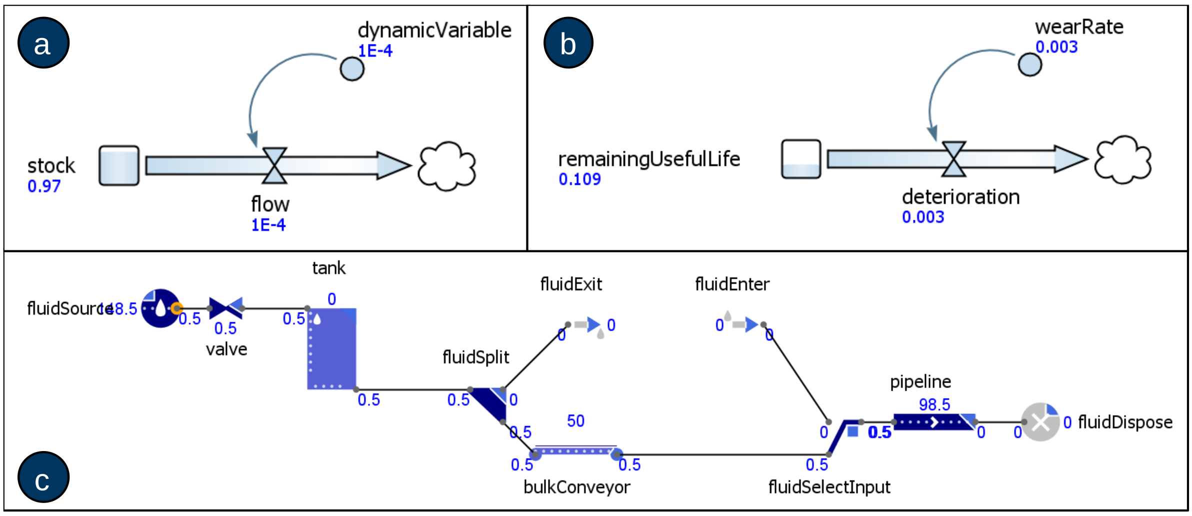


Figure 2-6: a) Stock and flow for the SD modeling and b) the application for wear modelling. c) Material flow with the fluid library of the software tool AnyLogic.

A combination of these methods gives the opportunity to model different behaviours for a variety of system elements and processes that can be found in construction processes. A hybrid modelling approach that combines DES and SD modelling has been proposed repeatedly for construction simulation, to reflect both, the construction schedule and the material flow (Zhou et al. 2009; RazaviAlavi and AbouRizk 2015; Moradi et al. 2015). Further, a combination of all three methods is possible using a multi-method approach (Borshchev 2013). For such an approach, all necessary objects of the construction side are modelled as agents. Their behaviour is given by the processes and states defined with the DES. The material flow within each agent and between different objects is modelled using the SD method (Rahm 2017).

Procedure

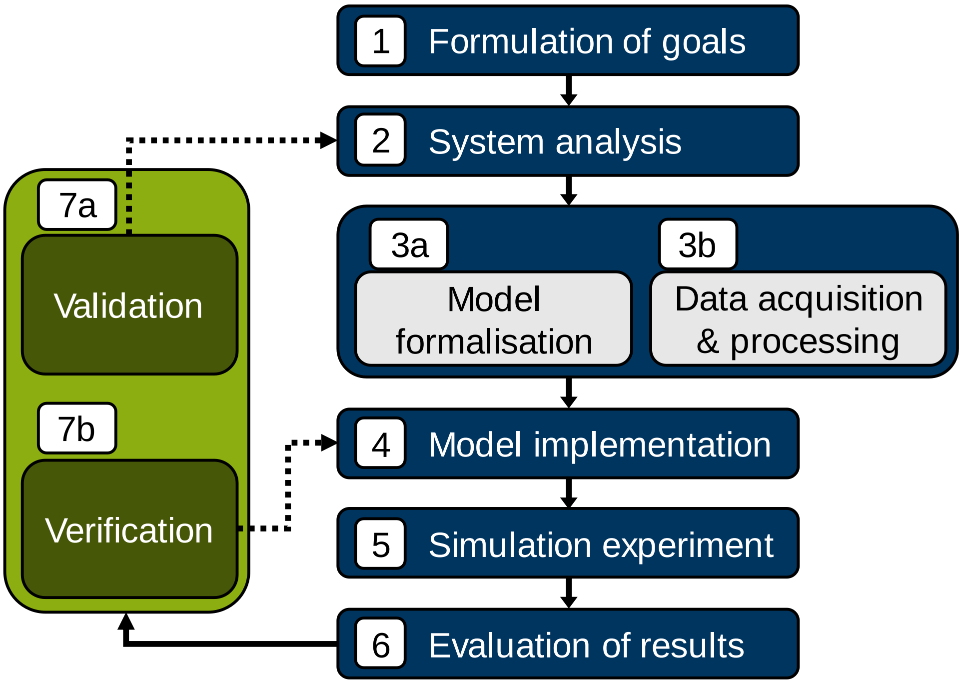


Figure 2-7: General procedure of the development and application of a simulation model.

To evaluate a system with the help of a simulation model, the procedure shown in Figure 2-7 must be followed. The first step is to define the goal of the simulation (1). It is important that the purpose of this investigation as well as the resulting parameters, which are required for the evaluation, are defined beforehand.

Regarding the problem statement, the system is analysed (2). The main components are identified and the level of detail is defined. Furthermore, the boundaries of the system must be set. Depending on the defined goal, a consideration of the whole system is not always required. A simplification of subsystems reduces the modelling effort, but it has to be checked, whether the simplification has an effect on the quality and reliability of the simulation results regarding the defined goals. A hierarchical structure of the model enables a flexible adaptation of system components and the level of detail.

The abstracted system is then formalised (3a) using the System Modelling Language (SysML) (OMG 2017). SysML offers a variety of diagrams to map processes, elements or the structure and interactions of the analysed system. This formalisation simplifies the implementation of the model by structuring it beforehand. This way, the suitable simulation methods can be chosen. For instance, the block-definition diagram (bdd) represents all necessary components that must be integrated into the simulation model for an agent-based approach. Furthermore, state-machine diagrams (stm) can be directly implemented for the corresponding element. Sequence diagrams (sd) are used to describe the interaction of different elements.

During the system analysis and model formalisation, the needed input data is identified and input parameters are defined (3b). Data documentation and evaluation is needed to gain information, for instance about the duration of processes. The quality of the input parameters has a major influence on the quality of the output parameters. If the used input values do not reflect the real system, the results will not represent the real behaviour of the system. Especially if uncertainties have to be taken into account, a good data evaluation is mandatory. The data generated during the project execution of mechanised tunnelling projects is discussed further in Section 2.3.

According to the formalisation of the model, the simulation model is implemented into a simulation framework (4). For the implementation of simulation models of construction projects, different simulation frameworks have been developed. One of the first and widely used frameworks is the CYCLic Operations NEtwork (CYCLONE) (Halpin 1977). Other approaches adapted the CYCLONE framework to deal with more specific problem statements, e.g. Symphony (Ebrahimy et al. 2011a) or COSYE (AbouRizk and Hague 2009). They are used to simulate different construction and in particular tunnelling projects (AbouRizk and Mohamed 2000). Another approach for the modelling of tunnelling projects has been developed at Ruhr University Bochum using the multi-method simulation framework AnyLogic (Rahm et al. 2012). A review of the different frameworks is given in Rahm (2017, pp. 17–21) or Duhme (2018, pp. 35–38).

In this contribution, the Java-based simulation framework AnyLogic (The AnyLogic Company 2019) is used for the modelling of the maintenance processes, since it offers a multi-method approach as well as the opportunity to implement additional Java classes (Borshchev 2013). This way, new modules that fit the unique character of the tunnelling components can be implemented.

The implemented model can then be used to conduct simulation experiments (5) and to calculate the requested parameters. Before the gained results can be used to evaluate the system (6), a verification (7a) and a validation (7b) of the simulation model is required. If the verification shows an error in the calculation, the implementation has to be checked again. If the model proofs not to be valid, all steps from the system analysis onwards have to be checked again. Only a verified and validated model can give reliable results. (Rabe et al. 2008)

Simulation experiments

Depending on the purpose of the experiment, there is a variety of simulation experiments that can be conducted. A single simulation run is sufficient if only discrete values are used to model the system. Furthermore, it can be used for visualisation. This way, the state of single elements can be observed at any point in time. The visualisation supports a better understanding of the system behaviour and simplifies the verification of the model.

A local sensitivity analysis can be used to estimate the influence of single parameters providing a better understanding of the system behaviour and sensitivities. For a global sensitivity analysis a parameter variation study is required. It enables the identification and evaluation of interdependencies of the input parameters and estimates their influence on the resulting values.

To consider the uncertainties in the process duration and system response Monte-Carlo Simulation (MCS) can be conducted (Vargas et al. 2014). As shown in Figure 2-8 several simulation runs are performed. For each simulation run, random numbers are used to generate the input values according to predefined distribution functions. The results of all simulations runs can be presented and analysed in a histogram and with statistical index values.

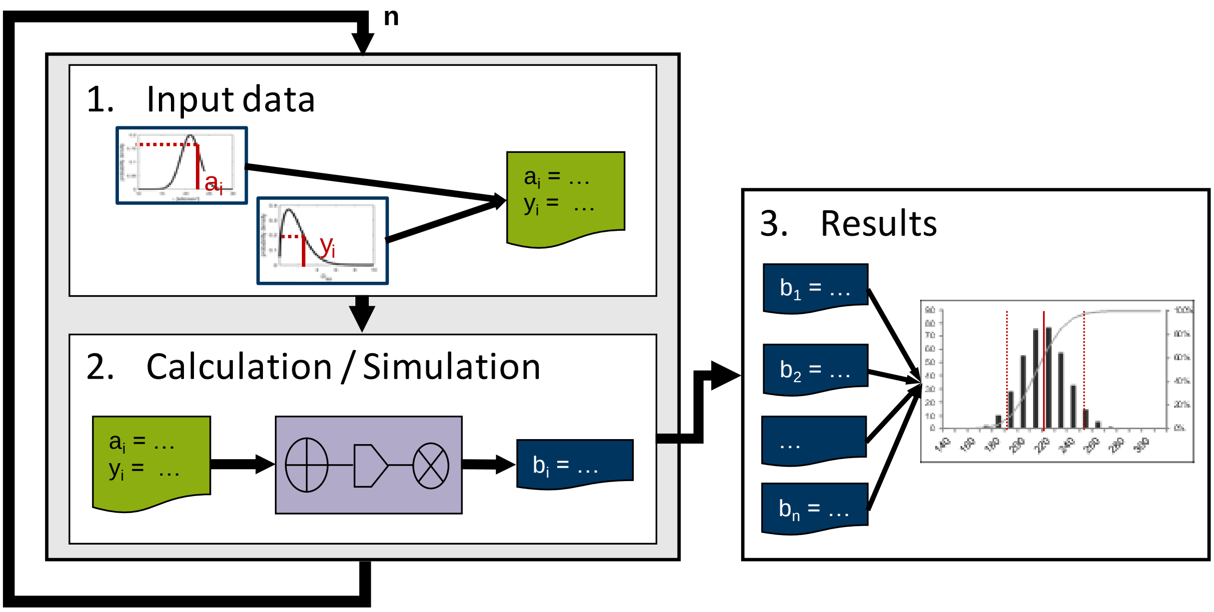


Figure 2-8: Procedure of a Monte Carlo Simulation.

2.2.2 Related work

In construction industry, there are several application fields for the use of process simulation. One often-simulated type of projects are earthmoving projects. A variety of case studies has been performed to analyse and improve the processes. For instance, AbouRizk and Hajjar (1998) propose a modelling approach to evaluate projects. This approach has been enhanced later on by, for instance, Hajjar and AbouRizk (2002), who developed a new simulation framework to reduce the modelling effort. Further case studies can be found for example in Cheng and Wu (2006), Fu (2012) or Akhavian and Behzadan (2013).

Several other application fields exist for simulation in construction. For example, simulation models for the analysis of pile construction processes (Zayed and Halpin 2004), for sewer pipeline installation processes (Chua David and Li 2001; Cheng and Feng 2003) or for the delivery of ready mixed concrete (Feng and Wu 2006) are proposed. Halpin et al. (2003) propose a web-based simulation and use this application to model asphalt paving processes. To evaluate disturbances in construction projects, Gehbauer et al. (2007) evaluated several projects to gain a database of typical disturbances, e.g. material fluctuations, availability of personnel or machine breakdowns, which can be considered in a simulation model. Wales and AbouRizk (1996) used simulation to estimate the influence of the weather on the productivity of different construction processes.

Mechanised tunnelling, which mainly consists of repetitive processes, is predestined for process simulation. The complexity of components, processes and interactions require a systematic analysis and modelling to be able to increase the productivity of the system. Therefore, simulation models have been developed to estimate the overall performance of a tunnelling or micro-tunnelling project by determining the utilisation of a tunnelling machine (Rostami 2016). Furthermore, simulation models have been used to compare and optimise different jobsite layouts (Zhou et al. 2009; Scheffer et al. 2016b) as well as the supply chain set-up (Ebrahimy et al. 2011a, 2011b) or to estimate the project costs (Chou 2011). Uncertainties of the process durations (Ourdev et al. 2007) or of disturbances (Rahm et al. 2016) but especially of the advance rate are considered in several models to gain more realistic results of the productivity and utilisation of tunnelling machines (AbouRizk et al. 1999; König et al. 2014).

In literature, many different simulation approaches and case studies can be found. Fernando et al. (2003) showed three case studies, where the use of the simulation models improved the productivity and costs of tunnelling projects. AL-Battaineh et al. (2006) compared different scenarios for the starting shaft and their effect on the project duration. Using the simulation model, they could evaluate different risk scenarios beforehand and define possible counter-measures.

Ruwanpura and Ariaratnam (2007) present several simulation tools for different problem statements in underground construction, e.g. . Marzouk et al. (2010) and Dang et al. (2018) proposed two different simulation approaches to evaluate micro-tunnelling projects. Al-Bataineh et al. (2013) analysed the influence of the shift length of the personnel and the number and position of switches for the train on the project productivity. König et al. (2014) present a simulation model to estimate the productivity of different supply chain set-ups. Rahm (2017) adapted this model to evaluate the influence of disturbances, for instance technical failures or insufficient material supply, on the overall productivity. Duhme (2018) compares the deterministic planning of the supply chain with the simulation approach to evaluate the benefits in using a process simulation model.

Some of the approaches to evaluate the productivity of a tunnelling project already include first attempts to consider wear and maintenance of the cutting tools. For example, Liu et al. (2010) include a cutter changing rate for a hard rock TBM to consider reduced performance due to the time needed for. This value was included in a developed simulation model of the TBM boring system. This approach has been used in Liu et al. (2015) for further risk analyses, which evaluate the influence of geological uncertainties.

First approaches at Ruhr University Bochum use an SD approach to consider the deterioration of the cutting tool condition (Mattern et al. 2016). The deterioration is then coupled with the DES modelling of the maintenance processes (Conrads et al. 2017b).

2.3 Data in mechanised tunnelling

A simulation model that is implemented to evaluate the productivity of a system can only produce reliable results if reliable input data is used. Therefore, it is necessary to gather reliable data that can be used for the definition of the input data. In mechanised tunnelling, the back analysis of finished projects can be used to gain the needed input data for a simulation model. However, a large amount and variety of data is generated during the execution of mechanised tunnelling projects and the complexity and uncertainties of the system complicate back analysis.

In mechanised tunnelling, two types of data can be obtained. One type is the automatically documented machine data that is gained by a variety of sensors mounted within the machine and backup trailer or in facilities of the surface construction site. The other type of data is heuristic data documented manually in a less frequent interval or from tests conducted either on site or in the laboratory. Depending on the type, quality and quantity of the data it can be processed and evaluated.

2.3.1 Machine data

The machine is equipped with at least 200-400 sensors. In most cases, the sensors are programmed to measure a value every one to ten seconds (Maidl and Nellessen 2003). To handle this amount of information, several process controlling systems have been invented. These systems are used to plot the system behaviour to analyse the interaction of the ground and excavation method and steering parameters for real-time decision making (Maidl 2008).

The main purpose of the sensor data is the steering and operation of the tunnelling machine. The control parameters that can be adjusted by the shield operator are visualised together with the machine response. Especially the surveying of the advance direction is needed for the steering operations. Further important control parameters are support pressure, material flow, tail gap grouting and forces.

Process controlling tools are used for real-time documentation and evaluation of the sensor data as presented for example in Schretter et al. (2009), who conducted an actual-target comparison, or for data visualisation as shown in Figure 2-9. It shows the real time visualisation of the settlement measurements and compare them with the grout pressure for a regarded tunnel section.

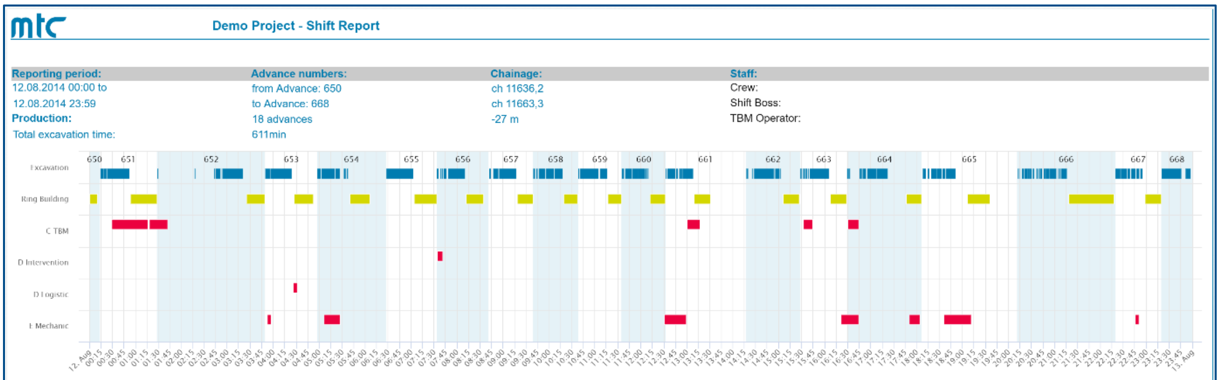
Figure 2-9: Example for process controlling data visualisation with PROCON (Maidl Tunnelconsultants 2019).

Maidl et al. (2011) used this process controlling approach to implement the observational method for a hydro-shield tunnelling project. The process controlling system has been further developed by Maidl and Stascheit (2014) to visualise the data in real-time and to implement an early warning system.

Similar tools for data visualisation and interpretation are given by Handke and Edelhoff (2016) or Babendererde Engineers (2019). Frenzel and Babendererde (2011) show, how the recorded data for cutter head torque can be related to the wear behaviour of the cutting tools.

Due to the high amount of data, the data evaluation requires a high level of expert knowledge to decide, which of the measured parameters are needed and to identify possible errors produced by the sensors. Using the right data evaluation method the high amount of data can be reduced to a usable maximum.

All data that is not gathered by sensors has to be documented by the personnel. Especially the process durations and disturbances are recorded in shift reports. Process controlling tools enable an automatically documentation of the process duration (see Figure 2-10), for excavation (blue), ring building (green) and disturbances (red) in general. However, for disturbances the cause and actual conducted work during the standstill still have to be added manually. The resulting Gantt-chart is then used to generate the shift report as shown in Figure 2-10.



Description	Code	Start	End	Details	Priority	Duration
C TBM						
Air System	T1	12.08. 01:29	12.08. 02:16	air problem	1	47 min
Air System	T1	12.08. 02:18	12.08. 02:42	air problem	1	24 min
Hydraulic	T3	12.08. 14:00	12.08. 14:17	hydraulic problem	1	17 min
Air System	T1	12.08. 16:32	12.08. 16:44	air problem	1	12 min
Cleaning	T4	12.08. 17:30	12.08. 17:44		3	14 min

Figure 2-10: Example of a shift report (Maidl Tunnelconsultants 2019).

Geological parameters are determined using a variety of methods from visual inspection and qualitative description of the tunnel face during intervention to laboratory tests conducted with samples from the tunnel face or from boreholes (Scholz and Spaun 2017). Therefore, in shield tunnelling projects with active face support the actual and undisturbed ground properties are not known for each point of the tunnel alignment. Wendl et al. (2010) propose a method for the indirect geological documentation for hydro-shield projects at the separation plant and direct documentation at the tunnel face during interventions. Here, also machine data is analysed to increase the significance of the results (Wendl et al. 2012). However, the approaches still have large uncertainties.

This data, in opposite to the continuously documented machine data, offers only discontinuous information about the state of a certain parameter. Furthermore, the measuring methods for these data are subject to higher deviations and to errors in the measurement. Therefore, information based on this data has a higher uncertainty that has to be taken into account.

Wear and maintenance are influenced by operational and ground parameters. In particular, the penetration of the cutting tools influences the wear rate. The penetration is indirectly adjusted via the pushing forces of the thrust cylinders and the rotational speed, which are set by the operator. Furthermore, other parameters, e.g. the torque of the cutting wheel, can be evaluated as wear indicators (Hollmann 2014, p. 178). However, for the evaluation of maintenance schedules, the documentation of the actual cutting tool wear is needed. Most approaches to develop wear prognosis are empirical, but have to deal with poorly documented data. Since the documentation of the measured wear or the qualitative assessment of the tool condition causes additional effort and even downtime, the documentation effort is reduced to a minimum.

Most of the process controlling applications already offer a tool for wear and maintenance documentation. This way, electronic data is available and can be used for automatic evaluation of tool wear (Maidl and Stascheit 2014). However, quality and quantity of information still depend on the personnel on site. An example for a software tool for wear documentation is presented in Figure 2-11.

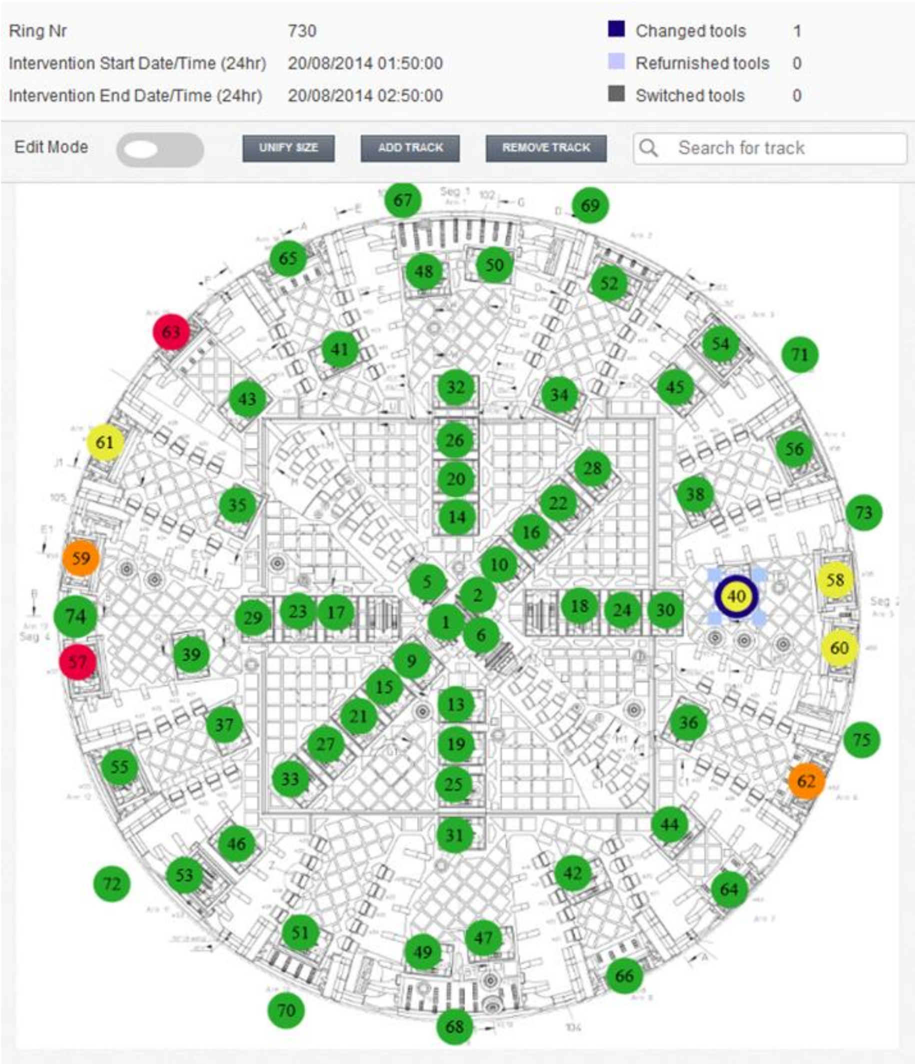


Figure 2-11: Wear documentation and visualisation of the tool condition with the process controlling application PROCON (colours- green to red - represent the wear condition of the tool) (based on: Maidl Tunnelconsultants 2019).

2.3.2 Data evaluation

Considering uncertainties during project planning, a reliable method has to be used to process and implement the uncertain input data into the scheduling model and to evaluate the resulting uncertain output data.

AbouRizk and Halpin (1990) presented how data for repetitive process duration can be processed, so that it can be used in a simulation model as uncertain input parameters. Distribution fitting methods are used to generate probability distribution functions that fit the documented data. The fitted function must be checked for quality of fit, e.g. chi-square or Kolmogorov-Smirnov tests. The identified distribution functions are needed if Monte Carlo Simulations (MCS) shall be performed. This way, the uncertainties of the input parameters can be taken into account to represent the real system.

This method can be used, if a sufficiently large amount of data is available. Similarly, Špačková et al. (2013) used distribution functions for the project planning and validated the results for the first 150 days. Afterwards, the prognosis was adjusted to the measured data to reduce the uncertainty for the remaining project.

Miro et al. (2014) use a global sensitivity analysis to estimate the key model parameters of a numerical simulation model for settlement calculations. Zhao et al. (2015) adapted this approach and validated the numerical model with data of a reference project.

For the overall data management Schindler et al. (2014) propose a tunnelling product model that handles all the information and different models that are used for the planning phase of a project. This model has been developed further by Koch et al. (2017) and can be used to provide the processed data in addition to new information and boundary conditions of the project in consideration.

The data that is produced during the execution of a tunnelling project is indispensable for the planning of new projects. The knowledge gained by back analysis helps to improve the productivity of comparable projects. It can be used to reduce the influence of uncertainties and to avoid similar errors in the planning through lessons learnt. However, the gained knowledge has to be put into a form that can be used for the next project planning, since most of the data is given in spreadsheets, a database of a process controlling tool or even in PDF format. The general procedure from data gathering to result evaluation is illustrated in Figure 2-12. There are three main steps that need to be performed. The first step is the gathering of data. This raw data is then processed to gain input data for the analysis. After the simulation experiment the output data has to be processed again to gain the results that are needed for the conclusion, e.g. the schedule or the maintenance costs.

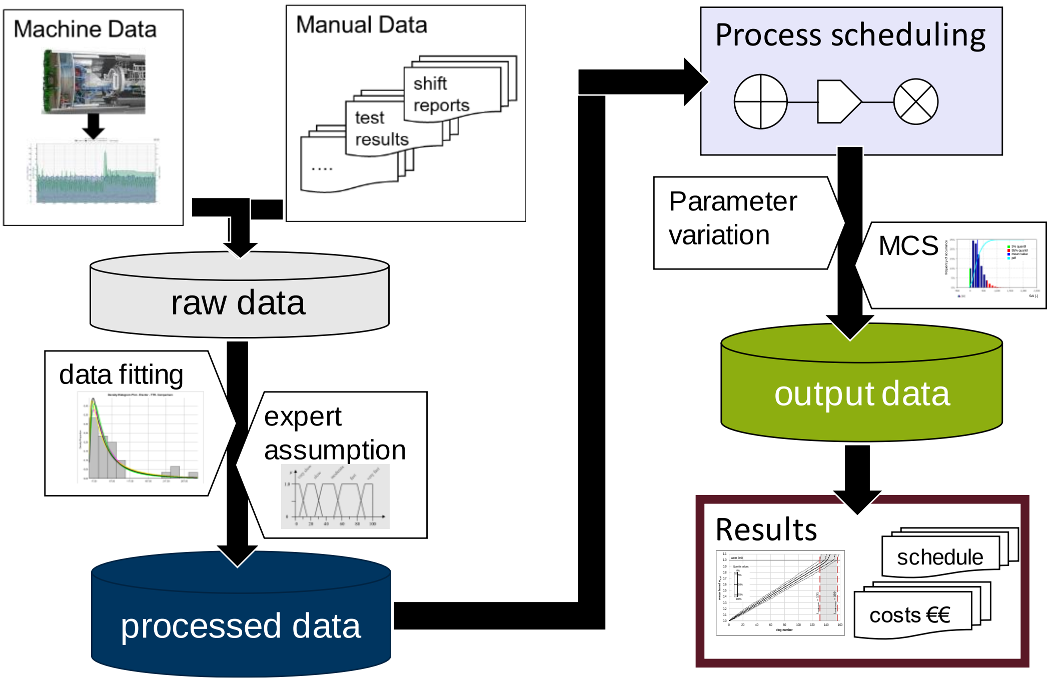


Figure 2-12: Procedure of data processing and result evaluation.

Generating the processed data, one value per advance cycle for each parameter is sufficient for most of the analyses. Therefore, the machine data, that is given for each ten seconds, has to be summarised into one value. The heuristic data has to be scaled to one advance cycle as well. The difference in the quantity of data is presented in Figure 2-14.

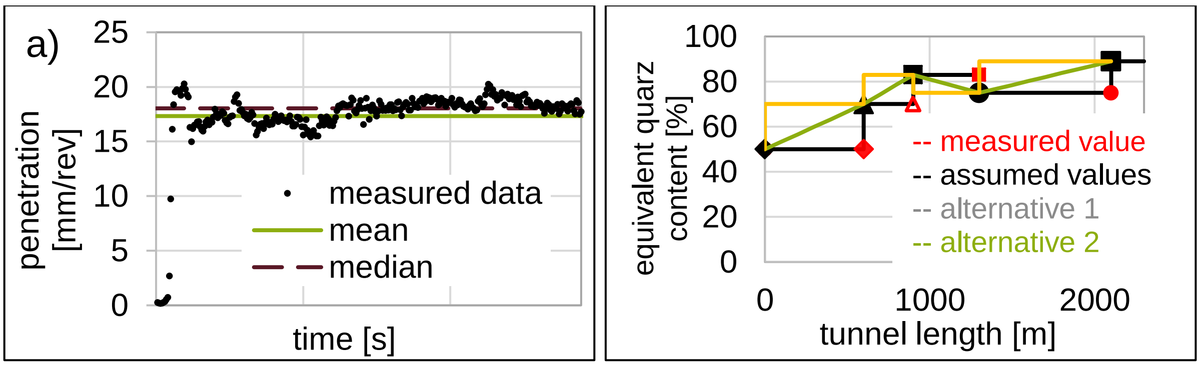


Figure 2-13: Data processing for a) continuous machine data for the advance of one ring b) data points of manually documented parameter and assumed additional values.

The process scheduling and analysis conducted with the help of a simulation model creates a high amount of output data that must be processed and evaluated. Depending on the method used for the analysis, there are several methods for the evaluation of the results. The most common method to present and evaluate results gained from

MCS is a histogram in combination with statistical indices, e.g. mean or quantile values. An optimisation of the schedule can be conducted using parameter variation. If there is more than one output value to optimise, a scatter plot can be used to find the Pareto-optimum of all parameter sets as shown in Figure 2-14. It also can be used for the estimation of the robustness of the output value, to not only consider the magnitude but also the deviation. Therefore, a combination of Parameter Variation Studies (PVS) and MCS is needed as explained in Section 5.3.5.

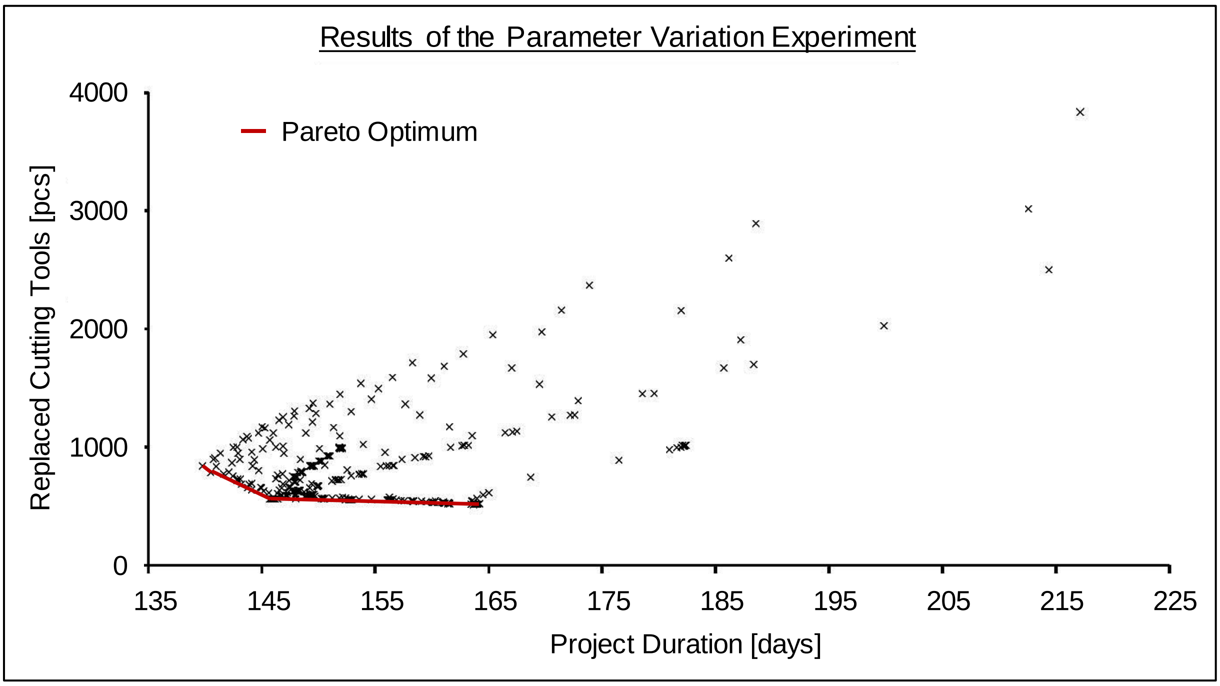


Figure 2-14: Evaluation of the project duration and number of replaced tools for a parameter variation experiment (based on Scheffer et al. (2016a).

2.4 Findings for further research

In this chapter the state of the art and basic principles of the processes in mechanized tunnelling, the process simulation and the data management in tunnelling have been reviewed. Based on this review the following findings for the further research have been found:

- The productivity of a tunnelling project depends not only on the production processes, but to a large extent also on the processes of the supply chain.
- It is important to consider the interaction and dependencies of all components and processes of the tunnelling system to improve the productivity and to avoid disturbances.

- Maintenance of the cutting wheel is one of the auxiliary production processes that may have a great influence on the productivity depending on which machine type is used and how much wear does occur.
- Maintenance processes have to be regarded more closely to improve the overall maintenance schedule.
- Process simulation is an efficient tool to model and analyse a complex system like mechanised tunnelling projects.
- Different simulation methods can be combined for the modelling of a system enable a flexible and hierarchical structure and to model the system behaviour.
- Input data needs to be generated for the simulation model and therefore it is needed in a high quality and quantity.
- Processing of data from finished projects supports the input data generation.
- The quantity and quality of available data strongly varies for the different parameters.

Summarising, a simulation model of the maintenance processes, with qualitatively and quantitatively good input parameters, can support the decision making of maintenance scheduling processes. Therefore, in this contribution a simulation model for the analysis of maintenance processes has been developed and implemented. Actual data of finished tunnelling projects has been processed to generate the required input data. The proposed model is described in Chapter 5 in more detail.

3 Wear and Maintenance of Cutting Tools

The wear of the cutting tools in TBM tunnelling is an important factor for the performance of tunnelling projects and thus is widely discussed in research and practice. The performance of maintenance schedule depends on the quality of the wear prediction. Even a good wear estimation faces uncertainties that have an effect on the maintenance schedule. In order to gain an overview of existing wear prediction models, the wear mechanisms and patterns of different cutting tool types are researched. Based on this, the wear prediction by index tests and especially the existing wear prediction models are reviewed and discussed.

3.1 Wear Mechanism and Pattern

In general, wear is defined as the loss of material at the surface of a solid body caused by a tribological loading induced by a solid, liquid or gaseous counter body (Czichos and Habig 2015, p. 127). In mechanized tunnelling, the main body affected by wear is the cutting tool, while the counter body is the rock or soil at the tunnel face.

In tunnelling, it is differentiated between primary and secondary wear, whereby different definitions exist. Tarigh Azali and Moammeri (2012), Düllmann (2014, p. 141) and Amoun et al. (2015) define primary wear as the wear behaviour of the cutting tools themselves, being in direct contact with the tunnel face during the excavation process. Secondary wear is then defined as the material loss of other parts of the cutter head and the transportation system due to the excavated soil mixed with the support medium or conditioning agent. Frenzel and Babendererde (2011) and Frenzel (2010, pp. 19–23) distinguish the tool wear of the cutting blade, which is actively in contact with the soil of the tunnel face (primary), and the wear of other tool parts due to passive contact with the excavated soil and the support or conditioning medium (secondary). Likewise, Nilsen et al. (2006a) define primary wear as planned wear of the tools and secondary wear as unplanned wear of other machine parts caused by excessive tool wear.

The wear of cutting tools is induced by different mechanisms, leading to different wear patterns. According to each wear mechanism and pattern, the extent of wear differs and therefore, corresponding wear limits have to be set. Furthermore, the interaction of the tools and the choice of tools have an influence on the wear behaviour. As a result, the overall design of the cutter head has to be analysed.

3.1.1 Wear mechanism

Different wear mechanisms exist that lead to the loss of tool material. Most important is that not only one material but also the complete tribological system has to be considered. Therefore, the whole interaction of different surfaces in relative motion is of interest (Jakobsen 2014, p. 15).

As shown in Figure 3-1, there are four components to be taken into consideration analysing the wear process of the cutting tools (Küpferle et al. 2018a). The steel matrix of the tools is the base unit that is affected by wear. The counter body is the soil at the tunnel face, which is excavated by the tool. In addition, there is an ambient medium, e.g. water, slurry and/or foam, which also has an effect on the wear of the tool. At last, the load spectrum of the tool interacting with the soil has to be taken into account.

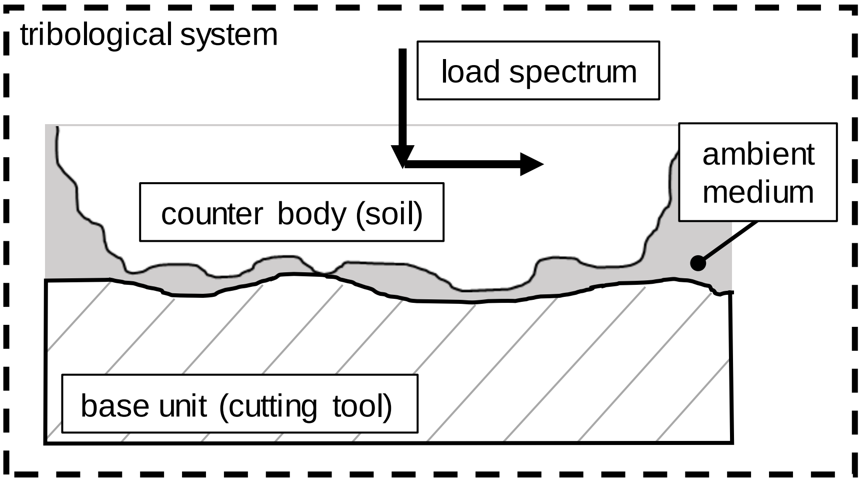


Figure 3-1: Tribological system of a cutting tool (based on Czichos and Habig (2015, p. 25)).

Resulting from this interaction, there are different mechanisms that may occur. The *Gesellschaft für Tribologie* (GfT – association for tribology) defines four main wear mechanisms: abrasion, adhesion, surface fatigue/spalling and tribo-chemical reaction (GfT-Arbeitsblatt 7).

Abrasion

The most researched and discussed wear mechanism in mechanized tunnelling is the abrasive wear. Since abrasion always occurs during excavation, it has a strong influence on the overall tool wear (Frenzel et al. 2008; Thuro and Käsling 2009; Amoun et al. 2015). Sometimes, abrasion is even set equal to the total wear of the tool (Büchi et al. 1995).

Abrasion means a continuous erosion of the tool material due to the mechanical loading of harder mineral particles (Röttger et al. 2015). The GfT (GfT-Arbeitsblatt 7) and Wilms (1995, p. 74) define abrasion as a grooving and scratching material removal. Soil particles indent into the tool steel matrix and, due to relative movement in addition to the mechanical loading, material is abraded of the steel surface (Küpferle et al. 2017a). Hence, the hardness as well as the roughness of the counter body in addition to the load spectrum is influencing the material erosion by micro wear processes (Czichos and Habig 2015, p. 137).

Zum Gahr (1998) describes the micro processes of the abrasion mechanism. As shown in Figure 3-2, it is differentiated between microploughing, microcutting, microfatigue and microcracking.

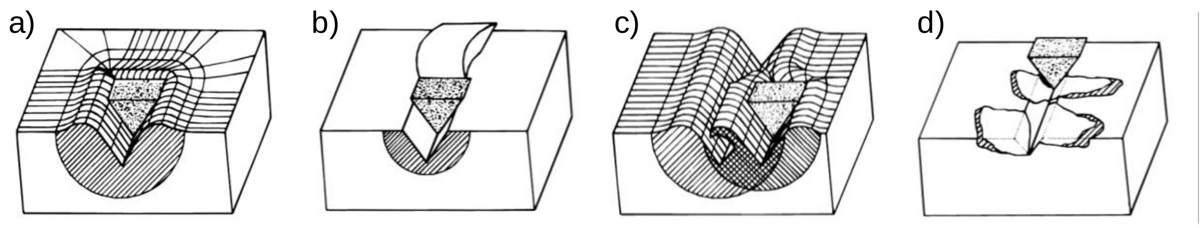


Figure 3-2: Micro abrasion processes. (a) microploughing (b) microcutting (c) microfatigue (d) microcracking (Zum Gahr 1998).

Microploughing mainly causes a deformation of the solid surface by an indenting particle (Figure 3-2 (a)). If several particles indent into the solid and cause single microploughing each, it can lead to volume loss due to microfatigue (Figure 3-2 (b)). Microcutting is the loss of material with the same volume as indenting particle that is cut out of the solid surface (Figure 3-2 (c)). Microcracking occurs in brittle material, when high local loads are imposed on the surface leading to crack propagation and spalling of solid chips at the surface (Figure 3-2 (d)).

It is considered that the amount of abrasion on cutting tools is depending on the abrasiveness of the excavated ground (Galler et al. 2014). The determination and the influence of the abrasiveness of the ground on the tool wear is further discussed in Section 3.2.2. Köppl (2014) analysed several hydro-shield tunnelling projects. The quantitatively measured wear of the cutting tools that has been documented in one of these projects has been evaluated. It can be seen that the amount of measured wear in one homogeneous section of the tunnel that has constant ground parameters is linearly correlated to the cutting path of each tool (e.g. see Figure 3-3). Here, only the tools with abrasive wear are taken into account.

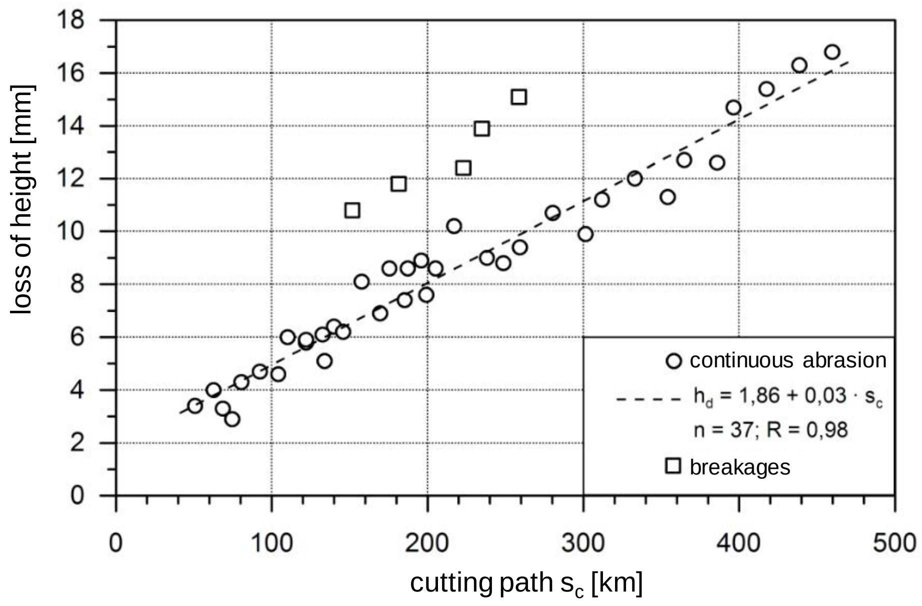


Figure 3-3: Correlation of the cutting path and the amount of wear for ripper tools (based on Köppl (2014, p. 142))

Although Bruland (2000c) observed that for hard rock TBM new cutting discs have a higher wear rate than used ones, in general there is a linear increase similar to soft ground conditions, if there are no changes in the influencing boundary conditions.

Adhesion

Adhesion is the binding of molecules of two different materials. This can cause a material loss of one material, if shear forces are applied on the contact surface. It is caused by high contact forces, which increase the binding of the surface particles on molecular level. If theses contact forces exceed the inner contact forces of the tool substrate, material removal may occur. This is called cold welding. (Wilms 1995, p. 74; Czichos and Habig 2015, pp. 140-142)

Köhler et al. (2011) state that adhesion is caused by pore water that is pressed out of the fine grained soil. The resulting negative pressure leads to a material loss of the tool's surface. Another reason for adhesion is the clogging of clay minerals that can be derived from the classification diagram of Hollmann and Thewes (2012).

Surface spalling

Due to high local forces, which exceed the maximum material strength of the steel, cracks occur in the steel matrix. The repeated impact leads to crack propagation and spalling of tool material. This failure mechanism mostly arises, when there are boulders or mixed face conditions. This way, the tool hits a hard rock part after excavating the softer soil, where it has a deeper penetration.

Furthermore, due to the low fracture toughness of the wear protection hard metal layers and parts, the cyclic loading of hard mineral particles causes cracks on the micro scale, even if the impact load is lower than the fracture strength. The propagation of these cracks leads to a degradation and a decrease of the resistance of the surface material thus causes material removal (Küpferle et al. 2018a). Küpferle et al. (2017b) analysed this wear mechanism for typical tool materials to gain a better understanding of the material behaviour under cyclic loading. This way, new insights for the design of cutting tool materials could be found.

Tribochemical reactions

In chemically aggressive media, there will be a disintegration of the tool material caused by chemical reactions. The most common tribochemical reaction of steel surfaces are corrosion of the iron molecules due to the influence of water and Ions. However, the wear rate of this mechanism is relatively slow compared to the other presented wear mechanism. Therefore, it can be neglected as long as no particularly aggressive media occur. Espallargas et al. (2014) analysed the influence of corrosion on the tool wear and showed the effect of conditioning additives on the reduction of the wear amount through a new laboratory test.

3.1.2 Wear pattern

The cutting tool design, the load induced by different ground conditions and the operational parameters of the TBM lead to different wear patterns of the cutting tools. By analysing the wear pattern, the main wear mechanism can be identified. Therefore, it is necessary to review the wear pattern of the different cutting tool types to gain a better understanding of the tool lifespan as has been done in detail by Frenzel (2010), Frenzel and Babendererde (2011) and Köppl (2014). Following, typical wear pattern of each tool type are reviewed and discussed with regard to tool durability.

Cutting disc

Cutting discs are used to remove hard rock at the tunnel face. They run in concentric tool tracks and apply high local pressures on the tunnel face so that cracks propagate and rock chips flake off. In soft or mixed ground conditions, cutting discs have a higher penetration than the other tools to prevent those from damage caused by impact loads of boulders or hard rock layers (Figure 3-4).

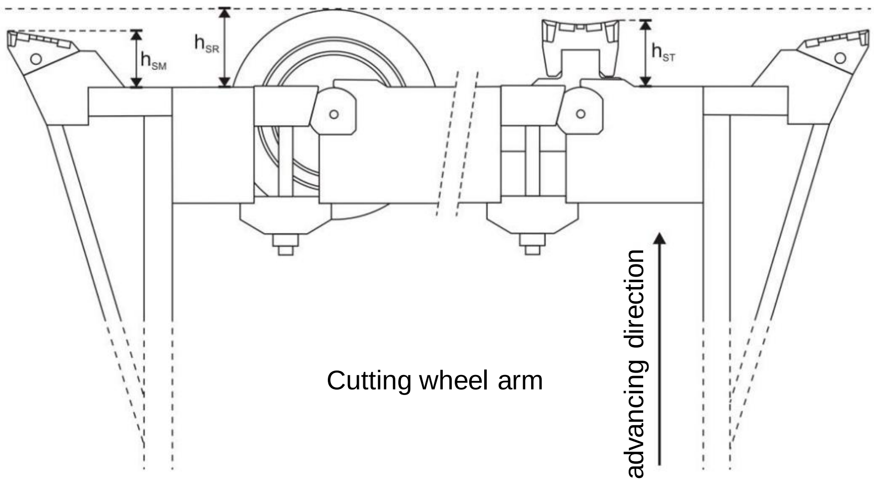


Figure 3-4: Absolute height or penetration of cutting rolls (h_{SR}), ripper tools (h_{ST}) and scraper (h_{SM}) in relation to the cutting wheel front surface (based on Köppl (2014, p. 31)).

The wear pattern of the cutting disc mainly depends on the soil type. In hard rock, only the cutting edge is in contact with the tunnel face. Therefore, only the edge is wearing out continuously due to abrasion. Figure 3-5 shows the typical pattern of abrasive wear in hard rock tunnelling. On outer tool tracks, the wear may be asymmetrical because of the skewed installation of the tools. (Thuro and Plinninger (2003)).

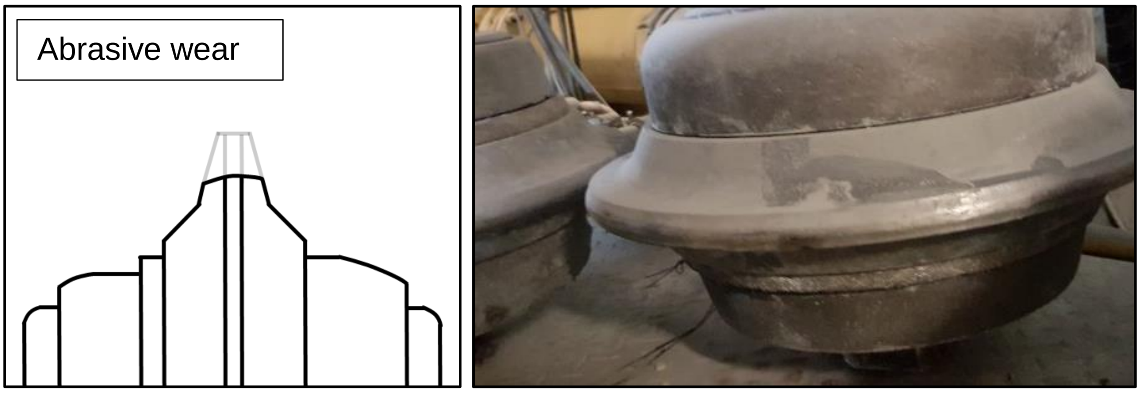


Figure 3-5: Wear pattern of abrasive wear of cutting discs.

If the compressive strength of the rock is extremely high, the cutting blade may be deformed by high contact pressure. This wear pattern is called mushrooming due to the mushroom-like deformation of the cutting blade (Ellecosta et al. 2018) as shown in Figure 3-6.

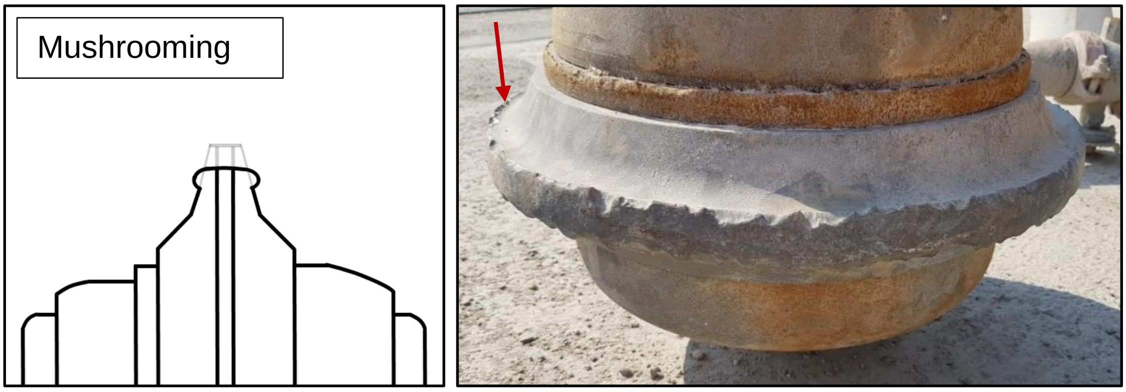


Figure 3-6: Wear pattern of mushrooming of cutting discs.

In soil, the cutting blade penetrates into the softer tunnel face so that the flanks of the tool are also in contact with the soil particles. This way, the soil is rather loosened and deformed then excavated. The cutting disc forms a groove into the tunnel face (Köhler et al. 2011). The soil material is displaced to the flanks and afterwards excavated by scrapers or buckets (see Figure 3-7). Consequently, the flanks of the cutting disc are exposed to abrasive wear as well, which leads to a sharpening of the cutting blade (Köppl 2014).

Figure 3-7: Wear pattern of sharpening of cutting discs(pictures from: (Köppl 2014, p. 93) and (Köhler et al. 2011)).

If the cutting disc is blocked and therefore cannot roll properly on the tunnel face, one-sided wear occurs, as the disc rapidly flattens on the side that is in contact with the rock (Figure 3-8). One of the possible causes of such blockage is a lack of friction, which is essential for the disc to properly roll on the tunnel face. Another possibility is that the bearing is jammed or broken due to a high impact force or it is damaged by fines that penetrated through the sealing (Frenzel and Babendererde 2011). In soft ground, clogging of the ground inside the cutting disc bearings can cause a one-sided wear as well.

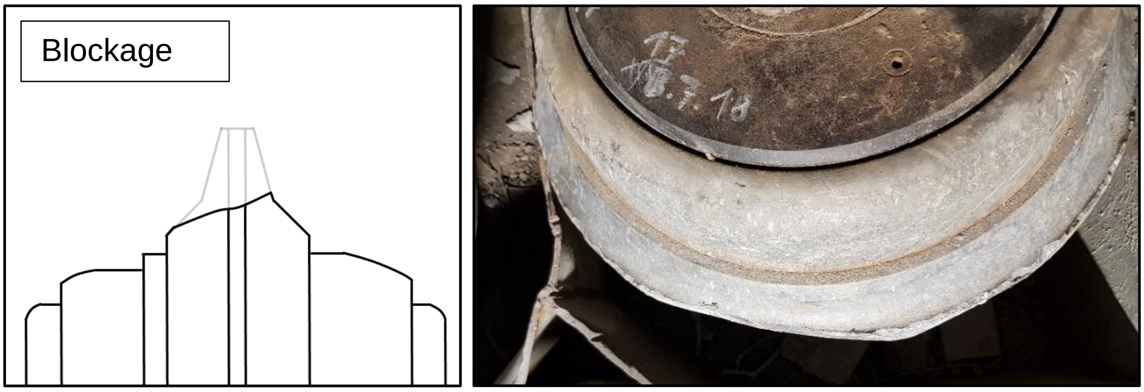


Figure 3-8: One sided wear of a blocked cutting disc.

In mixed ground conditions or when boulders occur, the cutting disc can be exposed to sudden high local loadings exceeding the tool's material strength. Especially hard but brittle tool material tend to crack and spall, as shown in Figure 3-9, when exposed to such impact loads (Plinninger et al. 2018).

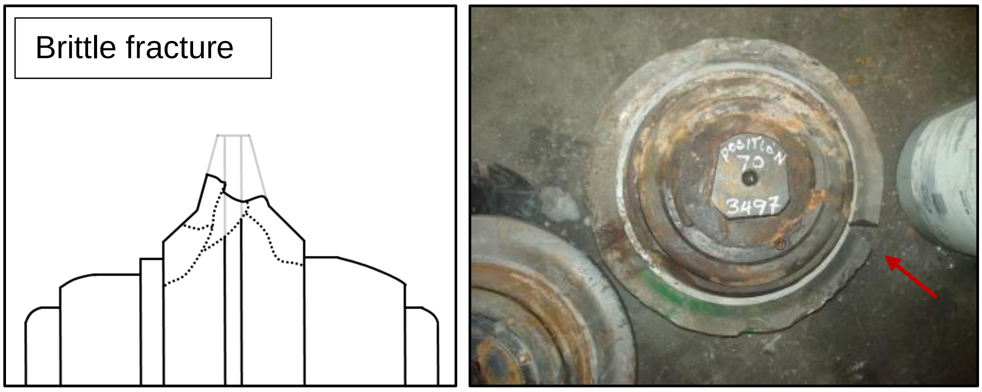


Figure 3-9: Brittle fracture of a cutting disc (Köppl 2014, p. 101).

Scraper

Scrapers remove the ground by scratching along the tunnel face. They are mainly used in soft ground and mostly with active face support. The cutting edge of the scrapers is reinforced with hard metal parts that are embedded into the softer steel of the tool body to ensure a high resistance to abrasive wear. The soft tool body is less brittle, thus more resistant against wear caused by high local impact forces.

The progressive abrasive wear can lead to a loss of the hard metal parts by abrading them completely (Figure 3-10-a). Another reason for their loss is the wear of the tool body between the hard metal inserts. This way, the hard metal bits are washed out of the tool base (Küpferle et al. 2018a). Although the brittle hard metal is embedded in the more ductile and soft tool substrate, there is still a possibility of material spalling when hitting a hard rock boulder (Figure 3-10-b). Without the wear protection of the hard metal insert, the amount of abrasive wear increases.

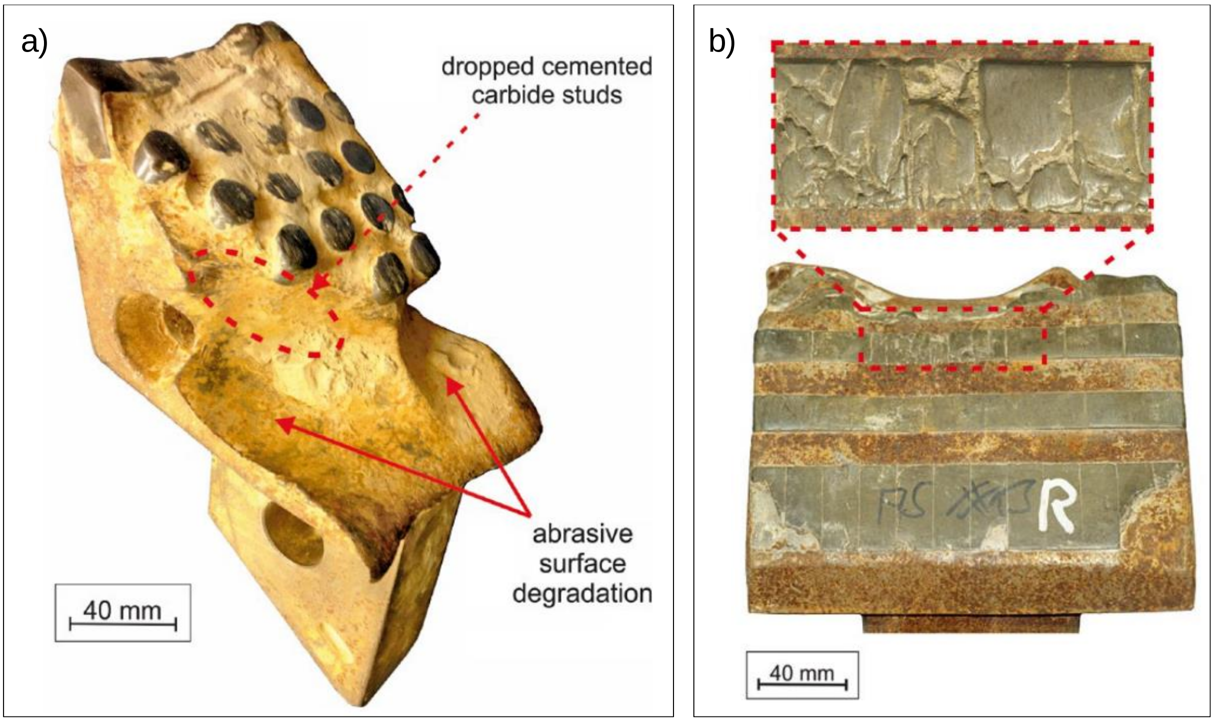


Figure 3-10: a) Chisel tool with severe abrasive wear damage; the surface degradation leads to dropped studs. b) Damaged surface of a chisel tool due to surface spalling (Küpferle et al. 2018a).

The worst-case scenario is an undetected excess of the wear limit until not only the tool but also the tool holder is damaged. This can also be caused by a high impact load, which leads to a sudden fracture of the tool and the holder. If the holder is damaged, the time for the maintenance of the cutter head increases significantly.

Buckets

Buckets work similar to scrapers. The main difference is that buckets excavate a bigger area of the tunnel face. Buckets are mainly used for the excavation of the outer tracks of the cutting wheel. If there are cutting discs or ripper tools installed in front of the bucket, the parts of the bucket that are on the same track are often less worn than the rest, due to the deeper penetration and excavation of the tools running ahead.

Similar to scrapers, buckets are equipped with hard metal bits for wear protection. Therefore, the same three typical wear patterns appear for buckets. Figure 3-11 shows a worn bucket with different wear patterns.

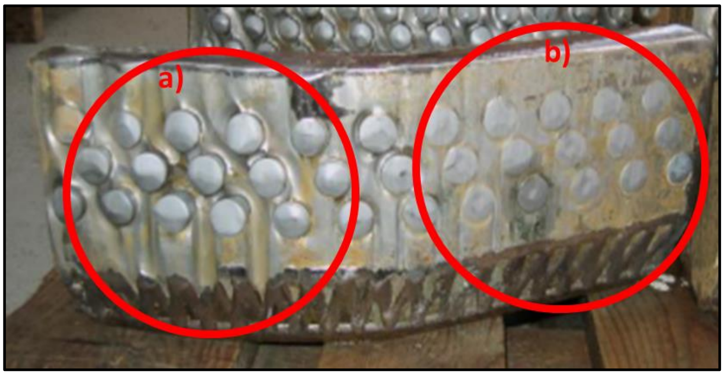


Figure 3-11: Worn bucket: a) washed out hard metal bits; b) even abrasive wear of the whole surface (based on Köppl (2014, p. 124)).

Ripper

Rippers have a similar shape as scrapers, consisting of a soft tool body and hard metal inserts. However, they differ regarding their interaction with the tunnel face. While scrapers and buckets cut off the soil or transport the cut and ripped soil into the excavation chamber, rippers break up and rip out the soil at the tunnel face. There are different shapes and designs of ripper tools (Fouda et al. 2017). The main difference in comparison to scrapers is, that rippers can excavate in both rotation directions leading to a mostly even loss of material (see Figure 3-12) (Köppl 2014, p. 28).

Figure 3-12: Worn ripper tools with different wear pattern (right picture: Köppl 2014, p. 109)

3.1.3 Wear measurements and units

During inspection of the cutting wheel, the wear of the cutting tools can be measured. Thuro and Plinninger (2003) differentiate between qualitative and quantitative wear measurement. Qualitative wear measurement describes the wear pattern, so that the wear mechanism can be determined. In comparison, quantitative wear measurement gives the wear rate, hence gives information about the amount of wear, which is more exact. There are different wear units that can be considered depending on the measured unit and the reference unit.

For disc cutters, in general, the loss of height in millimetres is measured with the help of a measurement gauge and a calliper (Figure 3-13). There might be a deviation in the measured values, if the flanks of the cutting blade is exposed to wear as well, since the calliper is set onto the flanks for measuring the height loss.

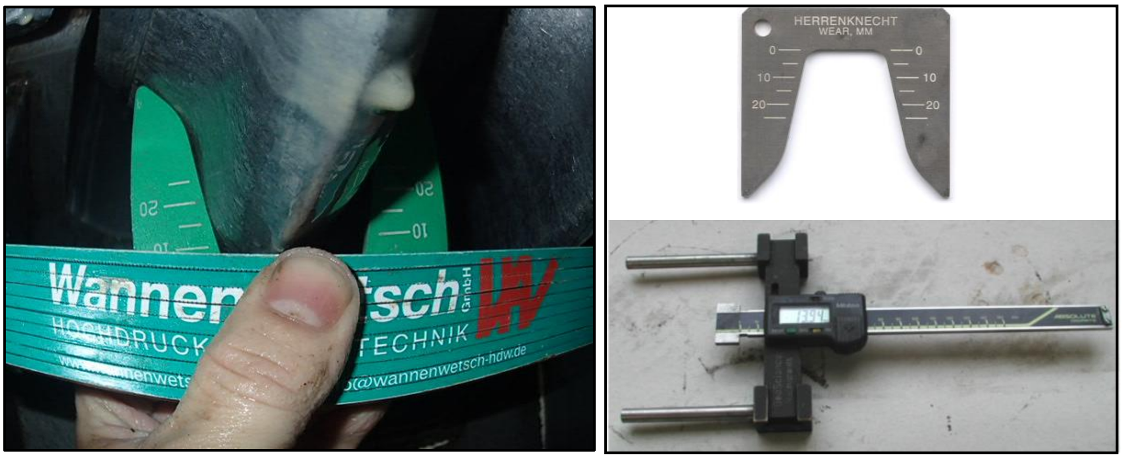


Figure 3-13: Wear measurement of cutting discs (pictures on the right side from Frenzel (2010, p. 56))

Due to the heterogenic build of the scrapers, buckets and ripper tools, the quantitative wear measurement is more complicated. However, if there is only uniform abrasive wear, the wear can still be measured in mm height loss.

Another possibility to determine quantitative wear is to measure the weight loss of each tool after removing them from the cutter head. Therefore, only one value per tool can be determined in this way. The measured loss of height or weight can then be set as a function of the reference unit, which can either be the length of the cutting path of each tool in km, the length of the excavated tunnel in longitudinal direction in m or the volume of excavated ground per tool in m³.

Both, the qualitative and the quantitative wear measurement are recorded for each maintenance stop using predefined protocols given by the machine manufacturer (Frenzel 2010, 55-57). In hard rock tunnelling projects, the wear measurement is normally conducted once a day, if the wear rate is not low enough to increase the inspection interval. In soft ground tunnelling, where the excavation chamber is not always accessible, these wear measurements are only performed at maintenance stops. Hyperbaric conditions, which reduce the maximum intervention time, and unstable ground conditions, which only allow a partial lowering of the support medium, may lead to a reduced number of tools inspected during the maintenance stop.

Especially in soft ground tunnelling, there have been recent attempts to get in-situ measurements of the tool wear. The most common way to obtain such measurements are pressure load cells that are mounted on the cutting wheel (Figure 3-14, left). If the wear of the tools exceeds a given height, the cell, which is mounted on the same track, gets into contact with the tunnel face and a signal is sent (Willis 2012).

In hard rock tunnelling there are sensors that measure the load (Galler et al. 2014) and the temperature as well as the vibration of the cutting discs to give an indicator for increasing wear (Figure 3-14, right). Rotation sensors measure whether the disc is still rotating or if a disc is blocked and will be subjected to one-sided wear. (Log 2018).

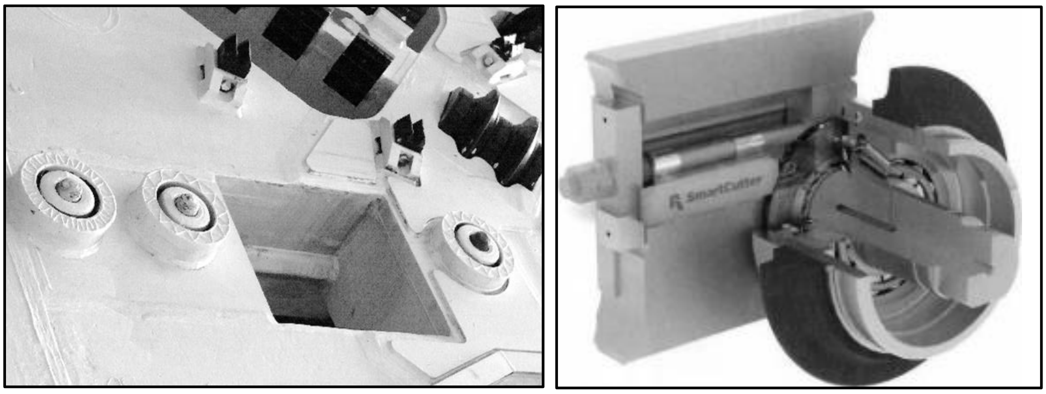


Figure 3-14: Smart Cutter with motion control (Log 2018) and pressure load cells mounted onto the cutter head.

Furthermore, there are first attempts to examine the wear of the gauge cutters indirectly, by measuring the gap width of the overcut from inside the shield (Gharahbagh et al. 2013b). The gap width verifies the minimal overcut of the shield.

Nonetheless, neither automatic nor real-time measuring systems provide continuous and exact knowledge of the cutting tool conditions.

3.1.4 Wear limits

Wear limits have to be defined to guarantee the usability and reparability of the cutting tools and to avoid secondary wear. The wear limits of cutting tools are determined for the different tool types in order to consider the respective structure of the tools.

Disc cutters

Disc cutters, which run in front of the other cutting tools, must have a higher penetration of minimal 10 mm in comparison to the penetration of the other tools to protect these tools from damage caused by boulders or other obstacles in the soil (Köppl 2014, p. 103). This way, hard rock layers and boulders can be broken into smaller pieces before getting in contact with the scraper or buckets, thus severe damage can be avoided. It concludes in a wear limit of approximately 25-30 mm for a 17’’ cutting disc.

In general, a quantitative wear limit can be calculated taking the cutter head design into account according to (Köppl 2014, p. 103):

(3-1) $$h_{d,\max(SR),1} = (h_{SR} - h_{SM}) - 10\ mm$$

Where: $h_{d,max(SR)}$: *wear limit – max. height loss of the disc cutter [mm]*
h_{SR}: *height of the disc cutter [mm]*
h_{SM}: *height of the scraper/bucket [mm]*

The cutting disc of the outer diameter that are needed for the overcut of the machine have a smaller wear limit of about 10-15 mm in total to permanently ensure the required amount of overcut, preventing the shield of the machine from jamming into the ground (Frenzel 2010, p. 23).

(3-2) $$h_{d,\max(SR),2} = 10 - 15\ mm$$

The last limiting factor is the total height of the cutting blade of the disc. If the cutting blade is completely worn, secondary wear of other parts of the disc takes place and the disc can no longer be repaired and reused. Furthermore, the wear of the tool holder shall be avoided. This limit depends on the type of cutting disc, since the composition of the disc differs, as does the maximum allowed wear. Monoblock discs have a smaller chance of losing the cutting ring, even if they encounter a greater amount of wear (Frenzel and Babendererde 2011).

(3-3) $$h_{d,\max(SR),3} = h_{CB} \quad \text{[mm]}$$

Where: h_{CB}: *height of the cutting blade [mm]*

The different wear limits have been summarised in Figure 3-15.

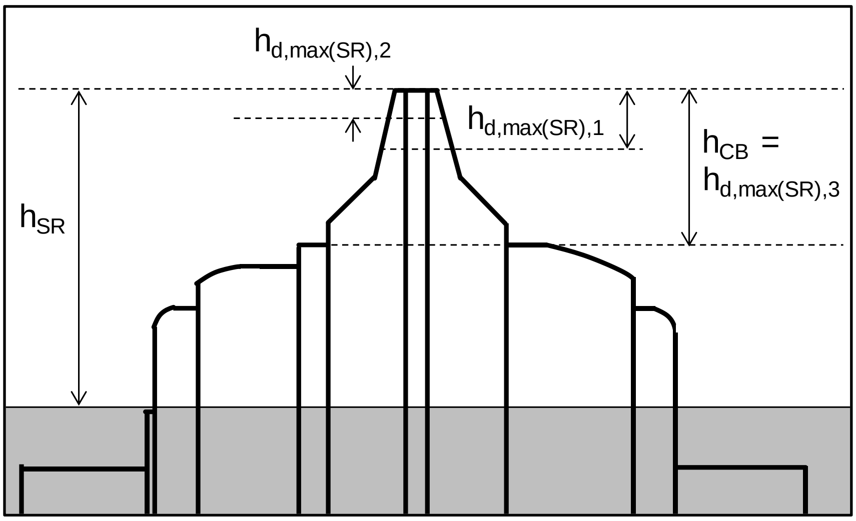


Figure 3-15: Wear limits of cutting discs.

Scraper and buckets

The wear limit of scrapers as well as buckets and rippers is limited either by the height of the hard metal inserts or by the height of the tool holder. To protect the tool holder from wear, Köppl (2014, p. 120) suggests a wear limit of the tool that leaves a protective layer of about 10 mm to the tool holder.

(3-4) $$h_{d,\max(SM),1} = (h_{SM} - h_{SMH}) - 10\ mm$$

Where: $h_{d,max(SM)}$: *wear limit – max. height loss of the scraper/bucket [mm]*
h_{SM}: *height of the scraper/bucket [mm]*
h_{SMH}: *height of the tool holder [mm]*

Furthermore, the wear limit has to differentiate between wear of the hard metal parts and wear of the tool body. If there is a greater wear of the tool body, the wear limit is reached, when the embedding of the hard metal bits is no longer given. This leads to a sudden loss of the less worn carbide inserts, hence a sudden reduction of the remaining tool height. Another reason for the loss of the hard metal bits is the sudden facture of the brittle carbonate steel due to surface fatigue or high local loadings. The total wear of the tool increases due to the lower wear resistance of the steel substrate that is no longer protected. Therefore, there is a second wear limit for scrapers and buckets that has to be taken into account as shown in Figure 3-16.

(3-5) $$h_{d,\max(SM),2} = h_{HM} \quad \text{[mm]}$$

Where: h_{HM}: *height of the hard metal bits [mm]*

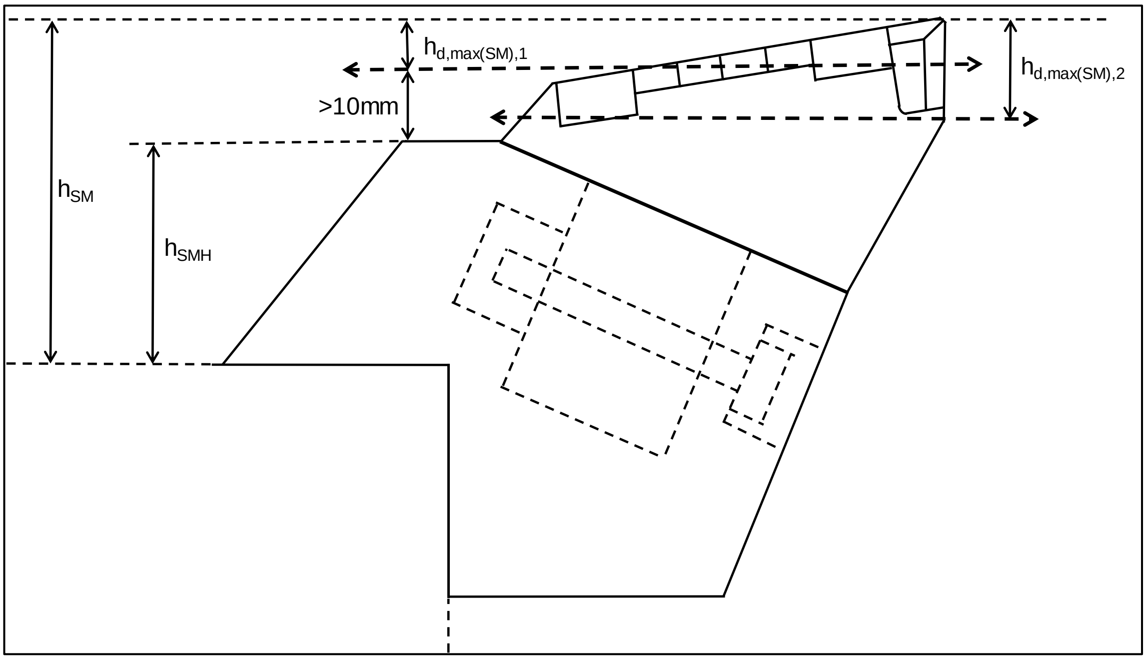


Figure 3-16: Wear limits for scraper and buckets (Köppl 2014, p. 121)

Ripper tools

The wear limit of ripper tools is also determined by the height of the hard metal bits as well (Köppl 2014). If the hard metal bits are worn out, the wear increases due to the softer tool body material. If the wear exceeds further, the tool holder is damaged and welding work will be required to replace the ripper tool (Köppl 2014). Furthermore, if the remaining height of the ripper tool is smaller than the penetration of the scraper or buckets, the other tools are no longer protected and their wear increases. Therefore, three wear limits are defined:

(3-6) $$h_{d,\max(ST),1} = h_{HM}$$

(3-7) $$h_{d,\max(ST),2} = (h_{ST} - h_{SM})$$

(3-8) $$h_{d,\max(ST),3} = (h_{ST} - h_{STH}) - 10\ mm$$

Where: $h_{d,max(ST)}$: *wear limit – max. height loss of the ripper [mm]*
h_{HM}: *height of the hard metal bits [mm]*
h_{STH}: *height of the tool holder [mm]*

The wear limits of ripper tools have been summarised in Figure 3-17.

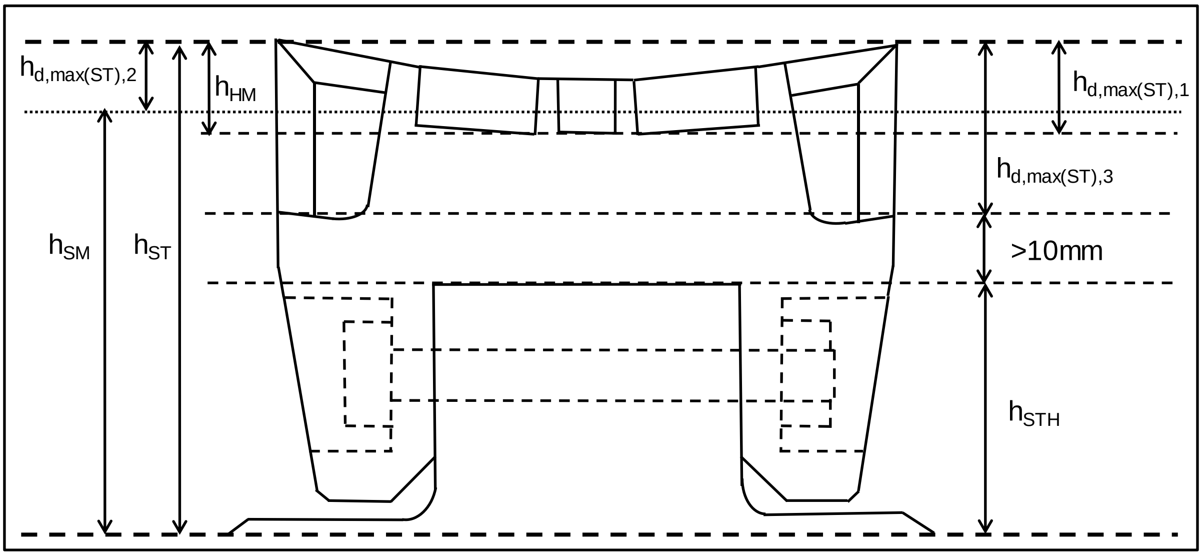


Figure 3-17: Wear limits of ripper tools.

3.1.5 Cutter head design

The design of the cutting wheel has a considerable influence on the wear of a single cutting tool (Burger 2011). As described in Section 3.1.2, scrapers or buckets, which are running behind a cutting disc or ripper tool, are less exposed to wear. Frenzel and Babendererde (2011) discovered this behaviour by looking at the wear pattern of scrapers and buckets, which have been less abraded in the area that runs behind a cutting disc. (Figure 3-18)

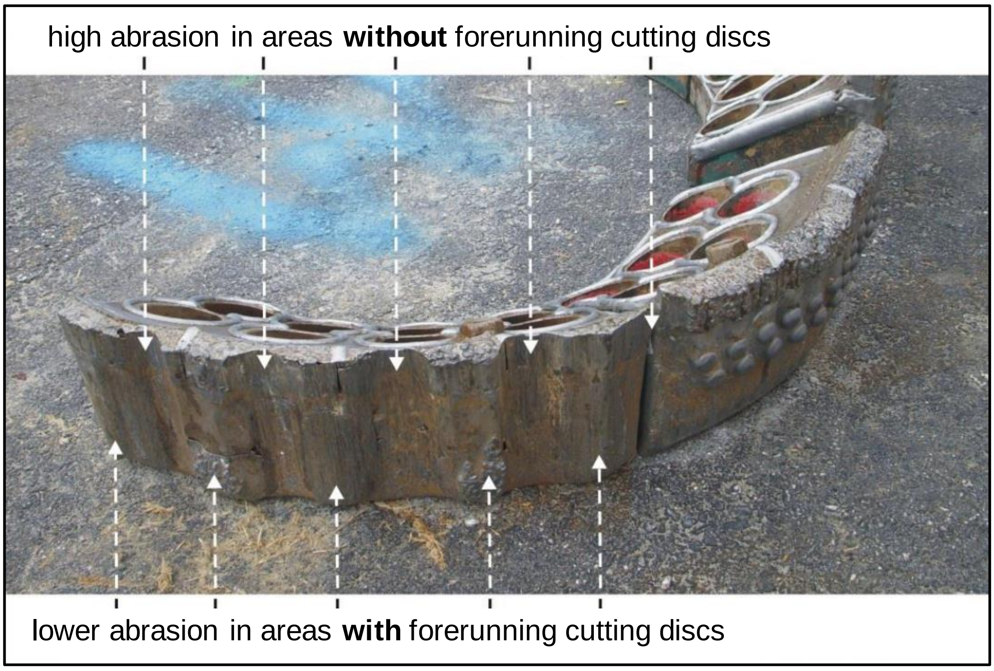


Figure 3-18: Wear pattern of a bucket with and without forerunning cutting discs (Köppl 2014, p. 123).

Furthermore, if there are several tools, especially scrapers, mounted on the same tool track, each scraper has a smaller penetration, thus the wear of the single scraper decreases (Köppl et al. 2015a).

Bruland (2000c, p. 35) analysed the wear documentation of cutting discs in hard rock excavation and observed that the wear of a cutting disc decreased after replacing the neighbouring disc. Since there is only one observation of this occurrence found in literature, further investigation is necessary in order to give a general statement.

The types of tools chosen for each track influence the wear mechanism and behaviour. Especially in clay or soft ground with a high amount of fine soil particles, clogging or a blocking of the bearing of the cutting discs cause an increase of wear. In these cases, the overall wear might decrease if the cutting discs are replaced by ripper tools. Nonetheless, this approach is not applicable for all soft ground conditions. In some cases, especially in mixed ground with hard rock parts, cutting discs are necessary to excavate and crush the hard rock parts and boulders or to cut through concrete walls of shaft constructions along the tunnel alignment (Fouda et al. 2017).

3.2 Wear Prediction of Cutting Tools

During the planning phase of a tunnelling project and especially for projects in soft ground, where the excavation chamber is hardly accessible, a wear prediction of cutting tools is essential. When planning the necessary maintenance stops, the different wear mechanisms have to be taken into account. Furthermore, the wear prediction has to cope with the uncertainties of the ground conditions and steering parameters. The variety of parameters that have an influence on the wear behaviour has not fully been assessed. For wear prediction, only a few parameters can be taken into account, even though the influence of other parameters is presumed.

There are two main approaches to predict the wear of cutting tools. One approach is to use laboratory index tests that have been invented to classify the ground according to its abrasiveness. This way, the abrasive wear of the cutting tools shall be estimated. Other approaches analyse measured wear data to find an empirical prediction model by correlating the wear of the cutting tools with certain ground parameters. Sometimes, if there is sufficient data as it is the case in hard rock TBM tunnelling, both approaches are combined.

3.2.1 Influencing parameters

The identification of relevant input parameters is mainly possible by the back analysis of collected data of finished tunnelling projects. Therefore, an extensive and preferably detailed documentation of the amount of wear and pattern of cutting tools as well as the ground properties is needed. The measured amount of wear has to be normalized to exclude the geometrical influence of the cutting path depending on the radius of the tool on the cutting wheel. However, most times the given data is not as detailed as needed, so that the uncertainty of the results increases. Furthermore, short homogeneous sections of the ground and inhomogeneity in general make it difficult to isolate correlations of a single parameter.

Another approach to estimate the influence of a certain parameter is to conduct parameter studies using laboratory tests. This way, only one parameter is changed for each test and the effect of this value on the wear behaviour can be estimated qualitatively.

In general, the parameters that have an influence on the wear amount and pattern can be divided into three categories: ground conditions, machine design and steering parameters (Figure 3-19). Furthermore, it has to be differentiated between hard rock TBM, Hydro-shield and EPB-shield as well as the wear mechanism.

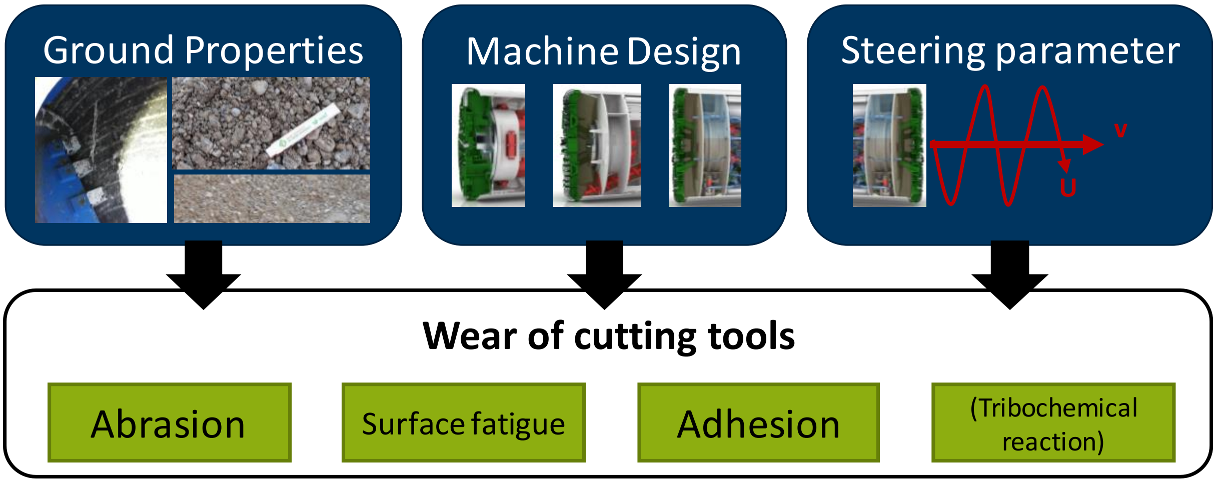


Figure 3-19: Three categories of input parameters with influence on wear of cutting tools (pictures from (Herrenknecht AG 2019a, 2019b, 2019c)).

Ground properties

Große and Borchert (2015) summarise the ground parameters that are demanded by German standards (DIN 18312) to define homogeneous sections. One of these parameters is the abrasiveness of the ground, which has to be evaluated by using the Cherchar index test (NF P 94-430) for hard rock and the test invented by the Laboratoire des Ponts et Chaussées (LCPC) (NF P 18-579) for soil (Feinendegen and Ziegler 2018), which are described in Section 3.2.2. Even though these tests are recommended, further ground parameters are needed to provide a sufficient estimation of the abrasiveness of the ground, hence of the abrasion of the cutting tools. Therefore, all influencing ground parameters for hard rock that have been regarded in literature have been summarized in Appendix A-1.

Boulders, steel components inside the ground or mixed ground conditions increase the probability of surface spalling or cracking of the cutting tools. Sticky ground leads to more adhesive wear and additionally increases the probability of a blockage of a cutting disc due to clogging. Furthermore, a high percentage of fines and mixed face conditions also increases the possibility of damaged bearings.

Machine design

The machine design has a great influence on the wear of cutting tools. The choice of the tool type, position and their total count directly influences the wear mechanism and the amount of contact with the tunnel face. The opening ratio of the cutting wheel affects the flow of the excavated ground into the excavation chamber. The wear protection of the tools themselves and also of the cutter head structure can reduce the amount of secondary wear (Willis 2012).

Steering parameters

Especially the penetration of the cutter head has a very high influence on the quantity of wear, since it directly affects the length of the cutting path per excavation meter. Figure 3-20 shows the relation between the cutting path per meter and the penetration as well as the cutting track radius. It can be seen that especially for small penetration rates there is a significant difference in the cutting path even for small deviations of penetration. For example, for a radius of r_s = 5000 mm a reduction of the penetration of 2 mm/rev from 12 to 10 mm/rev results in an increase of the wear path of 0.5 km/m.

Likewise, the cutting path increases significantly with enlarging the cutter head diameter, thus the maximum radius of a cutting track.

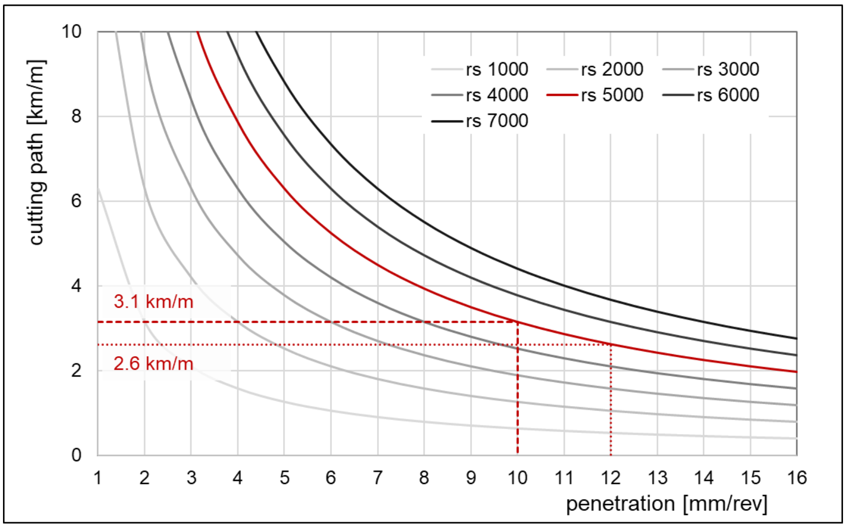


Figure 3-20: Influence of the penetration and cutting path radius r_s [mm] on the length of the cutting path per excavated tunnel meter

Furthermore, the speed of the cutting tools resulting from the rotational speed of the cutter head in combination with the pushing force of the TBM has to be limited to avoid sudden breakages or surface spalling of the cutting tools in mixed ground or blocky ground conditions.

Since there are active and passive steering parameters not all parameters can be adjusted as planned. For example, Köhler et al. (2012) evaluated the correlation of the thrust force with the penetration and showed that depending on the ground conditions the penetration is either positively or negatively correlated. The high deviation, however, indicates that there are several other input factors that have to be taken into account for the passive steering parameters.

Uncertainties

While the parameters given by the design of the TBM are known single values, the ground parameters are highly uncertain values with a considerable deviation. Similarly, the steering parameters, even if they are directly adjustable, may deviate from the expected value used for maintenance scheduling. Passive steering parameter that are influenced by other steering, design or ground parameters, e.g. the penetration of the cutter head, are subject to uncertainty as well. Using only mean or expected values for the wear predictions will very likely lead to a wrong estimation of the wear. Overestimating the wear quantity will unnecessarily reduce the productivity of the project. An underestimation of the wear quantity can lead to severe damages of the cutter head and other machine parts resulting in a long downtime for repair.

One approach to consider uncertainties is to evaluate documented project data or data gained from several laboratory tests to determine the index values of rock and soil. This way, distribution functions for single parameters can be fitted. These functions can be used within the wear prediction model to consider the influence of a certain deviation. First examples of the distribution of the Uniaxial Compressive Strength (UCS) are given by Köppl et al. (2009) and Frenzel (2010, p. 90).

3.2.2 Index tests

Many index tests have been invented to analyse the abrasiveness of the ground. First tests have been conducted by Schimazek and Knatz (1976), who investigated the influence of the quartz content on the wear amount of a steel pin scratching on a rock sample. Similar to this attempt, several further tests for hard rock and later on for soil have been developed. Those test that are used for quantitative wear prognosis are presented. Furthermore a summary of the variety of further index test is given.

Cerchar Abrasivity Index

The most common and widely used index test for hard rock is the Cerchar Abrasivity Index (CAI). The three different test setups that are used are shown in Figure 3-21. Nonetheless, the main test design is similar for each test. A predefined steel pin with a conical peak slides on the surface of a rock sample over a distance of 10 mm, loaded with 70 N and with a given speed (NF P 94-430-1). Afterwards, the increase of the diameter caused by the abrasion of the steel pin is measured to derive the CAI. The rock can then be classified qualitatively from not very abrasive to extremely abrasive (Thuro et al. 2006).

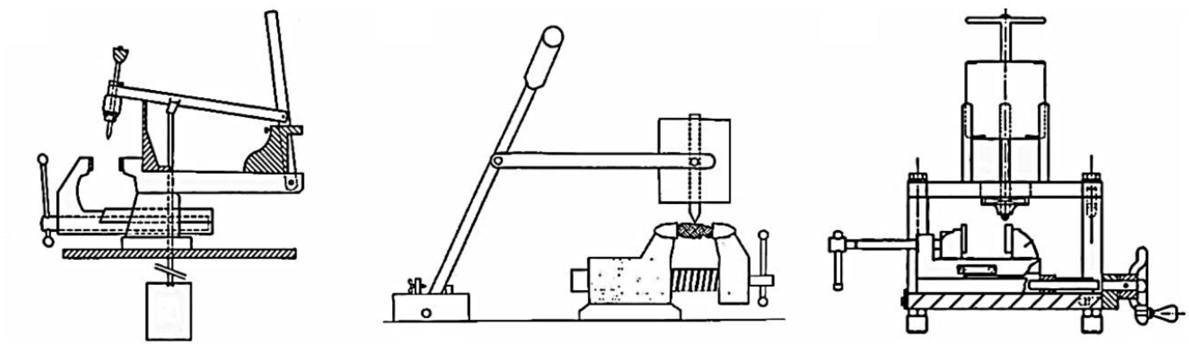


Figure 3-21: Testing devices for Cerchar abrasiveness (Hamzaban et al. 2018).

The Cerchar test and the usage of the CAI has been widely discussed in literature (Suana and Peters 1982; West 1989; Al-Ameen and Waller 1994; Plinninger et al. 2002; Plinninger et al. 2004, 2005; Rostami 2005; Alber 2008; Käsling et al. 2007;

Hamzaban et al. 2014; Alber et al. 2014; Rostami et al. 2014). Especially the experimental setup and procedure differ for different laboratories. Nonetheless, these differences have been evaluated as well.

The comparison of the determined CAI and the measured wear of cutting tools is further discussed in Section 3.2.4.

LCPC

Another test setup that can be used for the abrasiveness analysis of hard rock as well as soft ground has been invented by the Laboratoire des Ponts et Chaussées (LCPC) (NF P18-579). The test consists of a predefined steel plate that rotates with 4,500 rpm for 5 min in a 500 g dry soil sample, with a grain sizes of 4.0-6.3 mm (Firgure 3-22). Subsequently, the weight loss of the plate is measured. The weight loss is then used to determine the LCPC Abrasivity Coefficient (LAC).

This test, even though it is demanded in German standards (Feinendegen and Ziegler 2018), has several disadvantages, e.g. missing ground parameters, which are not regarded within the test device, or deviating boundary conditions, as discussed in Thuro et al. (2006), Drucker (2011b), Düllmann (2014), Küpferle et al. (2015) and Feinendegen and Ziegler (2018).

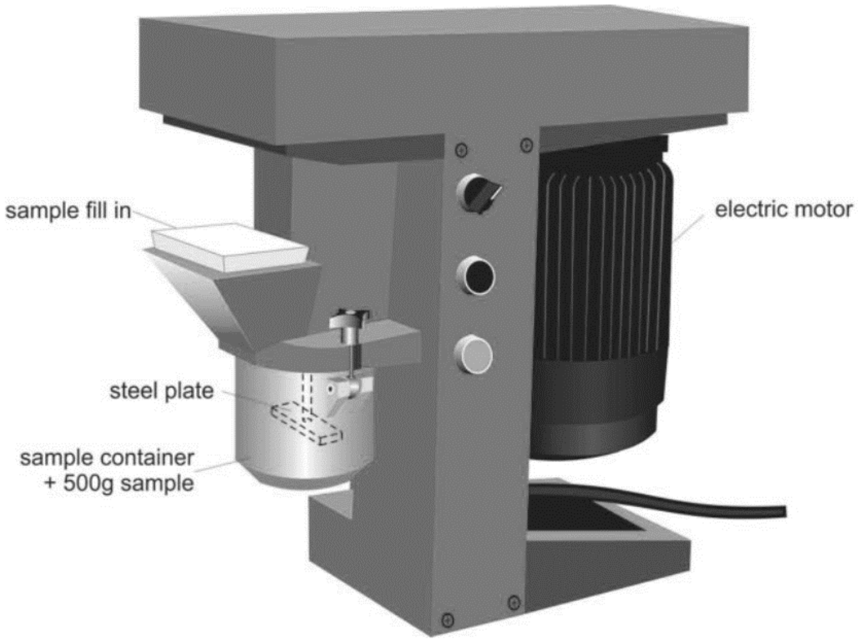


Figure 3-22: Schematic layout of the LCPC test (Düllmann et al. 2014).

Büchi et al. (1995) did one of the first comparisons of the CAI with the LAC finding a linear correlation of CAI and LAC. Thuro and Käsling (2009) correlated the CAI with the LAC and likewise found a good correlation for hard rock samples of different projects and laboratory tests.

NTNU/SINTEF abrasion testing

Further tests for hard rock and soil abrasiveness evaluation have been developed at the Norwegian University of Science and Technology (NTNU) and SINTEF (Nilsen et al. 2006c). The abrasion values AV and AVS for test bits which are made of tungsten carbide or cutter steel, are determined for crushed rock < 1.0 mm (Nilsen et al. 2006b). For soil samples the SAT (Soil Abrasion Tester) (Jakobsen et al. 2013a) and the SGAT (Soft Ground Abrasion Tester) (Jakobsen et al. 2013b) are introduced (Figure 3-23).

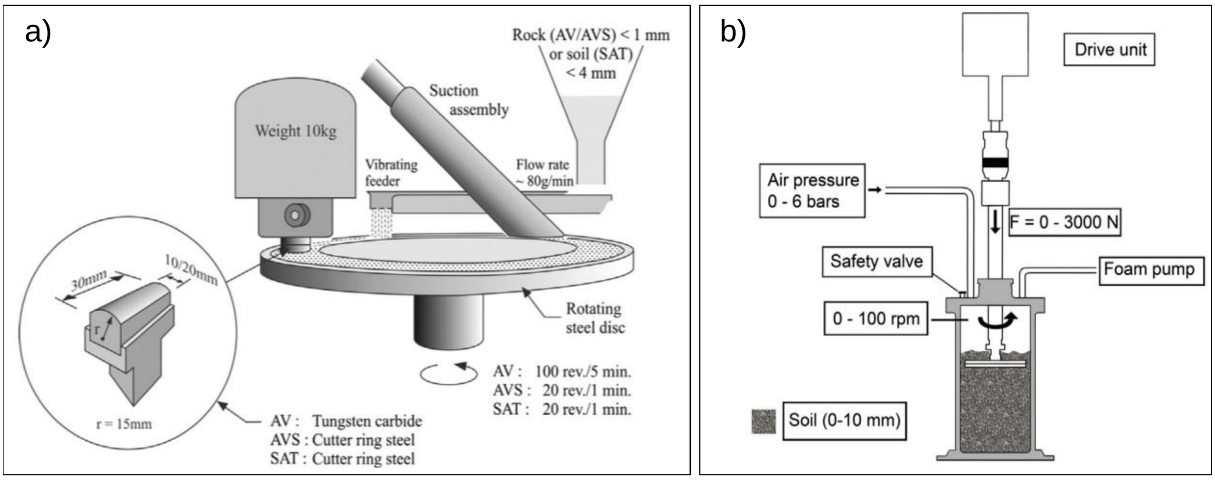


Figure 3-23: NTNU abrasion tester: a) for determining the AV, AVS and SAT values and b) for determining the SGAT value (Jakobsen et al. 2013b).

While the SAT uses the same test setup as the NTNU abrasion test with only small modifications (Nilsen et al. 2007), the SGAT consists of an impeller that rotates inside of a soil sample. The chamber containing the soil can be pressurized and foam can be added through a foam gun (Jakobsen et al. 2013b).

The results of the analysis of the ground for several projects were used to build a data base of different rock and soil types and their abrasiveness (Dahl et al. 2012). This database can be used for estimating the abrasiveness of the ground for new projects without having to perform more tests. Furthermore, Becker and Jakobsen (2013) compared the SAT-value with the tool life of pipe jacking projects, but found no correlation under consideration of only the SAT-value. However, the comparison has been conducted only for a few values that were given for each project.

Another test invented at the NTNU/SINTEF is the Sievers' J miniature drill test. This testing device has been developed to analyse the drillability of rock samples. Hereby, the SJ-value is determined by the depth of the drill holes that result from 200 revolutions of a predefined drill. New automatic measurements devices make it possible to monitor the penetration of the drill over time. This way, the Sievers' J Interception Point can be determined, giving the point in time when the edges of the drill are worn (Dahl et al. 2007). Nonetheless, this test is mostly used to determine the surface hardness and is used in combination with the AV or AVS for the cutter life prediction (Bruland 2000a).

Dahl et al. (2012) investigated and compared the different index tests of the NTNU/SINTEF, trying to find correlations between the parameters. The results show that two different tests do not describe the exact same rock property. In some cases, more than one property influences the result of a test.

Further index test

Several other wear tests have been invented during the last decades. For example, Wilms (1995) presented a wear measurement pot that can be used to investigate soil samples under pressurized conditions. Similarly, Drucker (2011a) presents the TU-Abrasimeter of the TU Wien.

The proposed abrasion tester of Gharahbagh et al. (2010) is an approach similar to the SGAT. The testing device consists of an impeller rotating in a chamber filled with soil (Rostami et al. 2012). This chamber can be pressurized and condition agents like foam can be added during the experiment or beforehand. With this device the Penn State soil abrasion index (PSAI) is determined (Gharahbagh et al. 2013a) and the influence of soil conditioning on the abrasive wear can be examined (Gharahbagh et al. 2014).

Küpferle et al. (2016) proposed the RUB-tunnelling device (RUB-TD) that has a horizontal set up consisting of a cylindrical container and a cutter head mounted on a shaft. Steel pins are mounted on the arms of the star shaped cutter head and move through a soil sample similar to the cutting path of cutting tools. This way, the pins always cut through fresh soil. The wear is determined by measuring the weight loss of the steel pins. For each run of the experiment, the steering parameters, e.g. the penetration rate and rotational speed can be varied. Furthermore, conditioning agents can be added through the cutting wheel centre and the whole soil sample can be pressurized (Küpferle et al. 2018b). The device has been used to analyse the influence of different steering and soil parameters and especially of different tool materials (Küpferle et al. 2018a). Furthermore, the influence of the water content, the grain size distribution and the filter cake of a bentonite face support has been examined (Küpferle et al. 2018b).

The conducted test showed that testing soil samples that are mixed with a bentonite slurry beforehand do not represent the wear behaviour at the tunnel face, where a filter cake is formed due to the injection of the bentonite slurry.

Peila et al. (2012) proposed a test device similar to the SGAT or PSAI test device. This device has been further adapted and used by Bosio et al. (2018). The device consists of a steel tank and an impeller on which the steel samples for the wear measurements are mounted. During the test, the impeller rotates with 160 rpm inside the soil sample and thereby moves up- and downwards for 90 mm three times. The whole testing duration is 15 min. In the end, the volume loss of the wear tools is measured. For the performed tests, they used mechanically crushed silica sand, dry and pre-conditioned. This way, the effect of the microstructure of the steel matrix on the wear behaviour for soil samples with and without soil conditioning has been analysed. Later on, Oñate Salazar et al. (2018) used the test device for further analyses of the wear behaviour and shape of the wear tool.

Barzegari et al. (2013a) proposed the Newly Developed Abrasion Test (NDAT), which consists of a tank that is filled with a soil sample. At the bottom of the tank, there is a rotating steel plate. The soil sample can be pressurized and water as well as additives can be added at the top of the container. The first results were compared to the CAI, LAC and SAT abrasivity index value. Here, the influence of the equivalent quartz content eQu is regarded as well. Later different parameter studies have been performed with the NDAT (later called: Newly Developed Device NDD) (Barzegari et al. 2013b) and again in Barzegari et al. (2015) (here called: Soil Abrasion Testing Chamber SATC).

At the Colorado School of Mines a Linear Cutting Machine (LCM) has been invented for penetration, thus performance prediction (Rostami 1997). A disc cutter rolls over a rock sample, so that full size cutting tests can be performed and real scale results can be obtained (Gertsch et al. 2007; Entacher et al. 2012). This testing device can be used to examine the wear of the cutting disc as well; even though there are no published results for wear analysis yet. In cooperation with the Colorado School of Mines (CSM), a minidisc test has been developed at the Montan University Leoben. This way, a smaller rock sample can be tested.

Similar to the CSM investigation Lin et al. (2017) developed a TBM cutter performance test bench to evaluate the wear of the cutter ring. However, no cutting discs are used, but cutter ring plates with adjustable material. This test is used to determine the mass loss and to examine the wear pattern of the plate’s surface (Zhang et al. 2017; Lin et al. 2017).

An overview as well as comparison of the presented and further laboratory tests for the estimation of the ground abrasiveness can be found in (Ozdemir and Nilsen), Plinninger and Restner (2008), Jakobsen (2012), Jakobsen and Lohne (2013), Köppl (2014), Jakobsen (2014), Barzegari et al. (2015) and Macias et al. (2016).

3.2.3 Wear prediction models

For the wear prediction of cutting tools in mechanized tunnelling, several prediction models have been developed over the last decades. The models combine an index values of the ground properties with an empirical evaluation of measured wear data of finished tunnelling projects. Especially for hard rock TBM, there are a number of prediction models, since the accessibility of the excavation chamber and the high number of worn tools during one project provide a larger amount of usable data.

Nonetheless, a few prediction models for Hydro-shield and EPB-shield TBM have been developed during the last years as well. Similar to the hard rock prediction models, they are based on an empirical evaluation of wear measurements and tool replacements. However, most of them take more values of the ground, steering and machine design properties into account than are used for the hard rock prediction models. The most common models are presented below.

Hard rock prediction models

In 1988 Lislerud introduced the Cutter Life Index (CLI), attained by evaluating data from finished tunnels. This index is used to estimate the disc cutter life in hard rock tunnelling for different rock types. The average cutter ring life is calculated by multiplying the CLI with given correction factors for the eQu (k_Q), the size of the disc cutter (k_d), the cutter head size (k_φ) and rotational speed in rpm (k_{RPM}). The CLI is an index value for the rock hardness and the rock abrasiveness. The range of the CLI value is given for different rock types.

The model has been elaborated later on at the NTNU by (Bruland 2000a) and Bruland (2000b). The CLI has been determined by the AVS, giving the abrasiveness of crushed rock powder and the Sievers' J-value for surface hardness (Kizaoui and Wax 2005).

(3-9) $$CLI = 13.84 * SJ^{0.3847} * AVS^{-0.3847}$$

Where: SJ: Sievers' J-value

The basic average disc cutter life (H_0) has then been plotted over the CLI for different disc cutter diameters. Furthermore, the correcting factors have been revised, giving new diagrams and adding a factor for the number of tools (k_N). The correcting factor for the disc cutter diameter is neglected here, since it has already been used for the estimation of the CLI. The average cutter life can then be estimated by:

(3-10) $$H_h = (H_0 * k_D * k_Q * k_{rpm} * k_N)/N_{tbm}$$ *[h/c]*

Where: N_{tbm}: *actual number of cutters*

Subsequently, the cutter life can be determined for other wear units. Multiplying H_h with the advance rate gives the maximum excavation length until a cutting disc has to be replaced (H_f [m/c]). Taking the diameter of the cutter head into account, the average mass of excavated rock per cutter replacement (H_s [sm³/c]) can be determined.

Gehring (1995) evaluated wear data of tunnelling projects for his wear prediction. The wear was determined as specific weight loss per meter of an excavated tunnel v_{si} [mg/m]. Gehring found relatively good correlation of v_{si} to the CAI value using a regression curve:

(3-11) $$v_{si} = 0.74 * CAI^{1.93}$$ [mg/m]

The average tool life V_c in m³-excavated rock can be estimated as follows:

(3-12) $$V_c = \frac{\Delta G_{zul} * \bar{F}_N * (k_1 * k_2 * \ldots * k_i) * D_c}{4 * \bar{D} * v_{si} * \sigma_c * N_c}$$ *[m³]*

Where: ΔG_{zul}: *maximum allowed weight loss of the cutting disc [g]*
$\bar{F}_N$: *average contact pressure of one cutting disc [kN]*
k_i: *correction factors (see: (Gehring 1995))*
D_c: *cutter head diameter [m]*
$\bar{D}$: *average cutting path diameter [m]*
σ_c: *Uniaxial Compressive Strength (UCS) [N/mm²]*
N_c: *Number of cutters on cutter head*

The given correction factors shall be adapted according to the gained knowledge of further project data evaluation.

Maidl et al. (2001) presents the relation between the cutter life [m³/cutter] and the UCS and the CAI shown in Figure 3-24. Thereby, they state that the diagram gives not an exact wear value, but an area of values instead, since there are always uncertainties that have to be considered.

Rostami et al. (2005) published the CSM wear prediction model. The CSM model uses the CAI value to calculate the linear feet (LF) for cutting discs traveling path using the following formula:

(3-13) $$LF = \frac{6.75 * d}{17 * CAI}$$ *[ft]*

Where: *d: diameter of the disc cutter [in]*

Taking the cutter head geometry into account the number of cutter head revolutions *#Rev* for a disc on average radius can be determined.

(3-14) $$\#Rev = \frac{LF}{0.32 * \pi * D_{TBM}}$$

Where: *D_{TBM}: diameter of the cutter head [ft]*

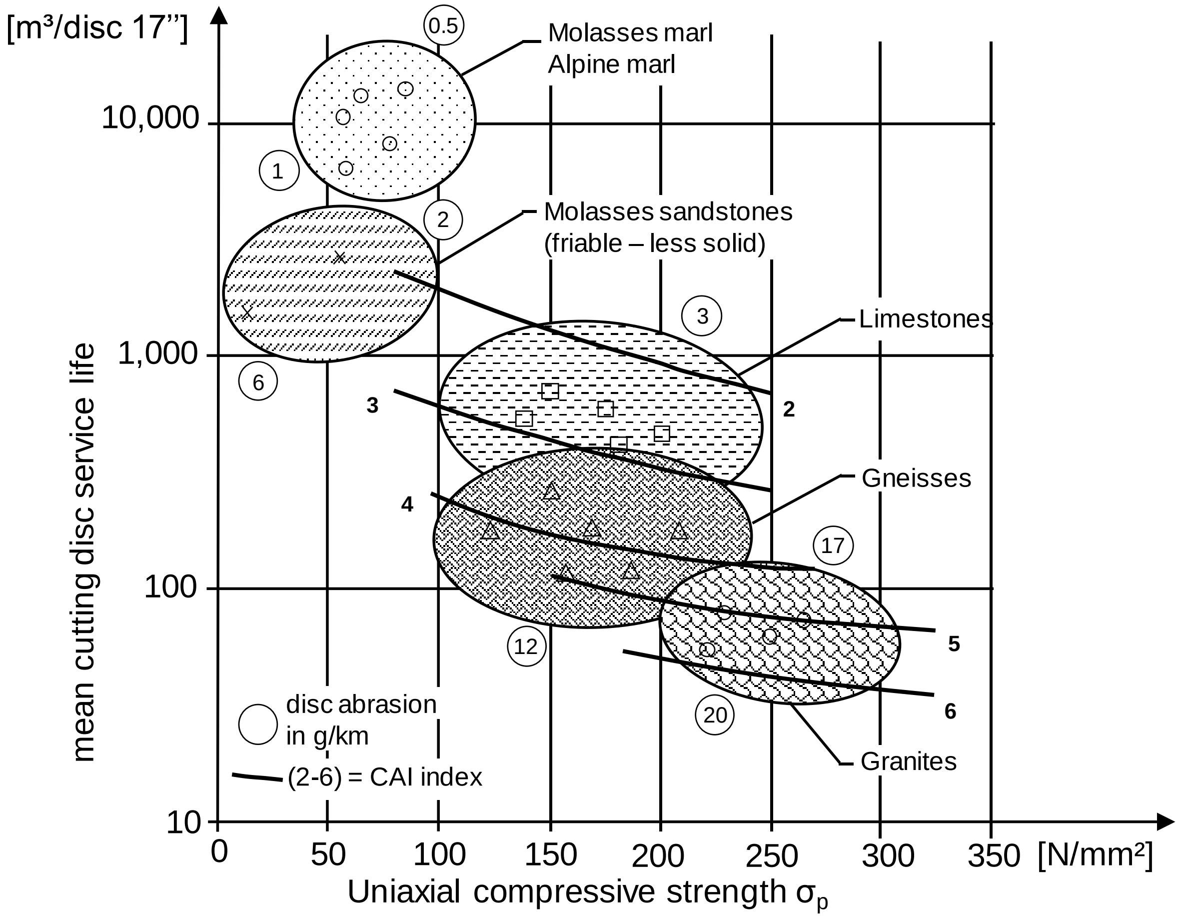


Figure 3-24: Mean cutting disc service life correlated to the uniaxial compressive strength and the CAI index value (based on Maidl et al. 2001).

Here, as well, the value #Rev can be translated into cutter life in hours and worn cutter per cubic yards (cubic meter) or tons of excavated rock per cutter change. Nonetheless, it is stated that the determination of the CAI is crucial to this prediction model. As mentioned in Section 3.2.2, different testing devices and setups have been established, which may lead to a significant difference in the resulting CAI value.

Frenzel (2010; Frenzel et al. 2008) evaluated several tunnelling projects and compared the resulting wear coefficient with the CAI value as Gehring (1995) proposed in his wear diagrams. However, even though the data does not fit the model of Gehring or

Rostami, a new regression model is not presented. The corresponding wear prognosis model uses the wear coefficient based on the CAI, the average cutting path of the tools and a correction factor for the distribution of the tools on the cutting wheel to determine the number of rotations of the cutting wheel, until the wear limit is reached. This value is then used to determine maintenance costs. Furthermore, it is suggested to perform a Monte Carlo Simulation (MCS) to take the uncertainties of the input parameters into account.

Similar to the NTNU data base for hard rock, Hassanpour et al. (2014) evaluated the wear data of a 30 km long tunnelling project in Iran to develop a prediction model for wear prognosis. They used linear and multiple regression methods, gaining two prediction formulas for the tool life H_f:

(3-15) $$H_f = -940.1 * \ln(ABI) + 6939.4$$ [m³/cutter]

Where: $$ABI = VHNR * \left(\frac{UCS}{100}\right)$$

ABI: *Abrasiveness Index [-]*
VNHR: *Vicker's hardness number of rock [-]*
UCS: *uniaxial compressive strength [MPa]*

For the multiple regression, the same two parameters have a significant influence on the tool wear: UCS and VNHR.

(3-16) $$H_f = -2.669 * VHNR - 7.891 * UCS + 3430.955$$ [m³/cutter]

Later on, this equation has been adjusted by Hassanpour et al. (2015) adding data from more tunnelling projects to improve the correlation. The formula showing the best correlation considers the data of all projects, resulting in:

(3-17) $$H_f = -2.544 * VHNR - 8.331 * UCS + 3288.248$$ [m³/cutter]

In Hassanpour (2018) another project has been evaluated using the wear prediction by Bruland (2000b). Afterwards, another multiple regression model has been found according to Equation 3-16 and (3-17). Here, the main influencing parameters are the UCS and the VHNR as well:

(3-18) $$H_f = -2.013 * VHNR - 8.074 * UCS + 2859.35$$ [m³/cutter]

Hassanpour concluded that each equation is only valid for the same boundary conditions as the associated project, since there is a difference in wear prediction, especially for low values of VHNR (Figure 3-25-a). Thus, this model can be used for different types of Limestone, sandstone, shale and low to medium grade metamorphic rocks with an UCS = 30-150 MPa.

In addition to the proposed equations, a general prediction diagram for the cutter life, shown in Figure 3-25-b, is offered to get a quick qualitative assessment of the tool life.

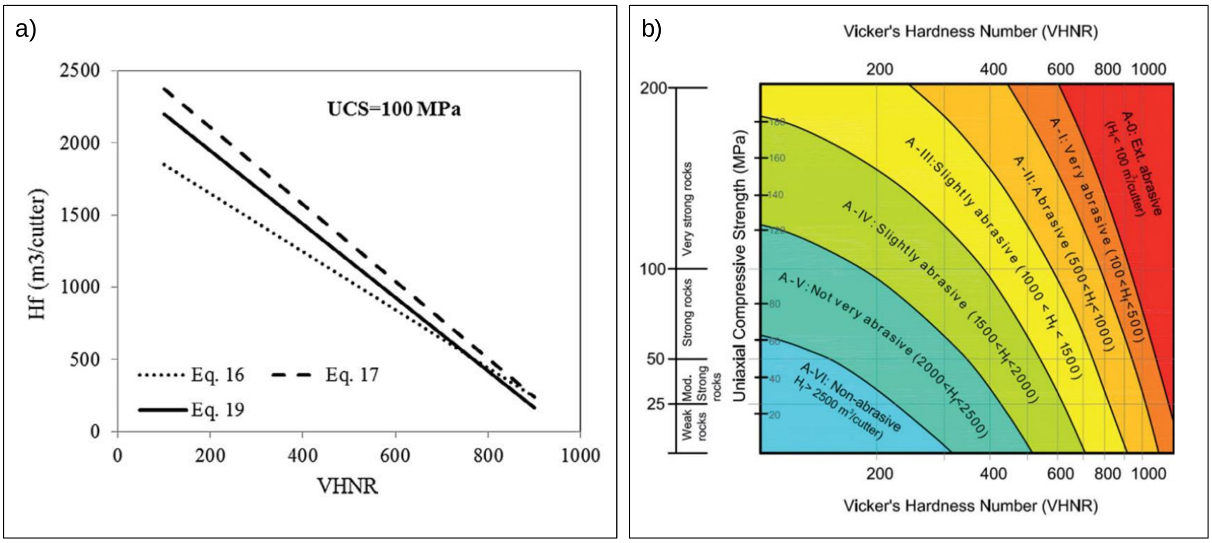


Figure 3-25: a) Comparison of prediction models (Hassanpour 2018) and b) General cutter life prediction chart (based on Hassanpour et al. (2015)).

EPB-shield prediction models

Jakobsen (2014) analysed several tunnelling projects in soft ground to find a prediction model for the wear of soft ground cutting tools. Therefore, he analysed the influence of different index values on the tool life. Thereby he discovered that the Geotechnical Uniformity Index (C_u), which describes the uniformity of grading of the grain size distribution ($C_u = D_{60}/D_{10}$), is statistically significant for the estimation of the Soft Ground Tool Life (SGTL), which represents the amount of excavated soil in solid-m³ per tool [sm³/tool]. Using the C_u, following regression curve has been found:

(3-19) $$SGTL = 1071.3 * e^{-0.28*C_u}$$ *[sm³/tool]*

Analysing the correlation of the SAT with the SGTL, he found a difference between the tool life of EPB and Hydro-shield TBM. Therefore, several regression models are presented as shown in Figure 3-26.

C_u and the SAT value are the only index parameters that were found with a significant influence on the SGTL. This might be due to the small amount of obtained data. Since both values are independent, a prediction formula for SGTL has been proposed:

(3-20) $$SGTL = 2245 - (44.7 * SAT) - (180.3 * C_u)$$ *[sm³/tool]*

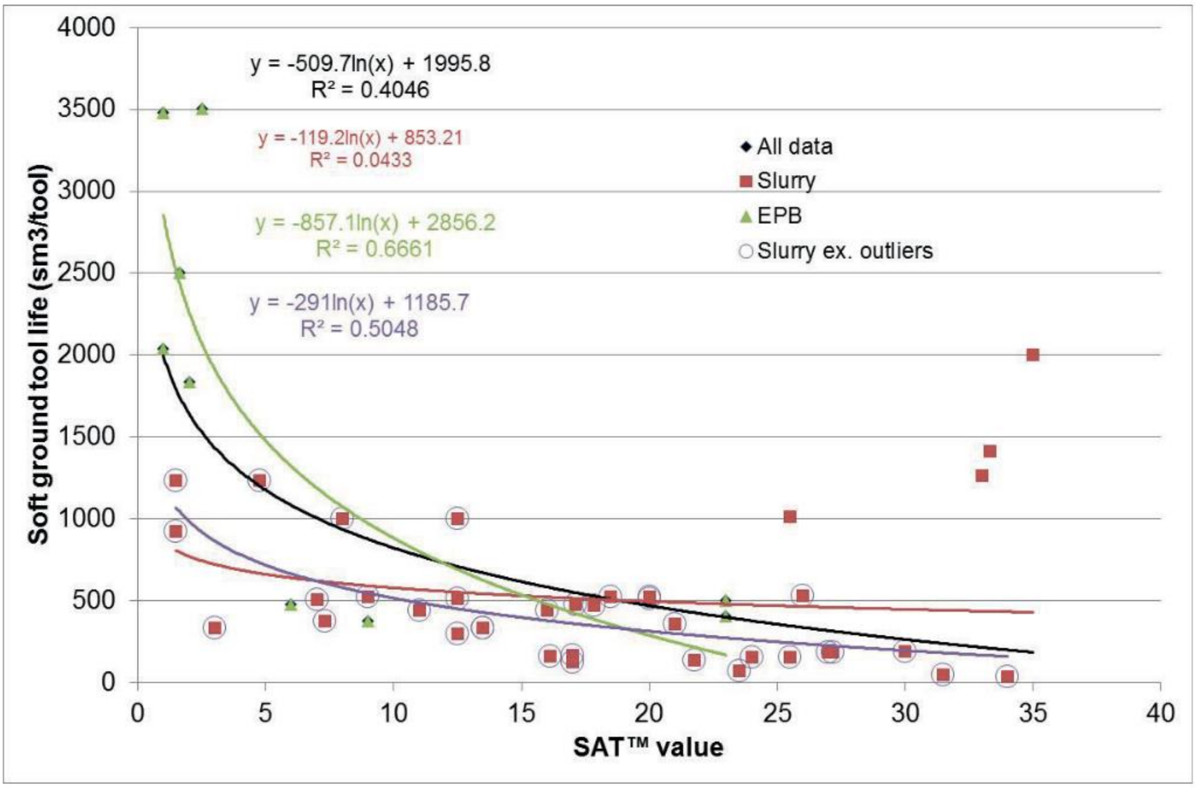


Figure 3-26: Correlation of the SGTL for EPB and hydro-shield (slurry) TBM with the estimated SAT value (Jakobsen 2014, p. 68)

This prognosis has the disadvantage of only being feasible for a certain range of input parameters. If the values are out of bound, a negative tool wear is estimated. Furthermore, this formula has only been validated by a comparison to one measured value.

Amoun et al. (2017) evaluated the wear data of an EPB tunnelling project in Tehran. Therefore, they investigated the influence of different machine and ground parameter on cutter life (CL). Thereby, four equations were found that show good correlation for this project:

(3-21) $$CL = 0.32E6 - 0.41E5 * D_{50} + 0.31 * C_f$$ [m]

(3-22) $$CL = 0.34E6 - 0.13E5 * D_{75} + 0.32 * C_f$$ [m]

(3-23) $$CL = -0.43E6 + 4.3E5 * (\log Passing200) + 0.41 * C_f$$ [m]

(3-24) $$CL = 0.43E6 - 0.07E5 * Gravel + 0.40 * C_f$$ [m]

Where: C_f: *concentration of used surfactant in the foaming liquid [%]*

D_{50}: *medium grain diameter of the sample at 50% mass friction [mm]*

D_{75}: *medium grain diameter of the sample at 75% mass friction [mm]*

Passing200: particles smaller than 75 µm [%]
Gravel: grains < 75 mm and > 4.75 mm [%]

Even though these equations show correlations with $R^2 \geq 0.97$, they are only valid for this project with its specific boundary conditions. For different projects, even with similar boundary conditions, they may not be valid. Hence, a validation with further different projects is needed. Nonetheless, these equations represent the first attempts for wear prediction for EPB tunnelling only.

Hydro-shield prediction models

Düllmann (2014) analysed two hydro-shield projects and showed that not only the eQu and the grain shape are decisive for the cutting tool wear. Based on his research, he proposed a diagram (Figure 3-27) that can be used to get a qualitative wear prognosis using selected parameters. These are divided into parameters for the resistance of the ground and the abrasiveness of the soil. Due to the lack of sufficient data this model has not been further specified.

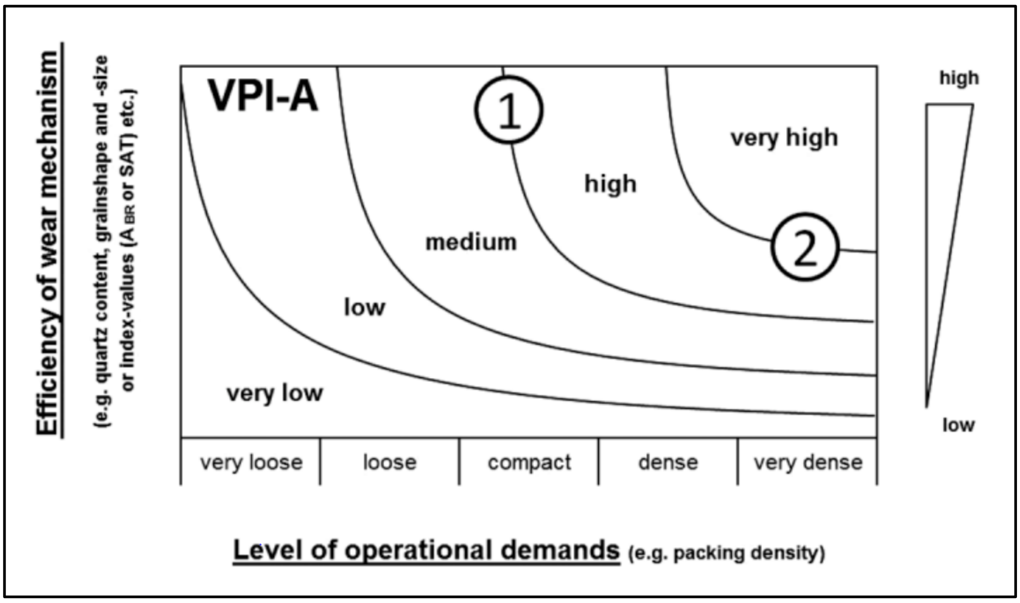


Figure 3-27: Conceptual schemes for improved diagrams for the assessment of soil abrasiveness related to the wear of excavation tools (Düllmann et al. 2014).

A quantitative wear prediction for hydro-shield tunnelling projects is given by Köppl et al. (2015a). The data of 18 excavated tunnels has been analysed to gain the wear data for each tool type and to identify the main influencing parameters for a hydro-shield TBM (Köppl et al. 2015b).

The presented prediction model considers the abrasiveness of the ground by using the eQu, because no sufficient data of any index tests has been provided within the used data. Additionally, the grain size D_{60} is taken into account. The forces acting on the cutting tools due to the ground resistance is approximated by the shear strength τ_c using the Mohr-Coulomb criterion:

(3-25) $$\tau_c = c' + \sigma_n * \tan\varphi'$$ [kN/m²]

Where: *c':* *cohesion [kN/m²]*
φ': *friction angle [°]*
σ_n: *normal stress of the ground [kN/m²]*

The normal stress of the ground is determined by the primary vertical stress at the tunnel face at the level of the tunnel axis:

(3-26) $$\sigma_n = \sum_i h_i * \gamma_i$$

Where: *h_i:* *thickness of the soil layers above the tunnel axis [m]*
γ_i: *unit weight of the soil layers [kN/m³]*

These soil parameters are combined using the Soil Abrasivity Index (SAI) and are hereby included in the wear prediction model.

(3-27) $$SAI = \left(\frac{eQu}{100}\right)^2 * \tau_c * D_{60}$$ [-]

It can be seen, that of all three values a greater influence of the eQu is considered. The SAI has been used to find a regression model for the determined wear paths of the cutting discs and scrapers. The basic value for the maximum cutting path $s_{c,b}$ of each homogenous ground section *z* can then be determined by:

Cutting discs:

(3-28) $$s_{c,b(z)} = 312.0 + \exp(-0.0048 * (SAI_{(z)} - 1398.2))$$ [km]

Scrapers:

(3-29) $$s_{c,b(z)} = 280.9 + \exp(-0.0050 * (SAI_{(z)} - 1300.7))$$ [km]

There is no regression model for buckets or rippers presented, due to the small amount of available data sets. Nonetheless, it is assumed that the cutting path of scrapers and buckets as well as rippers are similar, so that Equation 3-29 can be used to approximate their wear behaviour as well. (Köppl 2014)

Similar to the proposed wear prediction models, correction factors are presented to adapt the basis value according to the different boundary conditions of each project. For cutting discs there is a correction factor for the tip width, considering a tip width b_{SR} = 19 mm to be the most common value.

(3-30) $$f_{b(z)} = \frac{b_{SR}}{19}$$

For the scrapers there are two main correction factors. The first factor considers the actual penetration $p_{a(z)}$ of the scrapers. The actual penetration is determined taking the expected penetration $p_{e(z)}$ and the number of equal scrapers on the same cutting path k_{sc} into account. For a symmetrical build of the cutter head, it can be calculated as follows:

(3-31) $$p_{a(z)} = \frac{p_{e(z)}}{k_{sc}} \quad \text{[mm/rev]}$$

If the cutter head build is not symmetrical, the equation has to take the angular distance δ_a [°] of the scrapers on the same track into account that are cutting in the same direction:

(3-32) $$p_{a(z)} = \frac{\delta_a}{360} * p_{e(z)} \quad \text{[mm/rev]}$$

Using the actual penetration, the cutting path can be adapted by the factor:

(3-33) $$f_{p(z)} = \frac{1}{1.6^{\log_{0.5}\left(\frac{16}{p_{a(z)}}\right)}}$$

When there is a ripper tool running in front of a scraper tool, the maximum cutting path can be increased by the factor $f_{h(z)} = 3.4$. The expected cutting path $s_{c,e(z)}$ can be determined by multiplying the basis value with the necessary correction factors.

Taking the cutter head design into account, the excavation length $L_{c(k),i}$ until the maximum cutting path of each tool is reached, can be determined as shown in Figure 3-28-a. The minimum value of all $L_{c(k),i}$ gives the maximum excavation length until the next maintenance stop is necessary.

(3-34) $$L_{c(k),i} = \frac{s_{c,e(z)} * p_{e(z)} * 1000}{2 * \pi * r_s} \quad \text{[m]}$$

Where: r_s: *track radius of the cutting tool [mm]*

The chainage of the next maintenance stop can be calculated by adding the maximum excavation length $L_{c(k),max}$ to the current position.

When there is a change of the homogeneous section, thus a change in the boundary conditions of the ground, it is necessary to calculate the tool condition at the changing position. Therefore, Equation 3-34 can be reversed to obtain the partial cutting path $s_{cd,e(k)}$ for each section k:

(3-35) $$s_{cd,e(k)} = \frac{L_{d,e(k)} * 2 * \pi * r_s}{p_{e(z)} * 1000} \quad \text{[mm]}$$

Where: $L_{d,e(k)}$: *length of advance section k [m]*

The tool condition $e_{cd,e(k)}$ is then calculated comparing the driven ($s_{cd,e(k)}$) and the maximum cutting path ($s_{c,e(z)}$) of the homogeneous section:

(3-36) $$e_{cd,e(k)} = \frac{s_{cd,e(k)}}{s_{c,e(z)}} \quad \text{[-]}$$

The wear limit of a cutting tool is reached when the run cutting path is equal to the maximum cutting path, thus $e_{cd,e(k)} = 1.0$.

This prediction model cannot only be used to calculate the number and chainage of the needed maintenance stops, but also allows an estimation of the number of tools that have to be changed. For each maintenance stop, not only the cutting tools with $e_{cd,e(k)} \geq 1.0$ have to be replaced, but also those, whose remaining cutting path is smaller than the cutting path until the next maintenance stop (Figure 3-28-b).

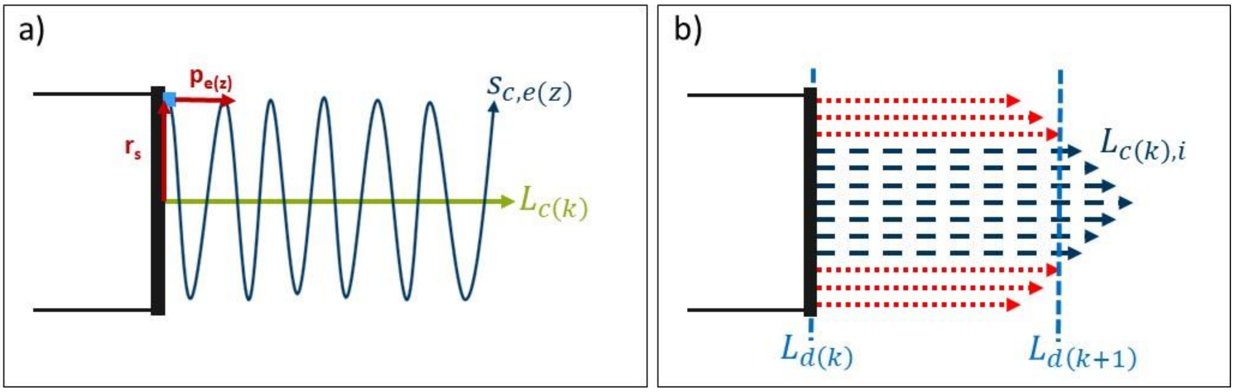


Figure 3-28: a) Helix shaped cutting path $s_{c,e(z)}$ and excavation length $L_{c(k)}$ of one cutting tool with the position given by the radius r_s and a penetration $p_{e(z)}$;
b) Maximum longitudinal length of each cutting tool $L_{c(k),i}$. Cutting tools that have to be replaced preventively are marked in red (dotted line).

Another wear prediction model of the Japanese Tunneling Society (JTS) is presented by Li et al. (2017). It is combined with the theory of interval analysis to consider uncertainties in the boundary conditions of soil and steering parameters. This prediction models uses a wear coefficient k that has been determined by the evaluation of tunnelling project data and determines the amount of tool wear δ for each cutting tool:

(3-37) $$\delta = \frac{k * \pi * D * N * L}{V} = \frac{k * \pi * D * N}{\sqrt{V^2 + \pi^2 N^2 D^2}} * S \quad \text{[mm]}$$

Where: k: *wear coefficient of soil [mm/km]*
D: *diameter of the cutter head [mm]*

N: rotational speed [rpm]
L: excavation distance [km]
V: advance rate [mm/min]
S: travel distance of the tool [km]

If there are several cutting tools mounted on the same cutting path the wear coefficient k has to be reduced:

(3-38) $$k_n = \frac{k}{n^{0.333}} \quad \text{[mm/km]}$$

Where: n: number of cutting tools on the same track

The wear coefficients for typical ground conditions in Japan and China are given by the JTS (Table 3-1) and have been proven valid for projects in the same region.

Table 3-1: Coefficient k of wear given by the JTS (Li et al. 2017)

Types of soils	EPB shield	Slurry shield
Alluvial clay	3.0-3.5*10^{-3} mm/km	1.7-2.4*10^{-3} mm/km
Diluvial clay	8.0-15.9*10^{-3} mm/km	5.0-11.3*10^{-3} mm/km
Sand	10.6-19.7*10^{-3} mm/km	4.8-15.2*10^{-3} mm/km
Gravel	15.9-29.6*10^{-3} mm/km	9.8-23.0*10^{-3} mm/km

3.2.4 Discussion of the wear prediction

In hard rock tunnelling, the use of index tests is a common method to determine the abrasiveness of the rock. Wear prediction models that base on the values gained from these test showed high correlation and they are already used to predict the amount of wear. The input parameters of the prediction models are summarized in Table 3-2. Since all prediction models are based on empirical data from analysed projects, it is plausible that the proposed models differ. A rough estimation of the extent of maintenance is sufficient, since daily maintenance shifts are scheduled for most of the projects in hard rock. Nonetheless, since most of the prediction models use the CAI, it has to be taken into account that there are deviations that might occur due to differing testing devices and procedures. A review of all hard rock prediction models can also be found in Frenzel (2010), Schneider et al. (2012) and Plinninger et al. (2018).

Table 3-2: Input parameters of the hard rock prediction models.

Prediction model	Rock properties	Machine design	Steering parameter
NTNU	SJ, AVS, eQu	d_d, D_{TBM}, n_{tools}, $n_{t,track}$	rpm, v
Gehring	CAI, UCS	ΔG_{zul}, $\bar{F}_N$, D_{TBM}, d_{act}, N_c	
Maidl	CAI, UCS	17'' discs	
CSM	CAI, Trennflächenabstand	d_d, D_{TBM}, N_c, A_{TBM}	p, v
Frenzel	CAI	S, D_{TBM}, n_{tracks}, n_{gauge}	p
Hassanpour	VNHR, UCS	D_{TBM}, N_c,	

p:	penetration [mm/rev]	v:	advancement speed [mm/min]
ΔG_{zul}:	wear limit [mm]	$\bar{F}_N$:	contact pressure cutting disc [kN]
S:	spacing [mm]	A_{TBM}:	area of tunnel face [m²]
d_d:	size of disc cutter [mm]	D_{TBM}:	cutter head diameter [mm]
d_{act}:	average diameter of tool tracks [mm]	n_{tt}:	number of tools on one track
N_c:	number of tools	n_{tracks}:	number of tool tracks
n_{gauge}:	number of gauge cutters		

For soft ground tunnelling several index tests were developed, but none has proven practicable yet. Even though the LCPC test is demanded by the European standards, it has a lot of discussed disadvantages. Therefore, no wear prediction model for soft ground exists that considers the LCPC value.

The reviewed prediction models for EPB and hydro-shield tunnelling are all based on the correlation of empirical wear data with the corresponding soil parameters. The considered soil parameters and index values are summarized in Table 3-3. Until now, no general prediction model for either EPB or hydro-shields could be found. All prediction models are only applicable for values in between the boundaries of the analysed projects properties.

For the model of this thesis, a quantitative wear prediction model for hydro-shields is needed. Köppl et al. (2015a) proposes a model that allows an estimation of the wear of each cutting tool and in addition offers a first attempt for maintenance scheduling based on this individual wear behaviour. Furthermore, compared to the other reviewed models, this wear prediction is based on data of a higher number of analysed projects, thus is not restricted to a certain area with the same known soil properties. Using common soil properties for the SAI this model is easily applicable on new projects. However, to use this model, a rough estimation of the cutting wheel design, e.g. the number of tools and their position, is needed. Furthermore, there is no differentiation between the wear limit of tools on the outer tracks and the inner tools, although the outer tools have to ensure a sufficient overcut.

Table 3-3: Input parameters of the soft ground prediction models.

Prediction model	Soil properties	Machine design	Steering parameter
EPB			
Jakobsen	SAT, C_u	N_c, A_{TBM}	
Amoun	C_f, D_{50}, D_{60}, Passing200, Gravel	N_c, A_{TBM}	
JTS	k	D_{TBM}	U, v, L
Hydro-shield			
Köppl	eQu, D_{60}, h/h', γ/γ', c', φ'	r_s, n_{tt}, b_{SR}	p
JTS	k	D_{TBM}	U, v, L

p: penetration [mm/rev]
v: advancement speed [mm/min]
A_{TBM}: area of tunnel face [m²]
b_{SR}: width of disc cutter [mm]
D_{TBM}: cutter head diameter [mm]
n_{tt}: number of tools on one track
N_c: number of tools
C_f: concentration of used surfactant in the foaming liquid [%]
D_{50} / D_{60} / D_{75}: medium grain diameter of the sample at 50/60/75 % mass friction [mm]
Passing200: particles smaller than 75 µm [%]
Gravel: grains < 75 mm and > 4.75 mm [%]

All of the presented models, even the chosen model of (Köppl et al. 2015a), can only be used to predict the linear abrasive wear. As Plinninger et al. (2018) stated, there are ground conditions where abrasion is not the only decisive wear mechanism. Blockages and sudden failures of the cutting tools have a great influence on the tunnelling performance, since they reduce the tool's lifetime significantly. Furthermore, a broken tool causes secondary wear on other parts of the cutter head. Therefore, sudden failure has to be included in the maintenance scheduling model.

3.3 Findings for further research

In this chapter, the state of the art and research work about cutting tools have been reviewed. Even though a great amount of research has been conducted, many index tests have been invented and prediction models have been developed, wear prediction is still subject to high uncertainties. The different ground conditions and scattering of values in properties complicate an efficient maintenance schedule. In order to develop a model, which support the decision making during maintenance scheduling, the following aspects must be considered:

- Index tests can be conducted to gain a qualitative assessment of the influence of the ground properties on tool wear.
- A quantitative estimation can only be obtained by correlating the index values with empirical project data gained from wear measurements.
- Most of the wear prediction models base on a limited amount of data and offer only a rough estimation of the number of replaced tools.
- The wear prediction model has to be chosen according to the boundary conditions of the prevailing ground. The regarded project has to be similar to the analysed projects for the model development to gain reliable results.

For the model development, the wear prognosis model of Köppl is chosen, as discussed in Section 3.2.4. The model is developed in order to support the maintenance scheduling of hydro shield machines being the most complicated machine type with respect to maintenance, because of the limited accessibility of the cutting tools during the advancement. Furthermore, the model offers a quantitative approach to estimate the wear of each cutting tool at all points in time. The wear prediction bases on a greater magnitude of data than the other empirical prediction models.

4 Maintenance of Cutting Tools

For maintenance scheduling, particular boundary conditions of each tunnelling project have to be considered in addition to the wear behaviour of the cutting tools. These boundary conditions are for instance unstable ground conditions, sensitive surface structures or high ground water pressure, where a maintenance stop is not feasible or bears a high risk for the face stability and safety of the workers inside the excavation chamber during intervention. The consideration of these factors increases the complexity of the whole planning and realization of the maintenance processes.

In order to gain an overview of existing maintenance scheduling methods, general maintenance strategies that are common in the stationary industry are presented and analysed with respect to the applicability in shield tunnelling. Therefore, the maintenance processes of inspection and replacing of cutting tools in soft ground tunnelling and the given boundary conditions are presented. Finally, to evaluate the feasibility and quality of a chosen maintenance strategy, evaluation criteria are defined and discussed.

4.1 Maintenance Scheduling Methods

In a deteriorating system that consists of several deteriorating elements, maintenance is a complex task that has a major influence on the system's productivity. Especially if the elements have a different wear rate, the maintenance scheduling becomes more complicated. Not only the wear limit, but also the remaining useful life (RUL) of the elements have to be taken into account for maintenance decisions (Mosayebi Omshi et al. 2018).

Maintenance includes a variety of processes. If the condition of the regarded element is not completely known, an inspection must be carried out. Based on the element's condition and the type of system, the worn element can be either repaired or replaced. Repair improves the condition of the element and in the ideal case afterwards, it is as good as new. A replacement of the element always restores the full condition, except already used but still functional elements are taken to replace the worn one. Imperfect maintenance also reduces the condition of the element or increases the wear rate and may be considered as well.

4.1.1 Maintenance strategies

The maintenance schedule consists of the point in time or state of progress, when maintenance is conducted, and the decision, which elements are maintained. Many maintenance approaches exist for a variety of application fields. In general, maintenance can be conducted correctively, condition-based or predictive, periodically or preventively.

Corrective maintenance

Corrective maintenance must always be taken into account during the planning of maintenance work. Especially if the condition cannot be monitored and uncertain parameters influence the wear rate, the actual wear may be higher than predicted. Even if the condition of the regarded element is known at all times, an error in the element's production, hence a sudden failure, can occur. As shown in Figure 4-1, corrective maintenance of the system causes unplanned downtime. Since the failure occurs at an unknown point in time, the production process is disturbed and preparatory work, e.g. providing the needed materials, tools or new elements, starts after the system stops working. Planned corrective maintenance can be used, if the failure of one element does not cause the failure of the system and maintenance can be conducted simultaneously to the production process. This strategy offers the highest utilisation rate of the elements, thus is one of the most economical strategies. However, in most cases corrective maintenance causes additional downtime and costs, so that the productivity is reduced and additional costs arise.

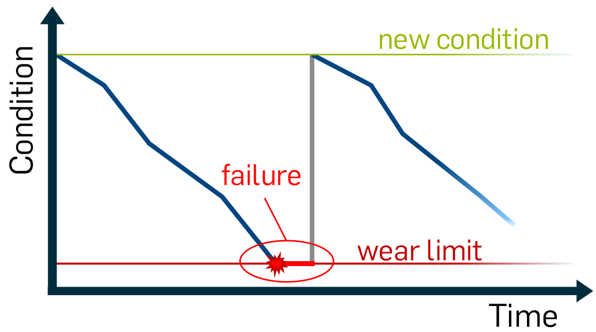


Figure 4-1: Condition of a system/element including corrective maintenance.

Condition-based and predictive maintenance

When the condition of the elements can be monitored, condition-based maintenance can be conducted. Before the condition of one element reaches the wear limit, the maintenance is prepared. The actual maintenance work is then conducted at a planned point in time and expected downtime (Figure 4-2). This way, it is a very economical strategy, but it requires a high degree of flexibility.

If the condition cannot be monitored, but a sufficient amount of experience or data of the wear behaviour is given, predictive maintenance can be conducted instead. Since the condition of the system is not known, the time of failure is predicted and the maintenance is scheduled accordingly.

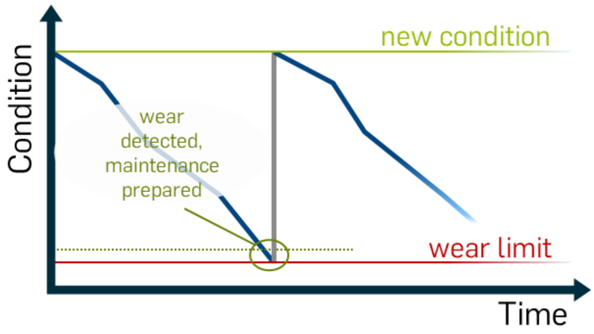


Figure 4-2: Condition of a system/element including condition-based maintenance.

Preventive maintenance

Is the element replaced or repaired before it reaches the wear limit it is called preventive maintenance. It is used, if the system offers only certain points in time for maintenance or if there are critical production processes scheduled that cannot be interrupted and the systems workability has to be ensured. This becomes necessary if the wear rate is subject to uncertainties, thus there are great fluctuations and the point in time the element will reach the wear limit cannot be predicted. For this purpose, a limit value of RUL can be defined as shown in Figure 4-3.

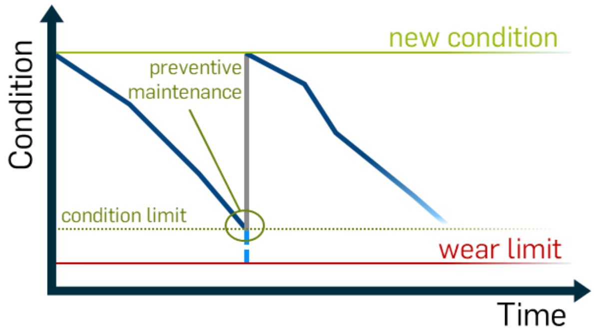


Figure 4-3: Condition of a system/element including preventive maintenance.

Periodic maintenance

The simplest scheduling method is periodic maintenance. After a certain time span or production volume, maintenance is performed regardless of the system's state. This method is disadvantageous, if the deterioration is under- or over-estimated. An underestimation of the deterioration leads to a premature failure and corrective maintenance has to be conducted. If the wear is overestimated, unnecessary maintenance of the elements is carried out as shown in Figure 4-4. This reduces the economic efficiency of the system. Most times if this strategy is used, the maintenance schedule is not flexible and cannot be changed easily.

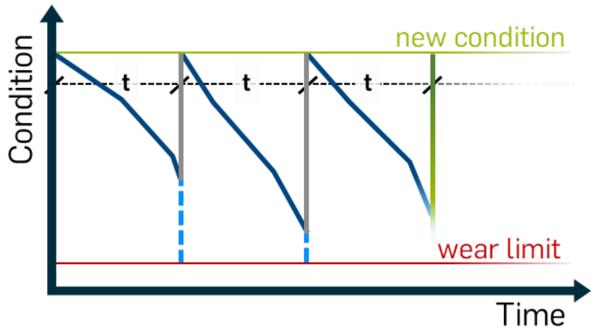


Figure 4-4: Condition of a system/element including periodic maintenance.

4.1.2 Cutting wheel maintenance

A cutting wheel is a multi-component system that consists of a variety of cutting tools, which are subject to wear. The condition of the cutting wheel is given by the condition of each single tool, which therefore has to be considered when planning the maintenance schedule. However, the actual condition of the tools is only known at the intervention points, as presented Figure 4-5, when inspection is performed. The actual wear behaviour between two intervention points stays unknown or can only be assumed based on the documented wear data and wear prediction. However, an exact prognosis is never possible, due to the uncertainties of the counter body soil and the deviations of the steering parameters.

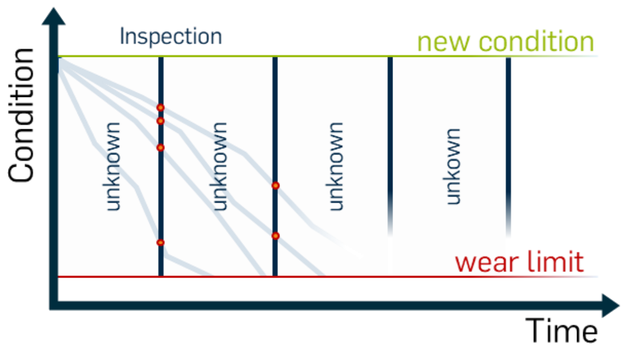


Figure 4-5: Wear of a multi-component system. Here, condition of several cutting tools of a cutting wheel.

Furthermore, even if the wear limit of a tool is reached, unplanned maintenance stops should be avoided. Therefore, preventive maintenance of cutting tools during the intervention becomes mandatory. Cutting tools that have not reached the wear limit yet, have to be replaced. A threshold defining the condition of a tool for preventive maintenance must be set. A tool has to be replaced, if the RUL of the tool is exceeded before the next intervention point is reached. If these tools are not replaced it leads to excessive wear or even a system failure and long repair work of not only the tools but also the cutting wheel structure and tool holders. Since the wear rate per excavation length differs for each tool, the condition limits for the tools differ as well.

Figure 4-6 shows how the maintenance for one intervention has to be scheduled. Part a) represents a newly equipped cutting wheel, the bars show the condition and maximum excavation length $L_{c(m)z,i}$ of the cutting tools for each tool track. The first maintenance stop must be carried out at the latest when the outer cutting tools (here: tools 1 and 18) reach their wear limit, since they have the longest cutting path per excavation length. When the machine reaches the first scheduled maintenance stop (b), an intervention is performed. The tools, which have reached or exceeded their wear limit, are replaced by new ones (c). Further, all tools that have reached the condition limit are also replaced (d). Therefore, the next maintenance stop must be scheduled and a wear prognosis has to be performed. In this case, tools 4 and 15 are replaced even though they did not reach the condition limit to cope with uncertainties of the wear rate.

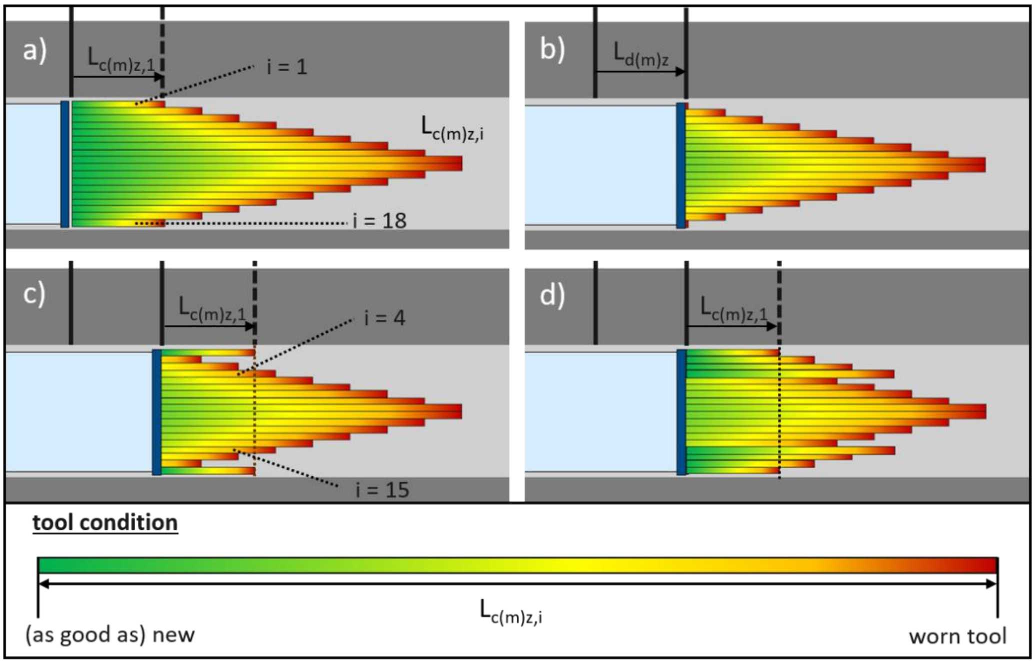


Figure 4-6: Schematic of the dependencies between the maintenance interval and tool replacements (Conrads et al. 2018).

4.1.3 Related work

In literature, a great amount and variety of attempts to analyse and schedule maintenance for single or multi-component systems can be found. Different maintenance strategies have been proposed and adapted to the system purpose to improve and optimise the maintenance policies with respect to the availability and costs. Here, some selected contributions, which have a relevance for the problem statement of the maintenance of cutting tools, are presented.

Grall et al. (2002) present a condition-based maintenance approach for a stochastically degrading system. The maintenance costs are estimated and the inspection intervals are chosen accordingly to gain an economic performance of the system. The deterioration model presented in Figure 4-7 includes a failure level L and a threshold λ for preventive maintenance during inspection. Corrective maintenance has to be carried out if the failure level L is exceeded. The condition of the system is only known at the points in time t_k when inspection is carried out.

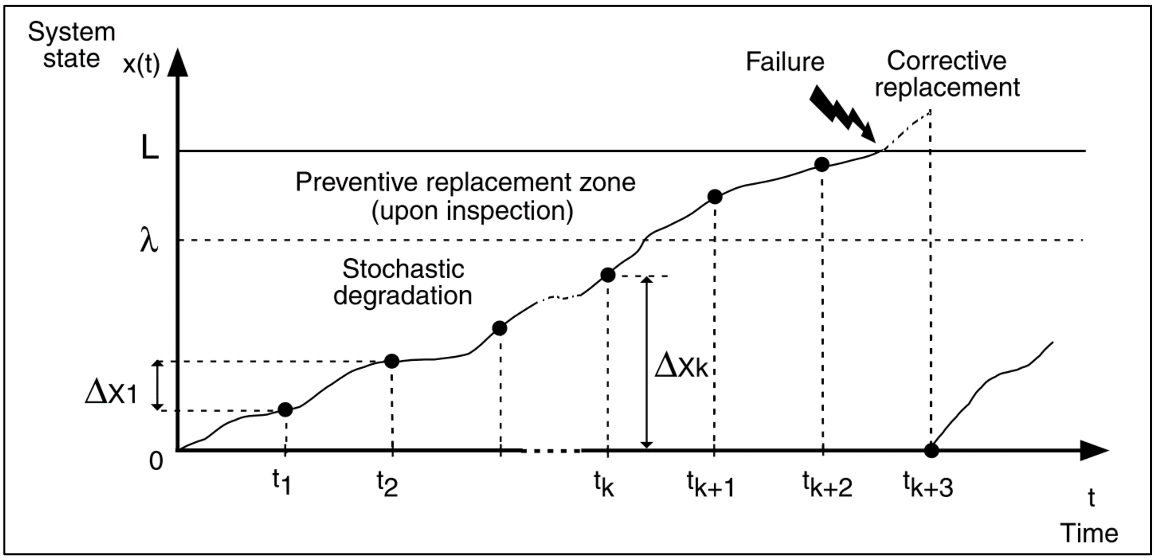


Figure 4-7: Deterioration mode with defined inspection points t_i (Grall et al. 2002)

The approach of a stochastic deterioration and the fixed points of inspection to determine the replacement can be adapted to the cutting tool wear and the intervention scheduling in mechanised tunnelling.

Do et al. (2015) analysed the effect of imperfect maintenance on the costs for a stochastically deteriorating system. The deterioration of the system is illustrated in Figure 4-8. It shows the resulting distribution of the times of failure. Based on the system state at the point in time T_i where maintenance is performed and a random value for imperfect maintenance Z^k the condition of the system after maintenance X_{Ti} is determined. Imperfect maintenance causes the system deterioration state to be not set back to as good as new or it causes a higher wear rate.

It is assumed, that the maintenance costs can be determined as a function of the improvement factor resulting for the system's maintenance, thus the quality of the maintenance work. Different shapes of this functions are presented depending on the ratio between the improvement of the systems condition and the maintenance costs.

Adapting this method for the maintenance of cutting tools is only partly useful. The determination of an initial failure distribution of stochastically deteriorating elements can perfectly be used for the modelling of tool wear and failure. However, since the worn tools are not repaired but replaced, imperfect maintenance hardly ever appears. Only if a new tool has a material defect or the tool is not mounted correctly. If this happens the wear state of the tool is as good as new but the wear rate might increase or a sudden failure is caused.

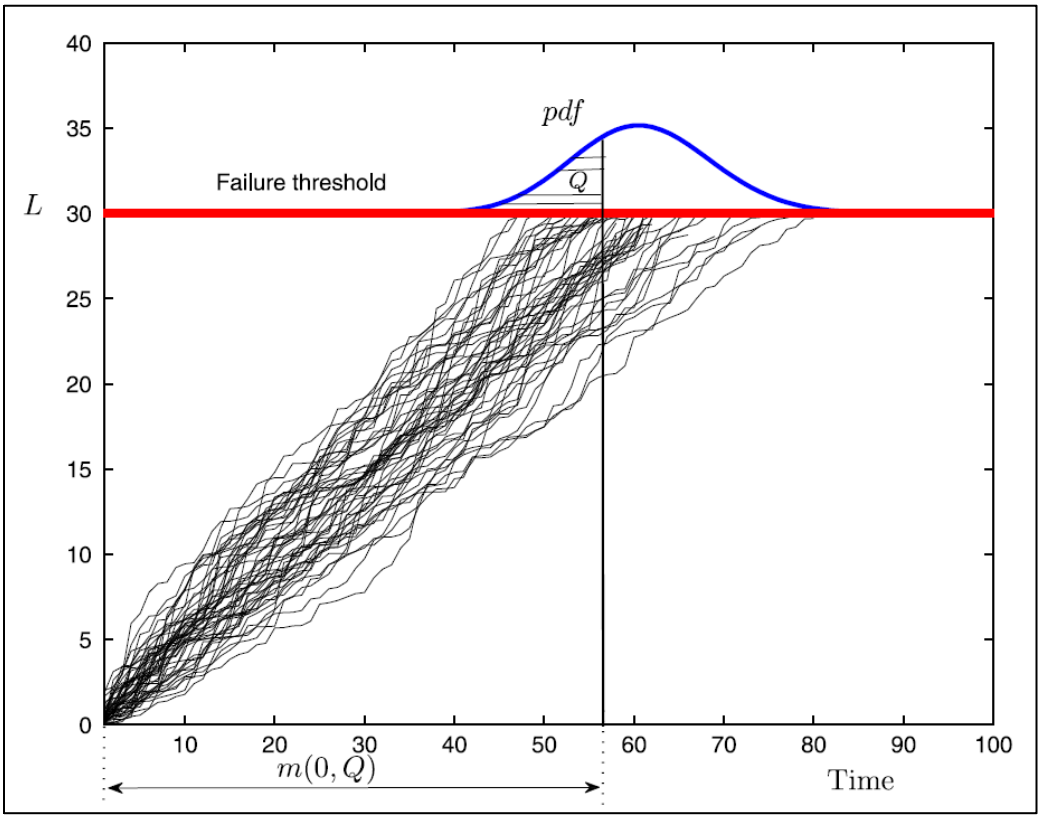


Figure 4-8: Illustration of possible degradation paths and initial failure distribution (Do et al. 2015).

Nguyen et al. (2015) present a decision making approach to optimise the maintenance costs of multi-component systems. Therefore, condition-based and preventive maintenance of the system and components are considered. For the preventive maintenance two thresholds are proposed, one considering the system state and the other regarding the deterioration of the single components. Furthermore, cost-based improvement gained from grouping the maintenance of several components is analysed. All these parameters are included for the decision process of the maintenance process, to determine the preventive maintenance activities.

Here, the concept of the thresholds for preventive maintenance decisions for a multi-component system can be adapted for the cutting tool maintenance in mechanised tunnelling and is included in the later on proposed model.

4.2 Maintenance Processes in TBM Tunnelling

Similar to the wear of cutting tools, the maintenance processes differ for each type of tunnelling machines. The two main differences that are determining the maintenance processes are the design of the cutting wheel and the support mechanism for the tunnel face that mainly influences the accessibility of the excavation chamber for the intervention.

4.2.1 Sub-Processes

The overall maintenance process can be subdivided into mobilisation, maintenance and demobilisation processes. For the mobilisation and demobilisation the compression and decompression of the workers are the most crucial processes. The maintenance mainly consists of inspection and replacement of cutting tools.

Working under compressed air

The work under compressed air (CA) is in general regulated nationally. In Germany the maximum working time and the time for compression and decompression of the workers that are given in the National Compressed Air Regulations (BGBI I 10/4/1972) are summarised in Figure 4-9. The higher the needed air pressure inside the excavation chamber, the shorter the allowed time for maintenance work until the workers have to leave the pressurised area. If the maintenance work is not completed within given time, another shift of workers have to enter the chamber after the decompression of the first shift.

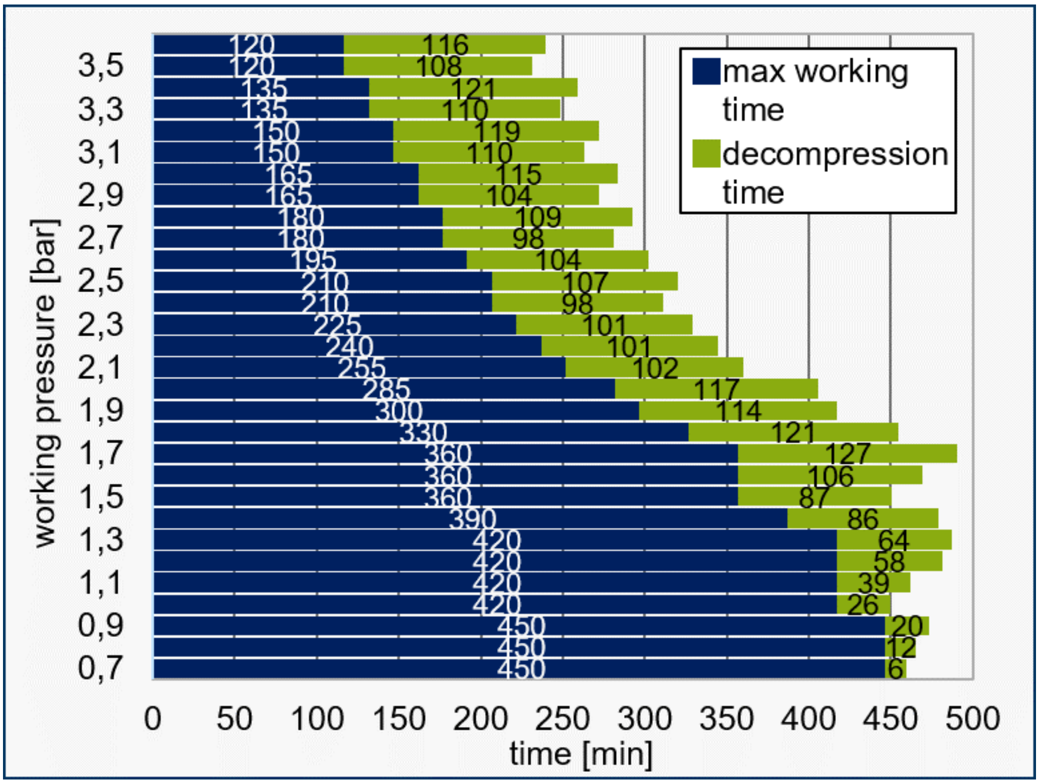


Figure 4-9: Maximum working time and the corresponding time for decompression given by DruckLV (Conrads et al. 2017a)

If the needed support pressure inside the chamber exceeds 3.6 bar, mix-gas interventions have to be conducted. For extremely high pressures saturation diving techniques become necessary (Och et al. 2018).

Air locks (Figure 4-10) are used for the compression and decompression of the workers. Additional equipment is needed especially for mix-gas and saturation interventions (Burger and Wehrmeyer 2013). The safety of the workers is always the top priority during the intervention. Therefore, it must always be possible to immediately give medical treatment.

Figure 4-10: Air lock on the TBM for compressed air interventions.

Replacement of cutting tools

The procedure of the tool replacement is illustrated in Figure 4-11. During the inspection process, the worn tools are identified (a). The worn tools are then removed from the cutting wheel and transported outside of the excavation chamber. The wear measurement and documentation is either conducted while the tool is still mounted on the cutting wheel, to support the decision process of a potential preventive replacement, or outside of the chamber, where the environment is more convenient (b). Especially for the maintenance of cutting discs, cranes inside and outside of the excavation chamber are needed to handle the heavy tools (c). If a compressed air intervention is conducted, a material air lock is needed to transport the tools out of the excavation chamber. The excavation chamber only offers limited space, so that only few workers and tools can be inside the chamber at the same time. The worn tools are then transported outside the tunnel and stored (d) before they are repaired or disposed.

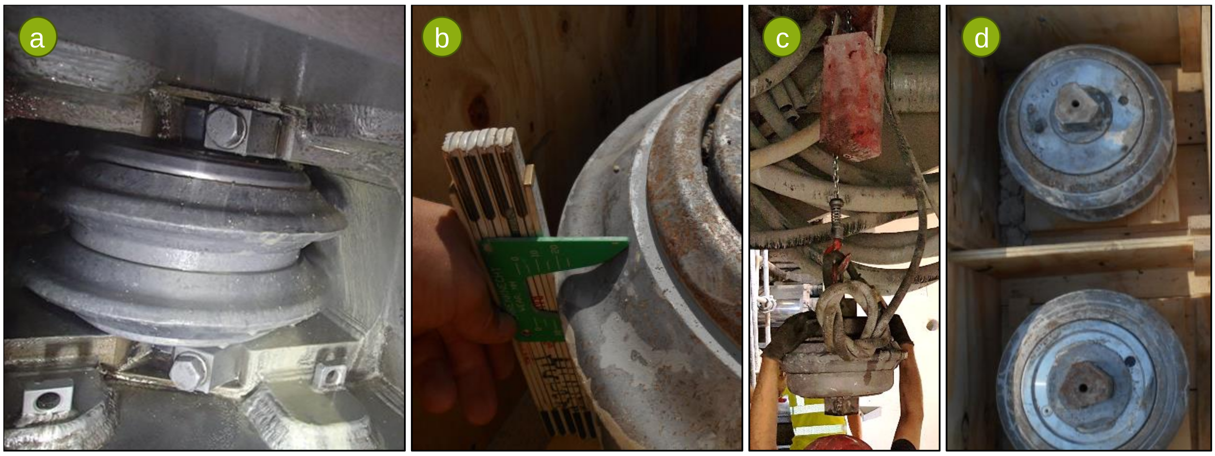


Figure 4-11: Maintenance processes for cutting disc replacement.

4.2.2 Process durations

All sub-processes are listed in Figure 4-12. For each process, a time t_i is needed. The total duration of the maintenance work is gained by the sum of all durations of the sub-processes. Therefore, the Equations 4-1 to 4-4 can be used:

The duration of the mobilisation can be calculated by:

(4-1) $$t_{mob} = t_{supply} + t_{low} + t_{comp} + t_{instal} + t_{clean} \quad \text{[min]}$$

Since the tools needed for the maintenance work can be provided beforehand, simultaneously to the advance processes, the duration t_{supply} may be neglected. If there is an unplanned intervention, where the number and type of worn tools is not known beforehand, the downtime caused by the supply with new tools must be considered.

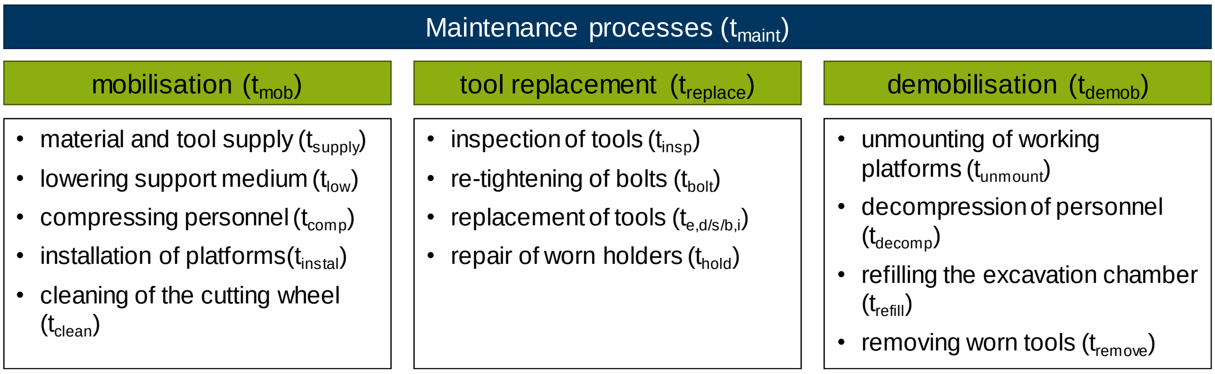


Figure 4-12: Maintenance processes for tool replacement.

For hard rock TBM or EPB-shields operating in open mode, the time for lowering the support medium as well as for compressing the personnel is not needed and thus can be set equal to 0.0 min. However, for EPB-shields time for cooling may be needed.

During the inspection, the bolts of the tools have to be checked and if necessary they have to be retightened. Here it is assumed that the duration of retightening process does not vary for different tool types. If there are significant deviations in the time needed for the retightening, different durations have to be set.

The actual maintenance process, consisting of cleaning, inspection, replacing and repair work, can be calculated as follows:

(4-2) $$t_{replace} = \sum_{i=1}^{n} t_{insp,i} + \sum_{i=1}^{n_{bolt}} t_{bolt,i} + \sum_{i=1}^{n_{e,d}} t_{e,d,i} + \sum_{i=1}^{n_{e,s}} t_{e,s,i} + \sum_{i=1}^{n_{e,b}} t_{e,b,i} + \sum_{i=1}^{n_h} t_{h,i}$$

where: n: *number of accessible tools on the cutting wheel*

n_{bolt}: *number of bolts*

$n_{e,d/s/b}$: *number of worn discs (d), scraper (s) or buckets (b)*

n_h: *number of broken tool holder*

During the intervention, the condition of all tools must be inspected and should be documented in the ideal case. Loose bolts of the tool holders have to be tightened again. Afterwards all worn tools have to be replaced. The duration for the replacement process differs for each tool type. Furthermore, if a tool holder is damaged due to excessive wear of a tool or a sudden breakage due to obstacles in the soil, it has to be replaced, too. However, tool holders are permanently welded to the cutting wheel and must therefore be removed and replaced at great expense. The necessary welding work can take several hours up to days, depending on the extent of damage.

Afterwards, the duration for the demobilisation process can be calculated:

(4-3) $$t_{demob} = t_{unmount} + t_{decomp} + t_{refill} + t_{remove}$$

For the demobilisation as well, the decompression of the personnel and the refilling of the excavation chamber is not necessary for hard rock TBM and EPB-shields operating in open-mode. In contrast to this, if high support pressures are needed, the decompression of the personnel lasts very long. Furthermore, the maximum working time under pressurised conditions is drastically reduced. If the maximum working time is shorter than t_{maint}, several interventions are needed to complete the maintenance work resulting in multiple compression and decompression processes. The duration for the decompression as well as the maximum working time under pressure is given by the national standards (BGBI I 10/4/1972).

Similar to the material supply process, the material removal can take place after the advance processes have started again. Hence, they can be neglected for the total duration.

The total duration of one maintenance stop is then determined as the sum of all process durations:

(4-4) $$t_{maint} = t_{mob} + t_{replace} + t_{demob}$$

4.3 Boundary Conditions for Maintenance Scheduling

The maintenance scheduling in general should be based on the wear behaviour of the elements that are maintained. However, mechanised tunnelling is a technically demanding field. In most cases, the maintenance interventions cannot be planned only based on the wear of the cutting tools. Especially if an economically successful schedule shall be obtained, further boundary conditions must be taken into consideration. Some boundaries are defined by the normative and contractual framework. Technical boundaries result from the used construction method. Therefore, in particular the risks of a compressed air intervention must be assessed.

4.3.1 Normative and contractual framework

The maintenance positions in mechanised tunnelling are currently still planned by rough estimation and based on experience of similar tunnelling projects. This uncertain evaluation leads to the need of additional maintenance stops and an excessive adaption of the maintenance schedule during the project execution to avoid severe damage of the cutting wheel structure.

According to the German contract conditions VOB (DIN 18312), the soil has to be categorised into homogeneous sections, where the soil properties are comparably constant with only small deviations. According to the VOB, the LCPC test is required for the geotechnical report. However, the applicability of the LAC value for the prognosis of abrasive wear in mechanised tunnelling is widely discussed and criticised, e.g. Feinendegen et al. (2017). There are several further geotechnical parameters required according to VOB, e.g. mineralogy of stones and boulders or the cohesion, that can be used for a wear prognosis model as proposed by Köppl et al. (2015a).

If there is no sufficient information on the soil properties for a proper wear prognosis, the observational method can be applied (DIN EN 1997-1). Maidl et al. (2011) present how the observational method was implemented for a tunnelling project and how it was used for target-actual comparison. The results can be important if the positions for the maintenance stops have been contractually agreed, but the wear behaviour deviates and additional stops become necessary.

4.3.2 Compressed air interventions

Especially if the tunnel alignment lies below the ground water level, not only the tunnel face needs to be supported but also the inflow of ground water must be avoided. During the intervention, the support medium is replaced partly or completely by compressed air. In compressed air tunnelling, the compressed air is mainly used to prevent ground water inflow. Especially in soft soil with high permeability, a support of the soil without additional measures is not possible.

In hydro shield operation, the used bentonite suspension penetrates into the soil forming a filter cake or a penetration zone. Thereby, the fine particles of the suspension fill the pore space of the soil matrix and reduce the permeability of the tunnel face. This filter cake remains after the lowering of the support medium, supporting the transfer of excess air pressure onto the soil matrix (DAUB 2016). Nonetheless, a long duration of the intervention may cause the filter cake to dry out and break up, so that the airflow through the soil increases. For longer duration of maintenance work, the excavation chamber has to be refilled with bentonite suspension in between to rebuild the filter cake (Babendererde and Holzhäuser 2000).

Another option is to conduct ground improvement measures, either from the surface (e.g. jet grouting) or from inside the machine. For example, for tunnelling under the Suez Canal, safe havens have been built at predefined positions to improve the working conditions during maintenance (Rizos et al. 2018). This method is especially recommended for EPB-shield application in coarse ground to stabilise the soil, while compressed air is used to prevent ground water inflow.

Even if the support of the tunnel face is ensured, there is still a risk of blowouts during interventions that lead to a collapse of the tunnel face. As presented in Figure 4-13 it is distinguished between two main types of blowout mechanisms: gasometer blow-out and erosion blow-out. The air inside the soil may lead to an erosion of soil particles resulting in a further increase of permeability and airflow until the face support is no longer given and the face collapses. Another possibility is that above a more permeable soil layer there is an impermeable soil layer. The air cannot flow through the upper layer and an air reservoir is formed. If the pressure inside this reservoir exceeds the resistance of the soil above, the layer breaks open leading to a sudden release of the air. Consequently, the support pressure of the tunnel face is no longer given and the face collapses.

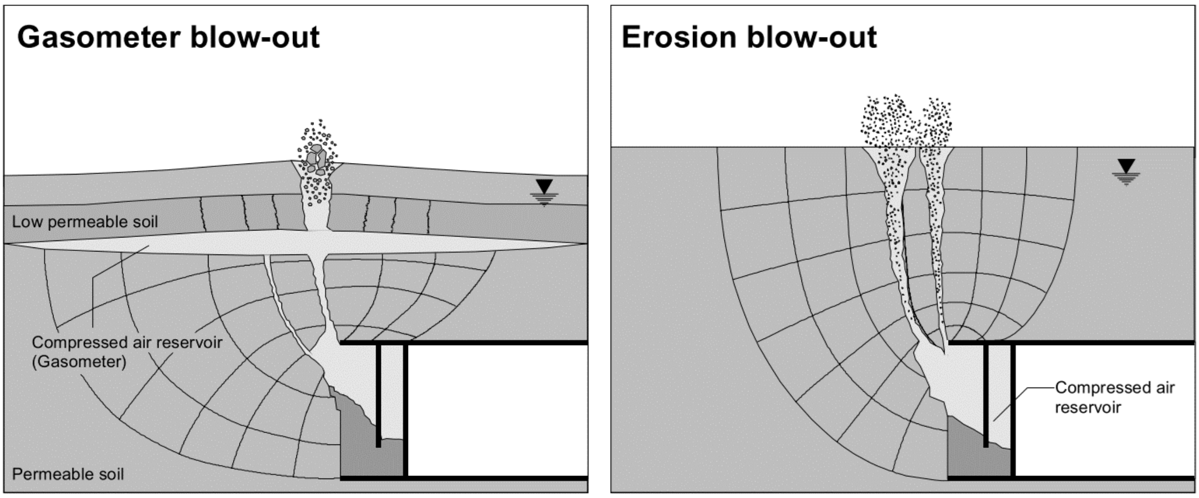


Figure 4-13: Formation of blow-outs (Holzhäuser 2002).

Furthermore, the pores inside the soil can be filled with artificial soil. Another option is to seal the tunnel face with a spray-able membrane. Nonetheless, these are mainly used when a high pressure drop is detected and no other method is able to ensure the necessary support pressure or if a collapse of the tunnel face already occurred (Babendererde 2015).

Calculation methods, analytically or numerically, to evaluate the face support with compressed air can be found for instance in (DAUB 2016; Nagel et al. 2008; Holzhäuser 2002).

4.4 Maintenance evaluation

To evaluate the maintenance schedule a multitude of criteria must be considered. The maintenance strategy not only has to avoid sever damages leading to long standstills, but also should not be too precautious and therefore costly. A balance has to be found of the risk of over and under estimation of the cutting tool wear.

The evaluation of the maintenance strategy must be conducted regarding a variety of criteria. One of the most important criteria is the amount of wear. The maintenance schedule must avoid any severe damages or unplanned interventions. Especially in critical sections, where the intervention bears a high risk or is not feasible, the need of a maintenance stop must be avoided. On the opposite, a too conservative maintenance schedule causes unnecessary costs, influencing the economic success of the project. Therefore, not only the number of maintenance stops, but also the number of replaced tools and the needed time to conduct maintenance must be regarded.

The consideration of uncertainties during maintenance scheduling enables a risk assessment of the regarded strategies. This way, not only the magnitude of, for instance, maintenance cost or the number of unplanned stops can be determined, but also the probability of their occurrence.

The criteria that are evaluated in later presented analyses are:

- Number of un/planned maintenance stops
- Number of replaced tools
- Duration of maintenance and repair work
- Maintenance costs
- Classification of maintenance position for CA interventions

4.4.1 Evaluation of maintenance costs

A common method to evaluate a maintenance strategy for a deteriorating system is the assessment of the maintenance costs (e.g. Grall et al. (2002)). However, an approach based on historical data, as for instance proposed in Yip et al. (2014) for construction equipment is not feasible, due to the unique character of each tunnelling project.

Jakobsen et al. (2013a) evaluated the effect of tool wear on the costs of a tunnelling project. Therefore, material costs for the cutting tools as well as time-dependent costs for the maintenance work were considered. Furthermore, the costs for personnel, especially the divers for the hyperbaric interventions are included. This way, the costs for the replacement of cutting tools for two different scenarios, one low-abrasive and the other highly abrasive, are determined.

Similarly, Conrads et al. (2018) classify the cost occurring due to maintenance work into time-dependent, material and fix costs. These categories include:

- time-dependent costs:

- general expenses of the jobsite [€/h]
- planned/unplanned maintenance stops [€/h]

* material costs:
  - cutting discs [€/disc]
  - scraper [€/scraper]
  - bucket [€/bucket]
* fix costs:
  - compressing/decompressing process costs [€/process]
  - planned/unplanned maintenance stops [€/stop]

The resulting maintenance costs were then used to compare different project setups or maintenance strategies and to evaluate the robustness of the results.

4.4.2 Evaluation of uncertainties

There are different approaches to cope with the uncertainties of the wear prognosis. One common approach is to use uncertain input parameters, e.g. distribution functions, to perform a Monte Carlo Simulation (MCS). This approach has been proven useful for the evaluation of uncertainties in, for instance, logistic scheduling (König et al. 2014). This approach can be applied on the wear prognosis and maintenance scheduling.

Conrads et al. (2018) combined a PVS with MCS to find a robust optimisation of the maintenance schedule. This approach evaluates a robustness index R for each parameter set. The procedure to determine R is shown in Figure 4-14. A MCS of each parameter set is conducted and the mean value μ_m and standard deviation σ_s of the resulting maintenance costs are calculated. These values can be compared graphically with a scatter plot. This way, not only the magnitude of costs, but also their deviation can be easily assessed.

The R value is then calculated using the weighted target function R(α). Minimising R, the optimal parameter set can be obtained. The weighting factor α represents the preference of analysis. If α = 0.0, only the standard deviation is taken into account for the identification of the optimum parameter set. Accordingly, if α = 1.0, only the mean value of the maintenance costs is taken into account.

To gain a comparable scale for the used values of μ_m and σ_s, relative values are used within the target function R(α):

(4-5) $$R(\alpha) = \alpha * \frac{\mu_{m,i}}{\mu_{m,max}} + (1-\alpha) * \frac{\sigma_{s,i}}{\sigma_{s,max}}$$

Where: $\mu_{m,max}$*: maximum of all mean values*

$\sigma_{s,max}$: *maximum of all standard deviations*

This approach can also be conducted while using the median instead of the mean value and inter-percentile ranges instead of the standard deviation. This way, the R value is less sensitive to extreme values and outliers.

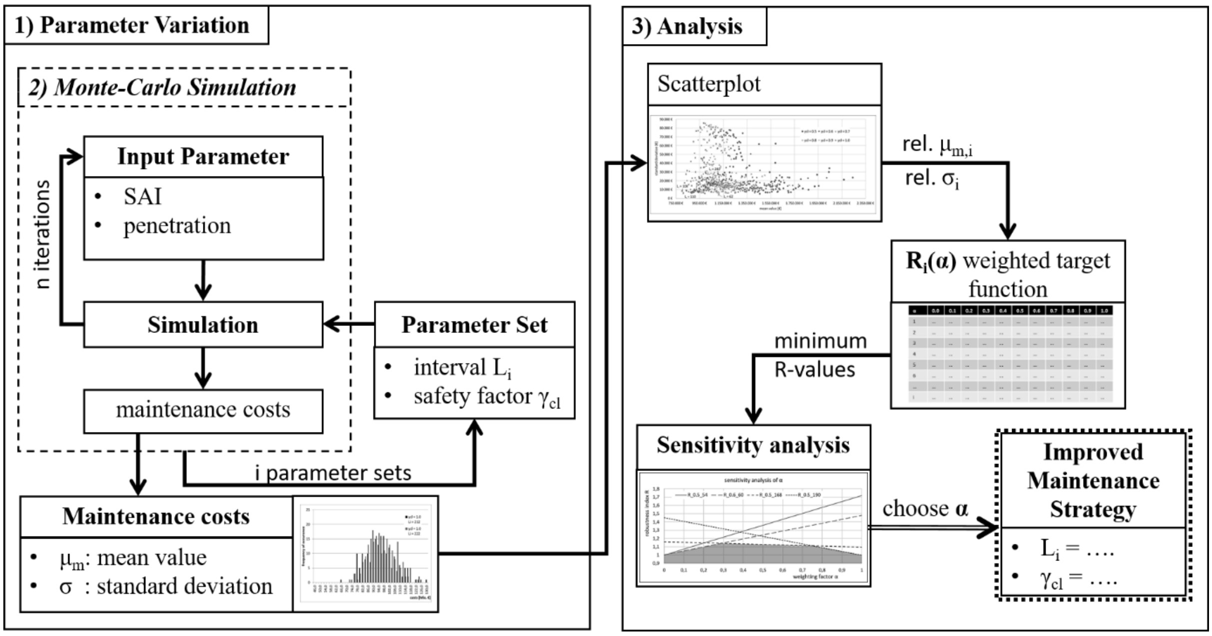


Figure 4-14: Procedure model for the evaluation of maintenance strategies with regard to their robustness by using process simulation (Conrads et al. 2018).

Another approach for the evaluation of the maintenance interval is included in the wear prognosis model of Li et al. (2017). They propose a dimensionless factor η that can be calculated using intervals for the input parameters:

(4-6) $$\eta = \frac{\underline{\delta_i} + \overline{\delta_i} - 2\delta_s}{\overline{\delta_i} - \underline{\delta_i}}$$

Where: $\underline{\delta_i}$: *lower bound of the calculated wear amount [mm]*
$\overline{\delta_i}$: *upper bound of the calculated wear amount [mm]*
δ_s: *predefined wear limit [mm]*

The probability of success is then given by:

(4-7) $$\xi = \begin{cases} 1.0, & \eta < -1.0 \\ \frac{1-\eta}{2}, & -1.0 \leq \eta \leq 1.0 \\ 0.0, & \eta > 1.0 \end{cases}$$

If ξ = 1.0, it is certain that a maintenance stop has to be performed during the regarded tunnelling section. If ξ = 0.0, there will not be any stops needed. In between those two values, ξ gives the probability that a maintenance stop is needed. In case ξ > 0.0, maintenance stops have to be included, so that for the excavation length within between two stops the probability of a needed stop is ξ = 0.0.

4.5 Findings for further research

The processes that need to be conducted to maintain the cutting tools of a tunnelling machine differ for the type of machine that is used and depending on the given ground conditions. In particular, when the access to the excavation chamber is limited and pressurised conditions are required, the maintenance has to be planned carefully to avoid severe damages of the tools and the cutting wheel and to reduce the downtime as well as maintenance costs.

The maintenance schedule is defined by two values: the maintenance position and the threshold for preventive tool replacement. The maintenance position is determined with the help of the maintenance interval L_{maint}, which is calculated with the help of the chosen wear prediction model. The identified positions have to be adjusted to the boundary conditions of the tunnel alignment, to avoid critical areas. According to the determined maintenance intervals, the threshold for preventive tool replacement can be estimated. All cutting tools, which will exceed their wear limit before the next intervention is scheduled have to be replaced beforehand. This threshold can be adjusted by a correction factor f_{prev}, which considers the uncertainties of the wear prognosis as well as the decision to accept a certain risk of massive wear.

Furthermore, uncertainties have to be taken into account during the scheduling processes. In addition, the boundary conditions of the maintenance position that have an influence on the feasibility of the intervention must be evaluated. In particular the risk of a compressed air intervention has to be evaluated. For the evaluation of the maintenance schedule, the calculation of maintenance costs is recommended to consider and compare different evaluation criteria. This way an improved maintenance schedule can be found.

For the optimisation of the two parameters defining the maintenance schedule, the following aspects have to be considered:

- Uncertainties must be taken into account and evaluated, when no certain values are given.
- A predictive maintenance schedule with preventive tool replacements is recommended. However, due to the uncertainties corrective maintenance cannot be completely avoided.

- The evaluation criteria for the maintenance schedule cannot be evaluated separately. Maintenance costs offer an approach to summarise the most criteria within one value.
- The determined strategy has to be checked on feasibility. The consideration of expert knowledge is indispensable.

The presented maintenance processes and their durations are used for the model development in chapter 5. Furthermore, the suggested maintenance cost and evaluation method for robust optimisation are implemented and used for the analyses conducted within chapter 6. One focus of the analyses is the evaluation of the values of the maintenance strategy L_{maint} and f_{prev} and their influence on the robustness of the results as well as the maintenance costs.

5 Model for Maintenance Scheduling

The planning of the maintenance schedule can be conducted in five steps as shown in Figure 5-1. These steps reach from the first information gathering to the detailed analysis by using a simulation model to evaluate possible maintenance strategies. The specific procedure differs depending on the quality and quantity of data and information.

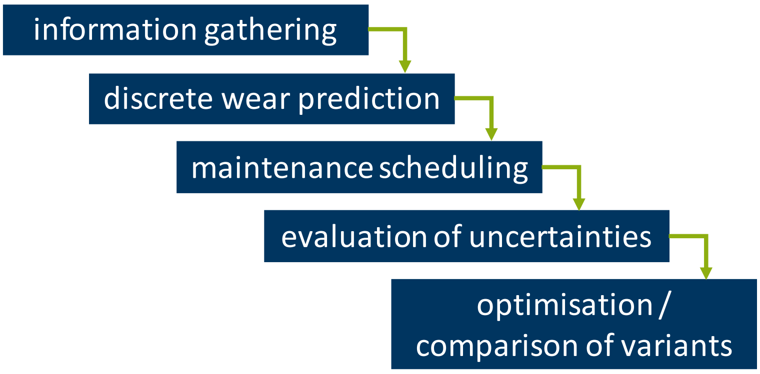


Figure 5-1: Procedure of maintenance scheduling and evaluation.

5.1 Input parameters and boundary conditions

Gathering information at the beginning of a project is necessary to gain all the input parameter and information about the boundary conditions, which are needed for maintenance scheduling. For providing the input data, the methods for data evaluation presented in Section 2.3.2 are used.

5.1.1 Input parameters for wear prediction and maintenance scheduling

As stated in Section 2.3, there is a variety of input parameters that have to be considered for the wear prediction and maintenance scheduling. For the wear prediction, geotechnical, machine design and steering parameters are needed. Due to changing ground properties along the tunnel alignment, the geotechnical parameters must be defined for each homogeneous section. The needed information is obtained from the geotechnical profile. Hence, the quality and quantity of these parameters depends on the quality of the ground assessment. Therefore, it must be ensured that all necessary parameters are analysed. In most cases, an expected value or range is given for each parameter, which are gained by laboratory index test of borehole samples.

Furthermore, the design of the tunnelling machine and especially of the cutting wheel must be known. Regarding the cutting wheel, the type and position of the cutting tools are important. For each tool, the radius of the cutting track is needed to calculate the cutting path. Furthermore, the number and type of tools on the same cutting track must be known, since the interaction of several tools on the same track leads to a reduced amount of wear. These parameters are given as sharp values and are some of the few certain parameters.

To evaluate the steering parameters, data from similar projects that have been executed are back analysed and used as input parameters. However, the data must be proven suitable for the project by comparing it to the expected values that have been estimated by expert opinion. The huge amount of machine data requires an automated processing to gain usable values. Figure 5-2 shows an example for the penetration values gained for one ring. The state value represents whether the machine is excavating, the ring building is in process or if there is an interruption due to a disturbance.

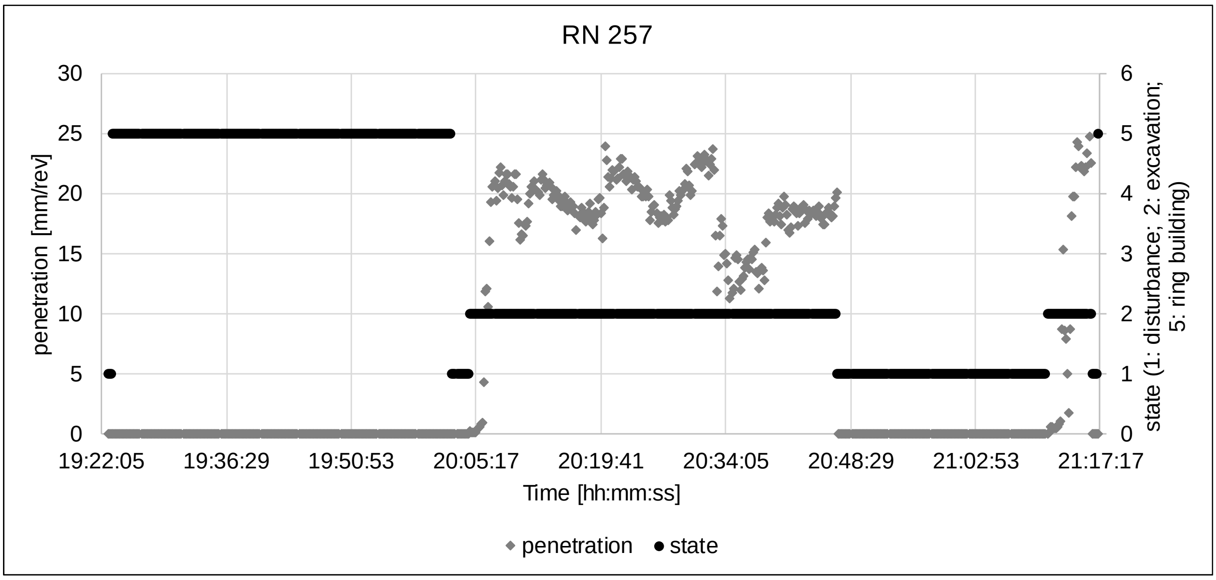


Figure 5-2: Penetration and machine state data for one advance cycle example

It can be seen that there is a fluctuation of the penetration value during excavation. Furthermore, the penetration increases when excavation restarts but falls back to zero when the excavation is stopped. Nonetheless, as an input parameter only one value per advancement cycle is needed. Therefore, for each ring the mean penetration is calculated. Figure 5-3 shows an example for the resulting penetration values of one project. Outliers that are completely out of range, for example penetration values above 50 mm/rev or advance durations of 0.0 min, have to be erased from the data set or be corrected with the help of further information gained for instance from shifts reports.

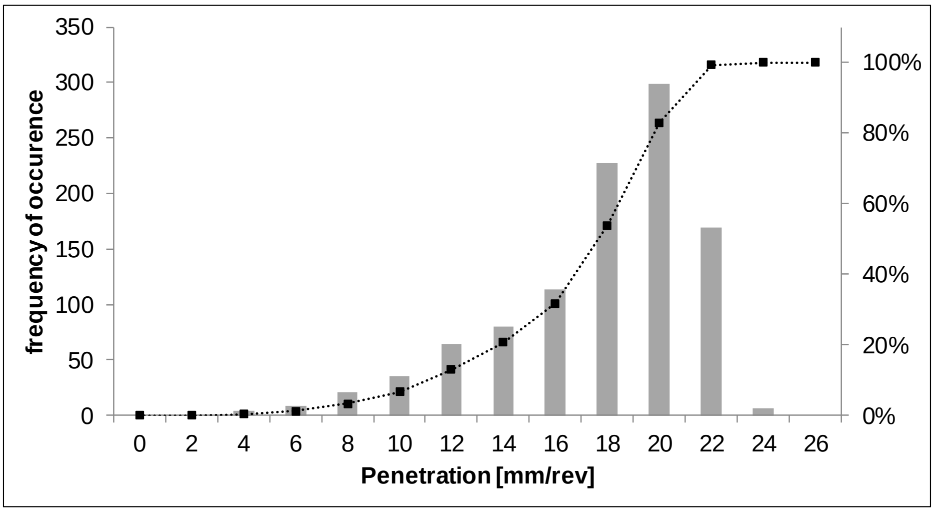


Figure 5-3: Histogram of penetration values

Using distribution fitting methods, distribution functions can be found for each uncertain input parameter. For the presented data, a skewed function with a lower limit value of 3.0 mm/rev has to be chosen. The distribution fitting is conducted using the software ExpertFit according to Rahm (2017, pp. 94–95). As shown in Figure 5-4, a variety of distributions can be compared to gain the best fitting distribution function for the data set. Furthermore, the software offers an evaluation of the chosen function by statistical tests. However, if the data set is too small, no suitable function may be found according to the tests. The main advantage in using the software tool is that it offers the corresponding java code for the simulation software AnyLogic that is used for the simulation of the maintenance model.

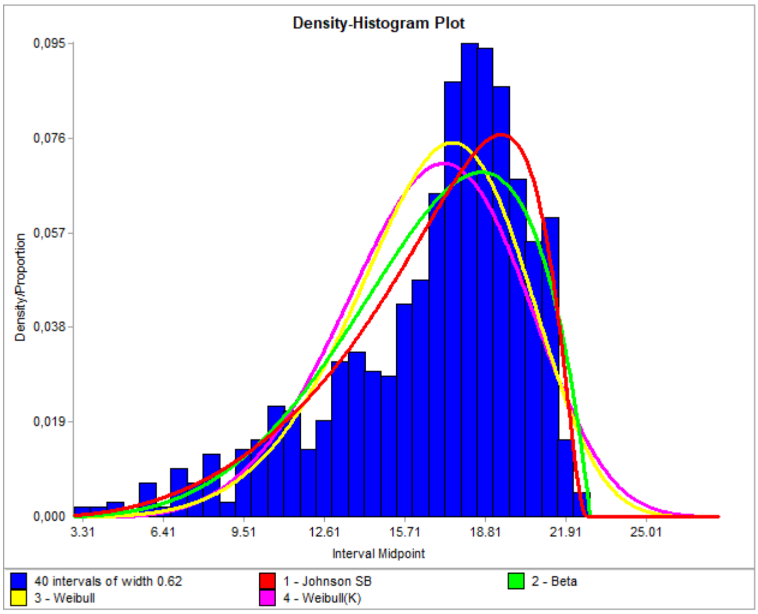


Figure 5-4: Distribution fitting for the penetration values. Graphical comparison of different functions with ExpertFit.

5.1.2 Boundary conditions for maintenance scheduling

As presented in Section 4.3, a variety of boundary conditions must be considered during maintenance scheduling. According to these parameters the tunnel alignment must be classified to evaluate the chosen maintenance positions. The four main classification parameters are the sensibility of the surface structure, the risk of compressed air support, the face stability and the propagation of the settlements from the tunnel face to the surface.

As presented in Table 5-1, the surface structures are classified from extremely sensitive structures, e.g. railroad tracks, which only allow very small settlements. If the given limit for settlements is exceeded, there is a risk of derailment including high costs for closing and rehabilitation of the tracks. The best class is the case of tunnelling under a green field, where settlements would not be harmful.

Table 5-1: Classification of the boundary condition Surface structures BC_{Sur}

Classification	**Nr.**	**Examples**
Extremely sensitive	6	Railroad tracks
Very sensitive	5	Old buildings
Sensitive	4	Buildings with robust foundations
Less sensitive	3	Streets
Hardly sensitive	2	
Not sensitive	1	Green field

Compressed air interventions are not possible at all positions. Depending on the required air pressure and the soil properties, the intervention bears a high risk of insufficient face support that may lead to a face collapse. A highly permeable soil leads to an increased air flow through the soil. If the air flow is too high, a compressed air (CA) support is not possible or leads to high pressure fluctuations. In addition, the risk of blowouts must be considered for this classification. The lower the possible air flow and pressure fluctuations are, the lower is the risk. The classification of the risk of CA intervention is given in Table 5-2.

Table 5-2: Classification of the boundary condition Risk of compressed air intervention BC_{comp}

Classification	**Nr.**	**Examples**
Very high risk	6	CA support not possible
High risk	5	High pressure fluctuations
Moderate risk	4	Risk of blowouts
Small risk	3	
Neglect-able risk	2	
No risk	1	No risk

Even if the CA support is possible and the tunnel face is stable, deformations may occur at the face. If these deformations propagate through the soil, settlements on the surface occur. Therefore, the amount of expectable surface settlements depends on the extent of tunnel face settlements and settlement propagation within the soil. These classifications can be combined to one, if a surface settlement prognosis has been conducted. The classifications are given in Table 5-3.

Table 5-3: Classification of Face stability BC_{FS} and Settlement propagation BC_{Set}.

Classification	**Nr.**	**Examples**
Face stability BC_{FS}		
Unstable	6	
Stable, very large deformations	5	
Stable, large deformations	4	

Stable, moderate deformations	3	
Stable, small deformations	2	
Stable, no deformations	1	
Settlement propagation BC$_{Set}$		
Complete transfer of settlements	6	All settlements are transferred to the surface
Very sensitive	5	Even small settlements of the face are visible on the surface
Sensitive	4	Moderate deformations are visible on the surface
Less sensitive	3	Only high settlements cause settlements on the surface
Hardly sensitive	2	Only a face collapse leads to settlements
Not sensitive	1	No settlements propagate to the surface

The tunnel alignment can be classified for each boundary condition according to the given classes as presented in Figure 5-5. Each boundary condition requires a different division of the alignment. This way, every possible maintenance position can be assessed.

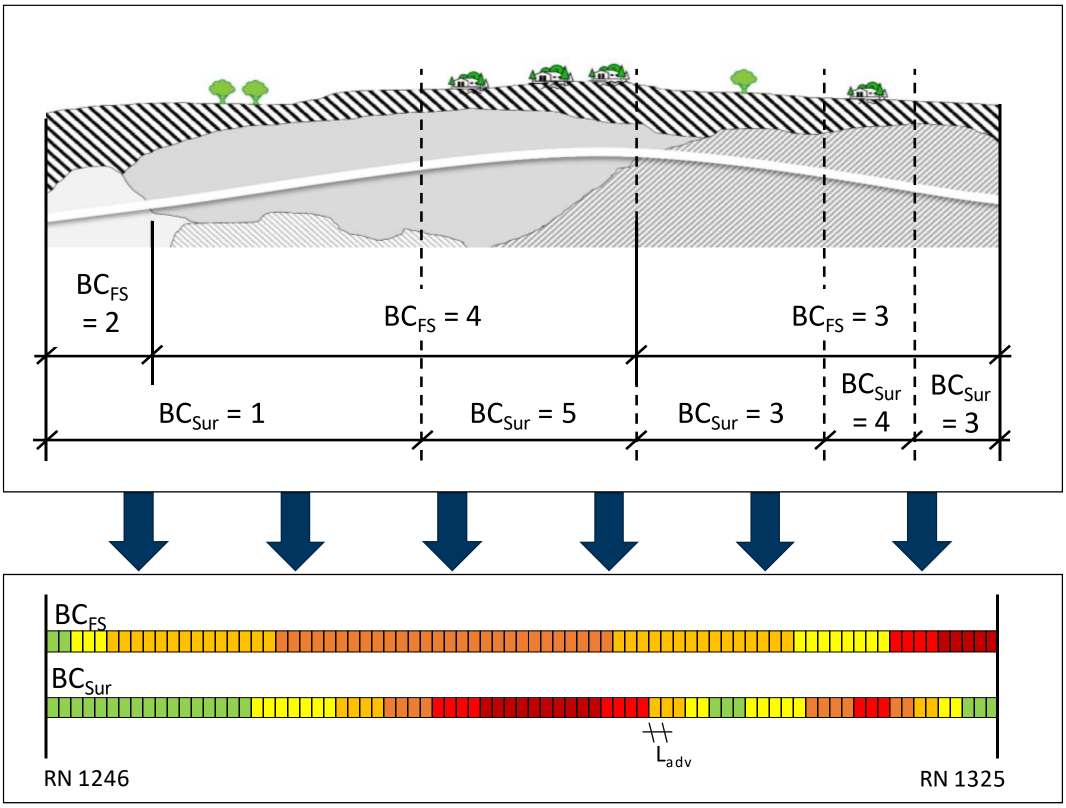


Figure 5-5: Classification of the tunnel alignment for each ring.

For the general qualitative classification of the maintainability of certain points of the tunnel alignment, the presented classifications have to be combined into one class. This can be done by rules or formulars considering the dependencies of the different aspects.

5.2 Deterministic wear prognosis and maintenance schedule

The second step after information gathering is to determine the maintenance schedule, thus the positions of the interventions. In addition to the boundary conditions being the main factor, the wear of the cutting tools is considered. The scheduling method depends on the level of information that is given. If no detailed information about the soil properties, machine design or steering parameters are given, a rough estimation has to be performed that considers the high degree of uncertainty. If the degree of information is high enough, the wear prediction models can be used and the gained maintenance intervals of the homogeneous sections (HGB) result in the maintenance positions that are classified by the boundary conditions.

5.2.1 Low level of information

If there is not enough information for the wear prediction, the wear rate has to be estimated. Babendererde (2010) proposes a schedule for projects where the real wear behaviour is not known when the excavation starts:

1. The first intervention should be conducted right after passing the shaft wall to make sure that no tools are damaged by the concrete and glass-fibre reinforcement.
2. The second stop should be after about 50-75 m, to gain a first impression of the expected wear rate
3. Afterwards, the tool should be inspected every 150 m until the actual wear rate can be estimated.
4. When the wear rate is determined, the maintenance interval can be increased accordingly.
5. If the geotechnical properties or steering parameters change, the distance between interventions should be decreased again until a fitting estimation is found.

This approach is rather time consuming, but the more interventions are performed the more accurate the prognosis is. Since some of the interventions are only for inspection of the cutting wheel, the downtime of the single maintenance stops is rather short, depending on the support pressure.

In addition to this schedule, the maintenance classification of the tunnel alignment has to be taken into account. If there are sections of the alignment that have a high classification, an intervention should be performed before excavating this area. Interventions within this section should be avoided. Areas with a low classification are also predestined to schedule at least one maintenance stop. Before the machine enters a shaft wall or other construction obstacles, it must be ensured that the outer cutting discs are not worn and a sufficient overcut of is guaranteed.

5.2.2 High level of information

If there is a high quality and quantity of data and information, then a detailed wear prediction using one of the models reviewed in Section 3.2.3 can be conducted. In the best case, uncertain input data is available, so that instead of one deterministic value of the maintenance interval, a probability function of possible maintenance intervals can be determined with the help of a MCS.

To further analyse the dependencies of the system in order to improve the maintenance schedule, a more detailed method is necessary. Process simulation has proven useful to analyse complex systems under consideration of uncertainties (see Section 2.2). In the following, the developed simulation model is presented.

5.3 Development of the Simulation Model

A simulation model has been developed according to the procedure described in Section 2.2.1. The goal of the simulation model is to use the quantitative wear prediction model of Köppl to analyse and improve the deterministically determined maintenance strategy. Therefore, uncertainties shall be considered to evaluate the time and costs of the strategies. The model can then be used to conduct several different experiments to gain a better understanding of the system behaviour and interdependencies.

5.3.1 System Analysis

The regarded system consists of four elements that can be structured as shown in the *bdd* in Figure 5-6. The main elements are *Project*, *CuttingWheel*, *Soil* and *CuttingTool*. *Project* contains all general information of the project to be analysed. This includes the *CuttingWheel* and the *Soil*. For each tunnelling machine that is used in the project a *CuttingWheel* is added to the model. Similarly, for each homogeneous section a *Soil* is added to the *Project*. Each *CuttingWheel* contains a list of *CuttingTools*.

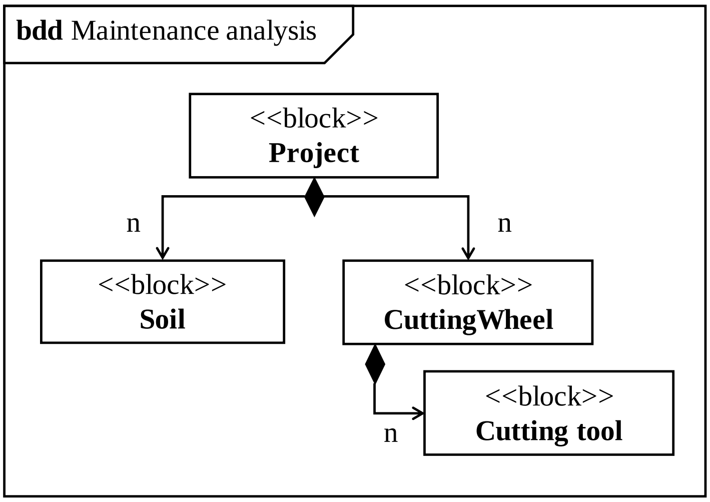


Figure 5-6: Block definition diagram of the necessary components for the simulation model of the maintenance analysis

The analysed processes of the project are defined within the element *CuttingWheel* that is the main performing element in this model. The processes have been formalized using a *stm*-diagram presented in Figure 5-7. In the beginning, during the *start* process, the project setup takes place. The project execution begins, when the project is completely built and all parameters are set (1). The *CuttingWheel* switches into the state *operable*, where the main processes *advance* and *ringbuild* are conducted. The change to the *ringbuild* state is triggered by elapsing a period of time (2), which is calculated by means of penetration and rotational speed. The timeout to switch out of the *ringbuild* state (3) is given by the duration of one ring building process. At the branch it is decided whether a maintenance is scheduled (5), repair is needed due to excessive wear (6) or *advance* can continue (4). After the maintenance or repair is finished (7, 8) the state switches back to *advance*. If a technical failure of the cutting wheel occurs, e.g. a breakdown of the engine, the current *operable* state is interrupted and the cutting wheel switches into the *inoperable* state (9), hence *tech_failure*. After the malfunction has been removed, the state switches back to the previous state, thus the state that has been interrupted (10).

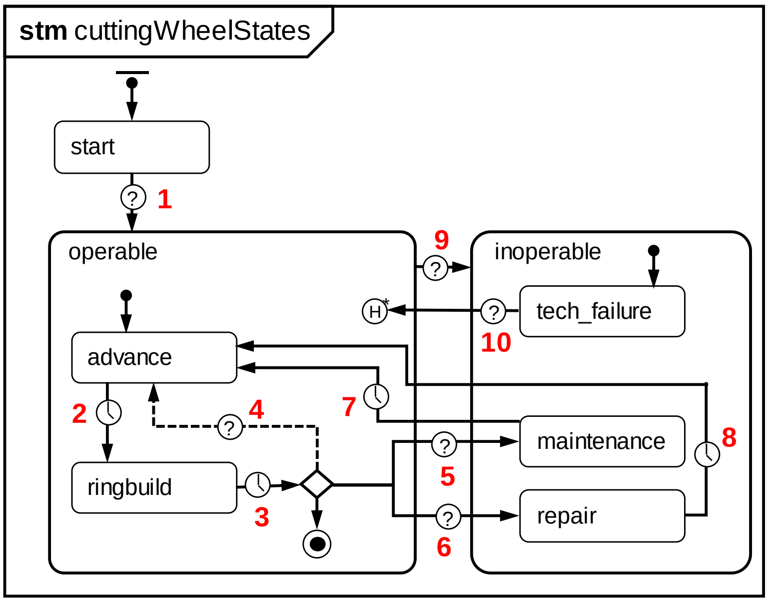


Figure 5-7: State chart diagram of the processes of the CuttingWheel

A dependent failure, which is caused by a failure of the supply chain, is neglected for this simplified model, since it has no influence or a negligible effect on the wear and maintenance of cutting tools. Only larger disturbances with longer downtimes, e.g. a face collapse, would have to be considered.

For each advance cycle, all uncertain parameters are recalculated using the defined distribution functions. This way, the fluctuation of these parameters can be modelled. The wear level of the cutting tools is updated when Transition 2 is used, thus after the excavation of one ring. Afterwards, the constraints for the maintenance and repair work are checked according to Section 5.3.3.

5.3.2 Input Data

The presented model requires a variety of input data that is needed for each analysed project. Some of the parameters can be set freely according to the project conditions. Other parameters are assumptions or are gained from back analysis, e.g. process durations or cost values, and stay the same until new knowledge has been gained.

The model uses the wear prediction model of Köppl. Therefore, the model is restricted to hydro shield machines. If other machine types shall be analysed, an appropriate wear model has to be implemented beforehand and this would change the needed input data.

The needed project boundaries and required assumptions of the steering parameters are summarised in Table 5-4. In addition, the design of the cutting wheel, including the cutting tool arrangement, is needed. For each tool, the distance to the cutting wheel centre and the tool type has to be listed. Further information, for instance the excavation direction of scrapers, the cutting blade width of disc cutters or the existence of forerunning ripper tools have to be added. If the cutting wheel and condition shall be visualised by the simulation model during a simulation experiment, further geometrical information about the cutting tool position is required.

Table 5-4: Project boundaries and steering parameters.

Input parameter		**Unit**
Project boundaries		
L_{tunnel}	Length of the tunnel	[m]
D_{TBM}	Diameter of the cutting wheel	[mm]
L_{adv}	Segment width	[m]
p_b	Required support pressure	[bar]
Steering parameters		
p_e	Expected penetration	[mm/rev]
U	Rotational speed	[rev/min]
t_{RB}	Duration ring building process	[min]

The soil is described using the required soil parameters of the wear prediction model. Some of the values can either be directly set or result from the other parameters according to the Equations 3-25 to 3-34. All soil parameters are listed in Table 5-5. Since most of the tunnels do not excavate only within one soil layer, HGB have to be defined. For each HGB all soil parameters according to Table 5-5 must be known.

Table 5-5: Geotechnical parameters for the wear prediction.

Input parameter		**Unit**
Geotechnical parameters		
SAI	Soil Abrasivity Index	[-]
eQu	equivalent quartz content	[%]
D_{60}	Grain size at 60% mass fraction	[mm]
τ_c	Shear strength	[kN/m²]
φ'	Friction angle	[°]
c'	Cohesion	[kN/m²]
σ_n	Normal stress	[kN/m²]
H_{TA}	Height of overburden above ground water level	[m]
W_{TA}	Height of overburden below ground water level	[m]
γ	Unit weight of soil above ground water level	[kN/m³]
γ'	Unit weight of soil below ground water level	[kN/m³]

The values for the process durations of the maintenance work and the costs incurred have to be chosen according to the experience and data of the contractor. These values are needed for the evaluation of the maintenance strategies. For the first estimation of these values, experienced tunnelling engineers have been interviewed (see Appendix B). The presented cost values are one example and differ for each project and company. When using the model for scheduling and evaluation of maintenance strategies, these parameters have to be set according the own cost estimation. The resulting ranges of the duration parameters and the example cost values that were obtained are summarised in Table 5-6.

The maintenance schedule can be set as certain positions given by a list of ring numbers or can be given by a maintenance interval for each homogeneous section. These intervals can be set automatically using the wear prediction model for the outer cutting tools to estimate the maximum excavation length until the first tools reach their wear limit. Therefore, the expected values for the soil properties and steering parameters are used. This way, sensitive surface structures as well as high water pressures cannot be taken into account and have to be evaluated afterwards.

If an input parameter is not given as a single value but is subject to uncertainties instead, a fitting distribution function must be found and implemented into the model. Each distribution function consists of coefficients that can be used as input parameters of the model instead of the single value that represents only an expected value.

Table 5-6: Input parameters: process duration and costs values.

Input parameter		**Unit**	**Range**
Process durations			
t_{mob}	Mobilisation processes	[min]	60-600
t_{supply}	Material supply	[min]	0
t_{low}	Lowering the support medium	[min]	15-120
t_{comp}	Compressing of the workers	[min]	5-10
t_{instal}	Installation of platforms	[min]	5-15
t_{clean}	Cleaning of cutting tools	[min/tool]	1-5
t_{insp}	Inspection of tools	[min]	5-10
t_{bolt}	Retightening of bolts	[min]	1-2
$t_{e,d}$	Replacing disc cutter	[min]	30-80
$t_{e,s}$	Replacing scraper	[min]	10-20
$t_{e,b}$	Replacing bucket	[min]	20-30
$t_{e,r}$	Replacing ripper tool	[min]	10-20
t_{hold}	Repair of broken holder	[h]	6+
t_{demob}	Demobilisation processes	[min]	30
$t_{unmount}$	Unmount working platforms	[min]	5-20
t_{decomp}	Decompression of the workers	[min]	(BGBI I 10/4/1972)
t_{refill}	Refilling the excavation chamber	[min]	10-20
t_{remove}	Removing worn tools and material	[min]	0-5
Maintenance costs			
$c_{p,f}$	Fix cost for a planned intervention	[€/intervention]	1500
$c_{p,t}$	Time-dependent costs for planned intervention	[€/h]	100
$c_{u,f}$	Fix costs for unplanned intervention	[€/intervention]	3000
$c_{u,t}$	Time-dependent costs for unpl. intervention	[€/h]	100
$c_{t,p}$	Time-dependent project costs	[€/h]	1200
c_d	Material costs cutting disc (17’’)	[€/disc]	2000

c_s	Material costs scraper	[€/scraper]	300
c_b	Material costs bucket	[€/bucket]	1200
c_r	Material costs ripper	[€/ripper]	(300)
c_h	Material costs holder repair	[€]	1000

5.3.3 Constraints for maintenance work/schedule

In order to model the real behaviour of the system, constraints must be implemented that define the conducted maintenance work and the penalties for insufficient maintenance. This is required since the real system responses to neglected maintenance, hence the developed model, must react similarly to evaluate the impact of advanced wear and unplanned maintenance stops.

Preventive maintenance

At each maintenance position, the advancement cycle is interrupted after the ring building process and the maintenance process takes place. The condition of all tools is checked to identify the worn cutting tools, hence the extent of maintenance work. Therefore, all tools that exceed the wear limit are replaced. For all other tools, the remaining wear path is determined considering the current condition as well as the soil properties of the upcoming homogeneous sections. Here as well, the expected values are used to predict the remaining cutting path of the tools. Afterwards, all tools, whose remaining path is smaller than the length of the next maintenance interval, have to be replaced preventively as shown in Figure 4-6. Equation 3-36 can be used to determine the preventive replacement condition limit. A correction factor f_{prev} can be used to reduce or increase this limit value to cope with the uncertainties of the wear rate.

Consideration of other wear mechanisms

The used wear prediction model only considers continuous abrasive wear. Nonetheless, at most projects there is the possibility of other wear mechanisms to occur. Especially sudden damages caused by obstacles or boulders inside the soil significantly affect the need of tool maintenance. Thereby, two cases of damage extent have to be considered. First, minor damage, where small parts of the tool spall off, suddenly reducing the condition of the tool without damaging other structures. Second, major damages, where not only the tool, but also the tool holder or cutting wheel is damaged as well and repair work is needed. For both cases, a probability factor P and a damage factor Δe for the extent of sudden wear are included in the model. The extent of damage is considered according to Figure 5-8. The probability factor P_{minor} and P_{major} give the probability of occurrence after each excavation step in [$ring^{-1}$]. The assumption of the probability is oriented on the expected percentage of obstacles and boulders inside the soil. Since no data is available right now, the following values are assumed:

- P_{major} = 0.1 %
- P_{minor} = 2.0 %

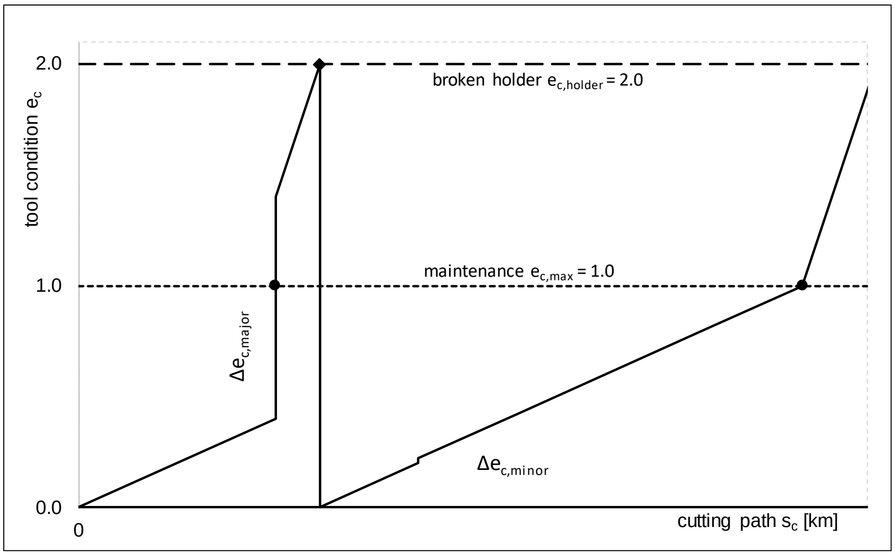


Figure 5-8: Tool condition $e_{cd,e(k)}$ with minor Δe_{minor} and major Δe_{major} damages.

Due to the lack of data, the amount of additional wear is assumed to be Δe_{minor} = 0.01 and Δe_{major} = 1.0. Nonetheless, the maximum condition $e_{c,holder}$ = 2.0 cannot be exceeded, because it marks the highest amount of damage. Above this limit, the wear behaviour is completely unknown and does not follow any wear prediction models anymore.

Corrective maintenance rules and penalty factors

An insufficient maintenance strategy causes severe wear of the cutting tools and of the cutting wheel structure. The shield driver or responsible engineer notices these damages at different stages by interpreting the reaction of the machine parameters due to the high wear amount. To consider this effect in the simulation model rules have to be defined that reflect the notification of the heavy wear, which initiates an unplanned maintenance stop and corrective maintenance of the cutting tools. Furthermore, a penalty for exceeding the wear limits must be defined, since the wear does no longer progress as predicted by the wear prediction model and the repair of the damage may become more time-consuming depending on the wear level.

The condition of each cutting tool is given according to Equation 3-36. If the wear limit $e_{cd,e(k)}$ = 1.0 is exceeded, the wear rate of this tool increases, because the wear protection of this tool has worn off. Since there has been no data evaluation conducted and no prediction model for further wear exists, here, the new wear rate is assumed by comparing the wear resistance of the wear protection layer and the tool body substrate, e.g. resulting from Küpferle et al. (2017a).

If these tools are replaced before wear affects the tool holder or the cutting wheel structure, the time needed for the replacement stays the same. This utilisation reserve defines the second wear limit. If these tools are not replaced in time and wear exceeds further, crucial wear of the tool holder occurs and the time for repair rapidly increases due to the necessary welding work.

For the definition of the threshold to conduct an unplanned maintenance stop, two options can be used:

1. The average wear limit of all tools exceeds a certain value e_{avg}.
2. The wear limit of a single tool exceeds a certain value e_{max}.

Since there is no data available yet to quantify these limits, first assumptions are made here. Later on, the sensitivity of these values on the simulation experiments are evaluated to ensure that the results are not greatly influenced by them. Therefore, in the beginning it is defined that e_{avg} = 0.8 and e_{max} = 2.0.

In addition, for the outer cutting tools, which are needed to guarantee a sufficient shield tail gap, a smaller value for e_{max} can be chosen. This way a jamming of the shield tail in the ground can be avoided.

5.3.4 Implementation

The formalised model has been implemented in the simulation framework AnyLogic (The AnyLogic Company 2019) version 8.2.3. AnyLogic is a java-based multi-method simulation framework that enables a combination of DES, AB modelling and SD simulation. Furthermore, additional java classes and code can be implemented to extend the model with flexible elements and algorithm.

The implementation of the model is done according to the logic previously mapped in SysML. The elements that are implemented as agents as well as the structure and the level of detail of the model can be taken from the *bdd* diagram (Figure 5-6).

Each agent has several input parameters, variables, functions and output data. Figure 5-9 shows the agent *Project*. The agent *CuttingWheel* and a population of agents

Soil are added according to the hierarchical structure. The input parameters of all agents can be imported from a spreadsheet defined within the parameter *input* and are set by the function *initialize*. The output data is used for the analysis of results, for visualisation and for the verification of the model. In agent *Project,* the output data that is visualised gives an overview of the projects progress and the distribution of the total project duration for the four processes advance, ring building, maintenance and repair.

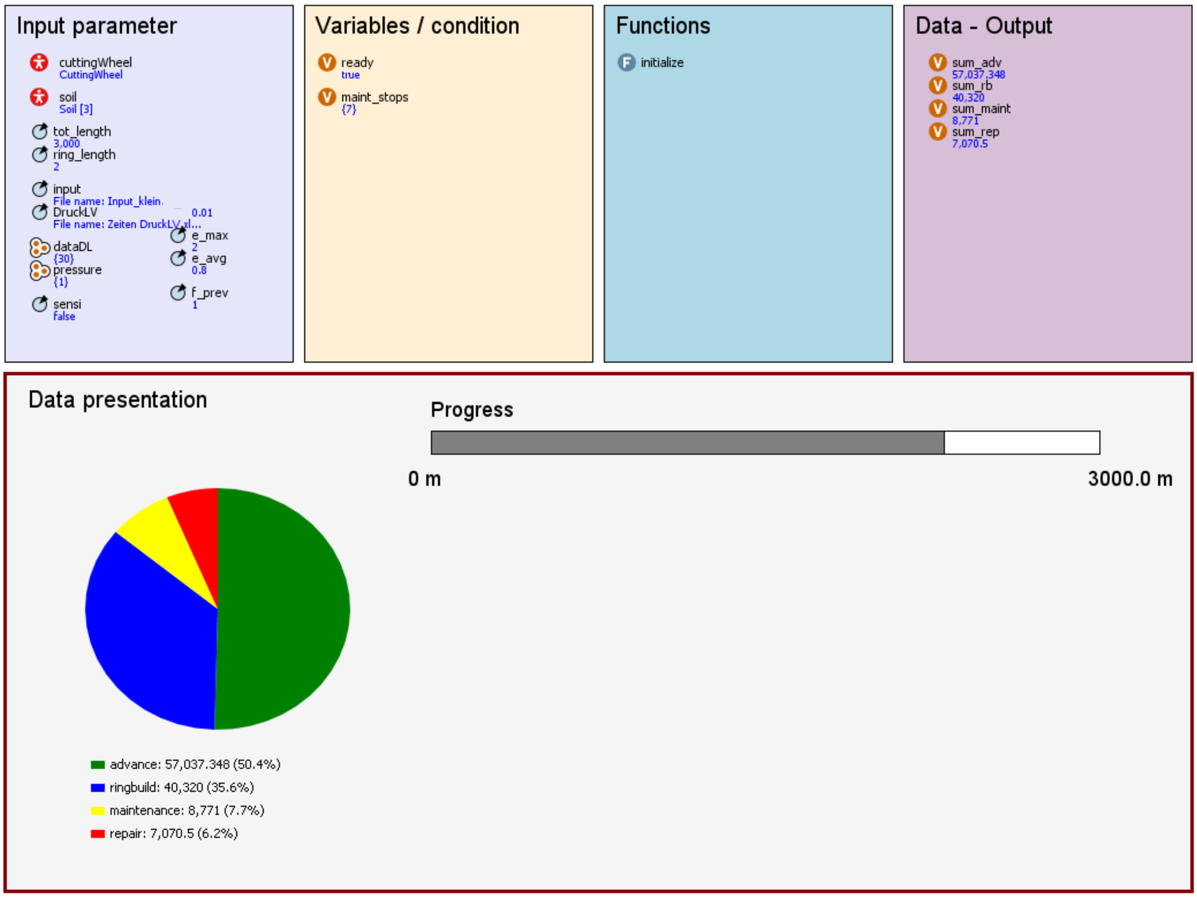


Figure 5-9: Implementation of the agent Project including the visualisation of the project durations and the progress of the system.

Each soil agent contains all geotechnical parameters that are needed for the wear estimation. For all uncertain parameters, distribution functions can be set using the *Distribution* agent. For each advance cycle, a random number generator (RNG) is used to pick a random number according to the distribution function. These values are then used to calculate the SAI value of the current advance cycle. To verify the used distribution functions, the estimated values are plotted in a histogram as shown in Figure 5-10. Furthermore, they are saved in a dataset for later evaluation. In addition to the geotechnical parameters, a distribution function is defined for the penetration. If no uncertainties shall be considered for the analysis the distribution function type can be set to be discrete. This way only one value for the whole homogeneous section is considered.

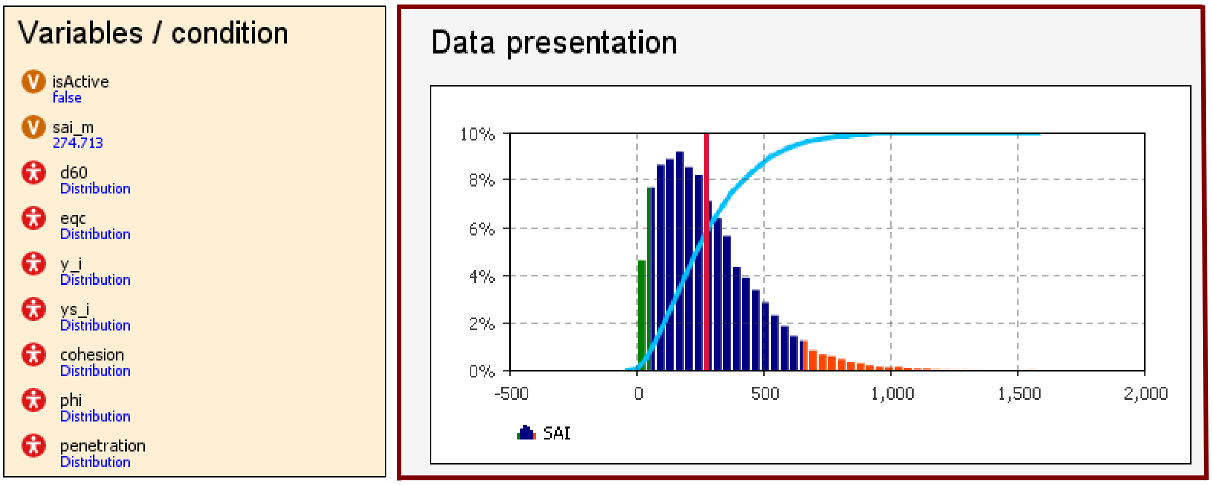


Figure 5-10: Agent Soil – Distribution of geotechnical parameters and histogram of the resulting SAI-value.

The behaviour of the agent *CuttingWheel* is implemented according to the state diagram of the model formalisation (Figure 5-11-a). The agent includes a population of the agent *Tool*. The position and condition of each tool is visualised during the simulation in different colours (Figure 5-11-b). Displayed in green are all tools that are still operable and do not have to be replaced during an intervention. Yellow are the tools that are still operable, but should be replaced preventively during the next intervention. Orange tools have exceeded the wear limit and red indicates a damage of the tool holder, thus repair work becomes necessary. The data presentation (Figure 5-11-c) is used for the analysis and verification of the model. The first chart shows the number of replaced tools of each tool type and the number of broken holders that have been repaired for each intervention. Accordingly, chart 2 presents the duration of the intervention. Red bars indicate an unplanned maintenance stop that is performed if one of the set constraints defined in Section 5.3.3 is exceeded. To evaluate the efficiency of the maintenance work the condition of the replaced cutting tools is summarised in the histogram of chart 3. Each tool type is regarded separately and marked in different colours.

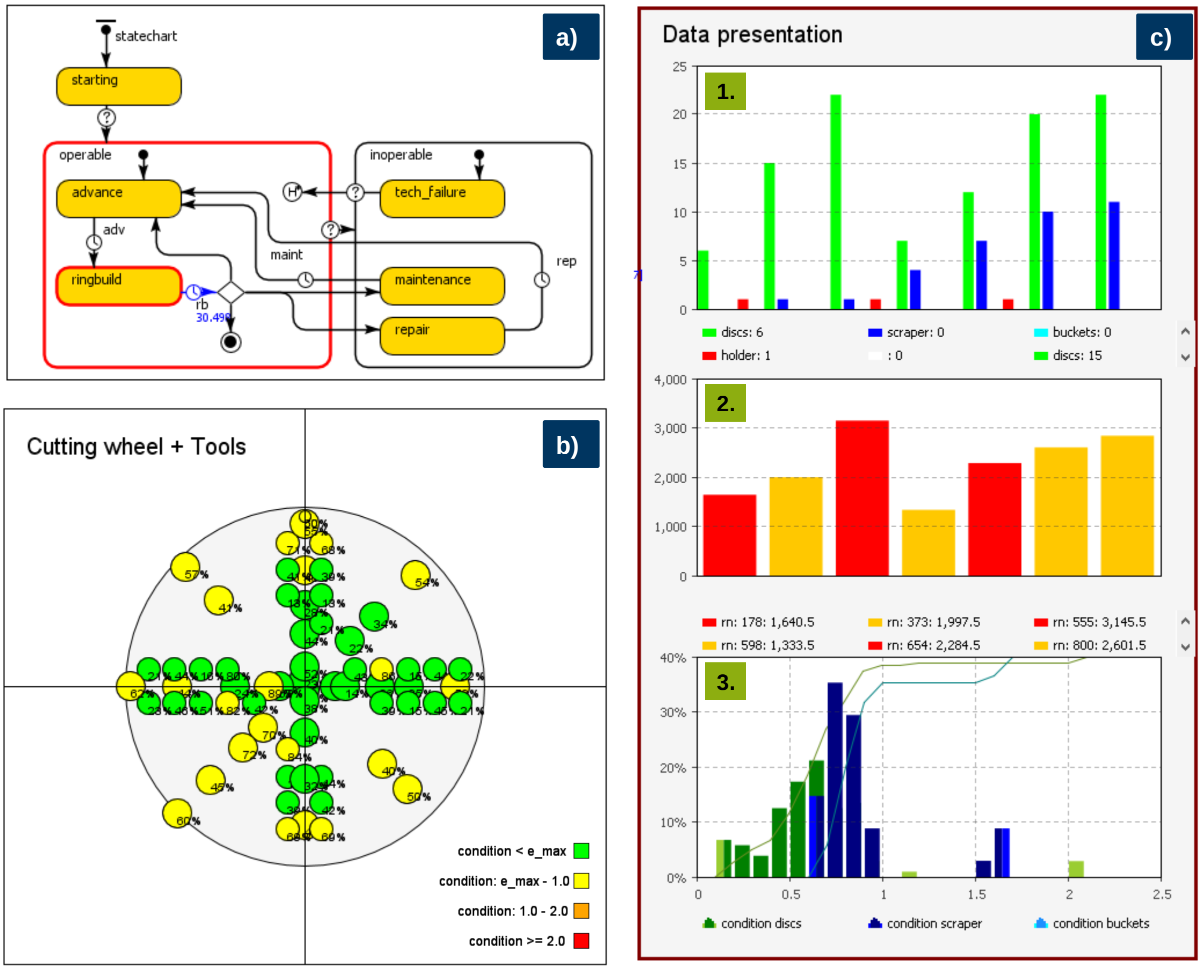


Figure 5-11: Agent CuttingWheel a) state chart, b) visualization of the cutting tool conditions , c) data presentation: 1 - bar chart replaced tools per intervention; 2 – duration of intervention [min], yellow: maintenance, red: repair; 3. histogram of the condition of the replaced tools.

All cutting tools are implemented in the population of the agent *Tool*. To model the variety of cutting tools, the type and position of each tool is set. For each homogeneous section the expected values for the SAI are used to estimate the expected wear path until the tool reaches the wear limit.

There are two approaches to model the wear of the cutting tools during simulation. An SD approach can be used to simulate the deterioration of the cutting wheel condition simultaneously to the advance process of the *CuttingWheel*. Therefore, a wear rate is set for each cycle according to the random geotechnical parameters of the *Soil* agent. This way, the exact point in time can be found, where a tool exceeds the wear limit during excavation. However, due to the high number of cutting tools and iteration steps, the simulation performance will decrease significantly, leading to long durations of the experiment calculation, especially when many simulation runs need to be executed.

The second approach for wear estimation is a discrete approach. After each advance process the actual condition is calculated using the actual soil parameter and the resulting cutting path for the penetration value of the cycle. This way, the actual wear is only simulated for one point in time. Consequently, the exact point in time when the wear limit is exceeded is not known. Therefore, an interruption of the advance process due to excessive wear cannot be modelled. It is assumed, that the advance cycle will always be completed before an intervention is performed. This assumption states that heavy wear is detected early before the machine is stuck. Even though in actual projects a corrective maintenance may interrupt the excavation process, the error in time and costs that occurs due to disregarding this case is negligibly small, whereas the modelling effort is reduced significantly.

Sudden major and minor damages of the tool are implemented according to the model formalisation. It is assumed that these damages affect all tools on the same tool track. An exemplary wear progression of one tool estimated with the simulation model is shown in Figure 5-12.

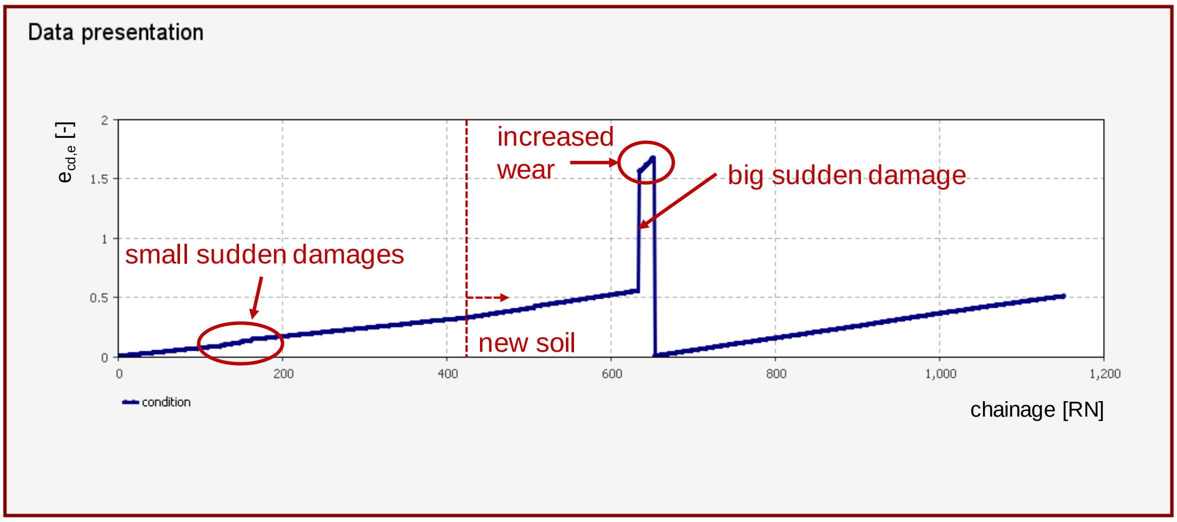


Figure 5-12: Agent Tool – Condition of the tool over the chainage of the advancement.

5.3.5 Simulation Experiments and Resulting parameter

The simulation framework offers different opportunities to conduct simulation experiments. The simplest option is to conduct a single simulation run. This way, all model elements can be observed during simulation. It is important for the comprehension of the interdependencies of the modelled system and for the verification of the implemented calculations. Based on this, further experiments can be performed according to Section 2.1.1.

Monte Carlo Simulation

The regarded system is subject to uncertainties, which must be considered during the analysis. To perform a MCS, distribution functions must be defined for the uncertain input parameters. The more uncertain input parameters have to be considered the more simulation runs are needed to gain statistically significant results. The experiment can be stopped when the resulting frequency distribution does not change shape or position anymore. Therefore, the deviation of the mean value of an output parameter is regarded. If the mean value only varies within a given range after adding further simulation runs, the experiment can be stopped.

For the analysis of the results, the output parameters must be defined. Possible output parameters that can be evaluated are:

- Total duration of the maintenance and repair work
- Number of interventions (planned/corrective)
- Number of replaced tools (discs/scrapers/buckets/rippers)
- Number of broken holders/repair work
- Maintenance costs

Furthermore, the degree of utilisation of the replaced tools can be evaluated as well. However, since no switching of tools onto a different track or repair of the worn tools are considered in the model yet, the resulting values will be too conservative.

The defined output parameters are saved in a list and plotted in a histogram. It can be used to compare different scheduling approaches or project setups. Therefore, index values, e.g. mean value, quantile values or standard deviations, can be compared in addition to the graphical comparison as presented in Section 2.3.2. Furthermore, evaluating the deviation of the output values and especially the frequency of corrective maintenance, the robustness of a maintenance strategy can be assessed.

Parameter variation study

A parameter variation study (PVS) can be used to analyse sensitivities of the model or to optimise the maintenance schedule. Therefore, parameters of input parameters have to be defined, which are then varied within a defined range and step size. Each combination of the varied parameters represents one parameter set and for each set at least one simulation run is conducted. If there are uncertainties to consider, for each set several simulation runs are needed according to the MCS. In general, the output parameters of the PV can be chosen according to the MCS.

5.4 Discussion of the proposed model

A simulation-based approach for the evaluation of the maintenance schedule for cutting tool replacement has been developed. The model has a structure, where each cutting tool can be evaluated separately.

The simulation model offers a number of further advantages for the scheduling and decision making process:

- Consideration of uncertain input data.
- Modelling of all cutting tools separately.
- Dependencies of the system elements are taken into account.
- Different maintenance strategies can be implemented.
- Comprehensible evaluation of results.
- MCS and PVS for the assessment of a system.

However, there are still some aspects remaining, which have to be kept in mind while using the proposed model for maintenance scheduling. The results of the experiments strongly depend on the input data that is provided. Poorly documented or processed input data, will lead to unreliable results. Therefore, a further calibration of the assumptions made is mandatory to increase the reliability of the results. When considering these aspects, the model supports the maintenance scheduling process. Performing experiments with the help of the implemented simulation model, an improved maintenance strategy can be provided.

6 Model evaluation and analyses

The presented model is used to conduct several analyses. A sensitivity analysis has been performed in order to gain a better understanding of the system behaviour and model sensitivities. Afterwards, a case study is presented, where MCS is used to compare different project setups and to evaluate the maintenance schedule according to the criteria given in Section 2.3.2. The results of the case study are used for the verification and validation of the model.

6.1 Sensitivity analysis

In order to analyse the sensitivities of the proposed model, the sensitivities of the implemented wear prediction model have been analysed first. This way, a better understanding of the effects of the prognosis model and the implemented uncertainties can be gained. Afterwards, a global sensitivity analysis has been conducted, to identify the most sensitive input parameters of the maintenance schedule. This analysis has been conducted without considering uncertainties, so that comparable results are generated while the number of simulation runs is reduced to an acceptable maximum, since no MCS is necessary. Afterwards the influence of uncertainties has been analysed separately.

6.1.1 Sensitivity of the wear prediction

According to the applied wear prediction model there are two influencing factors when determining the maintenance interval: the penetration of the cutting wheel and the soil properties summarised in the SAI value. The SAI value determines the maximum cutting path distance of the tools. The distance of the cutting path is translated into longitudinal direction by using the radius of the regarded cutting tool and the penetration of the cutting wheel.

The diagram in Figure 6-1 shows the magnitude of influence of the SAI and of the penetration value on the maximum maintenance interval for the outer cutting tools of different cutting wheel diameters. It shows that according to the prognosis model the SAI value has only a significant influence for SAI < 1,200. This behaviour corresponds to the course of the function used to determine SAI and fits the data that has been used to develop the prognosis model. Further, the diagram shows that the penetration value has a significant influence on the maximum possible maintenance interval as explained in Section 3.2.1. As expected, for tunnelling machines with a larger diameter a smaller maintenance interval is necessary, due to the larger radius of the cutting tools on the cutterhead.

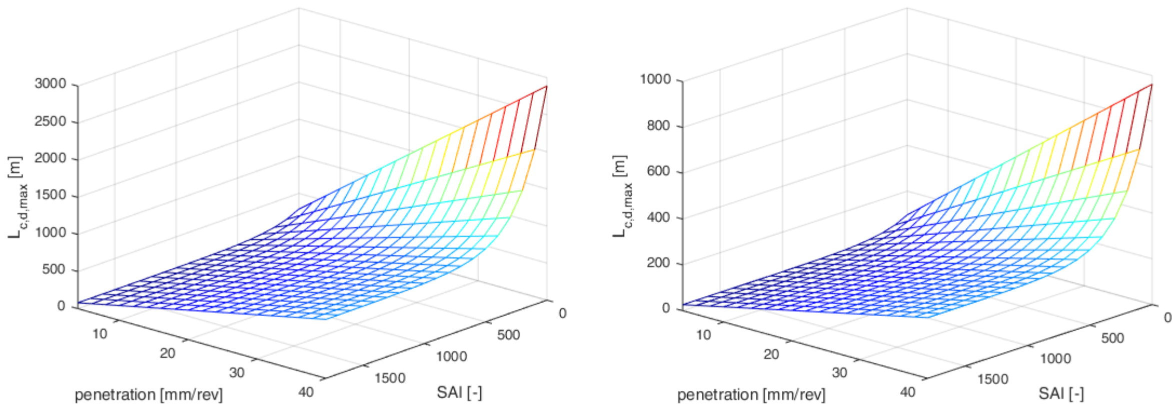


Figure 6-1: Influence of SAI-value and penetration on maximum maintenance interval for machine diameter D_{TBM} = 5.0 m (left) and D_{TBM} = 15.0 m(right)

The sensitivity of the SAI value against deviations of the soil parameters is analysed. Therefore, sensitivity analyses with the intervals and range of values given in Table 6-1 have been performed. The boundaries for these studies are chosen according to the boundaries of the wear prediction model given by (Köppl 2014, p. 187).

Table 6-1: Input parameters of the sensitivity analysis for the soil parameters

Parameter	**Min**	**Max**	**Step size**
eQu [%]	10	100	10
D_{60} [mm]	0.001	63.0	-
τ_c [kN/m²]	100	1,300	100

The influence of the variation of the soil parameters is shown in Figures 6-2 and 6-3. The shape of the surface plots, which results from the variation of eQu and τ_c, is equal for the different grain size values of D_{60}. However, the amount of the SAI is significantly higher for large values of D_{60} due to the wide range of values with the highest value being 63,000 times higher than the smallest.

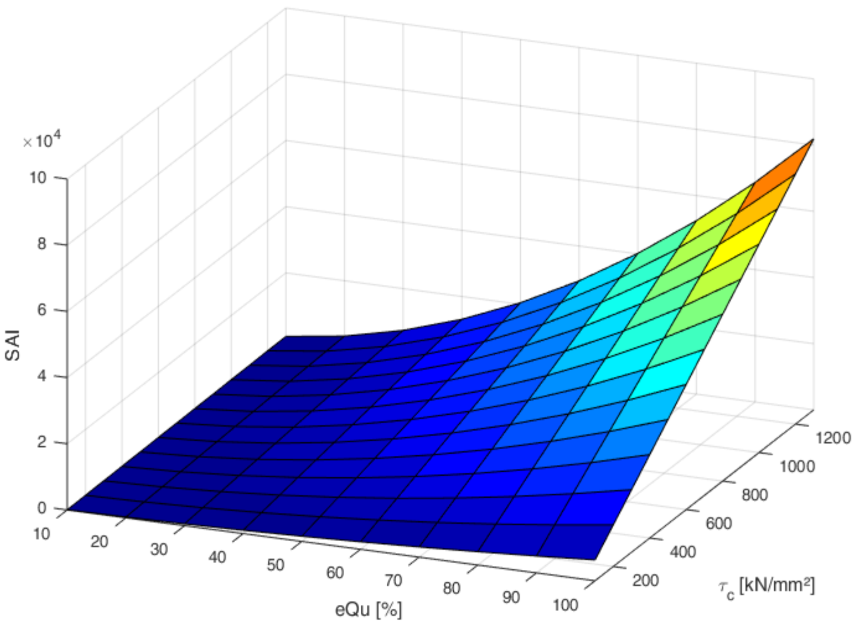


Figure 6-2: Influence of the eQu and τ_c, on the SAI value for D_{60} = 63.0 mm.

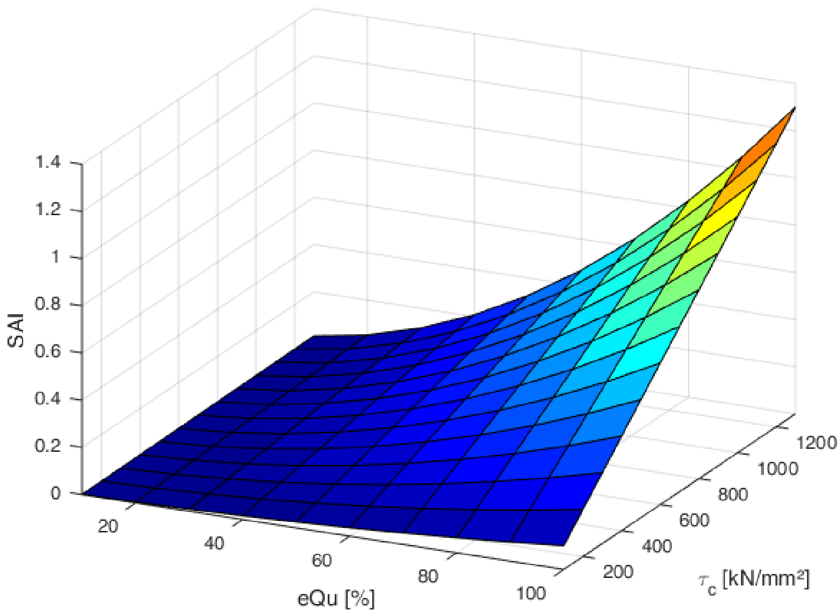


Figure 6-3: Influence of the eQu and τ_c, on the SAI value for D_{60} = 0.001 mm.

In order to investigate the influence of the uncertainties of the soil parameters on the SAI value, a MCS has been conducted for a given soil. Therefore, distribution functions for the soil properties are used according to Table 6-2.

Table 6-2: Input distribution function for the MCS to analyse the SAI value.

Input parameter	Distribution function	parameter	Unit
eQu	normal	$\mu = 85.0$, $\sigma_s = 3.0$	[%]
D_{60}	weibull	min = 0.01, $\alpha = 1.5$, $\beta = 2.0$	[mm]
φ'	normal	$\mu = 32.5$, $\sigma_s = 1.5$	[°]
c'	single value	0.0	[kN/m²]
H_{TA}	single value	3.0	[m]
W_{TA}	single value	15.0	[m]
γ	normal	$\mu = 17.0$, $\sigma_s = 1.0$	[kN/m³]
γ'	normal	$\mu = 9.5.0$, $\sigma_s = 0.5$	[kN/m³]

Here the distributions of the parameters σ_n, τ_c and SAI are calculated according to the equations presented in Section 3.2.3. The procedure of this MCS is presented in Figure 6-4.

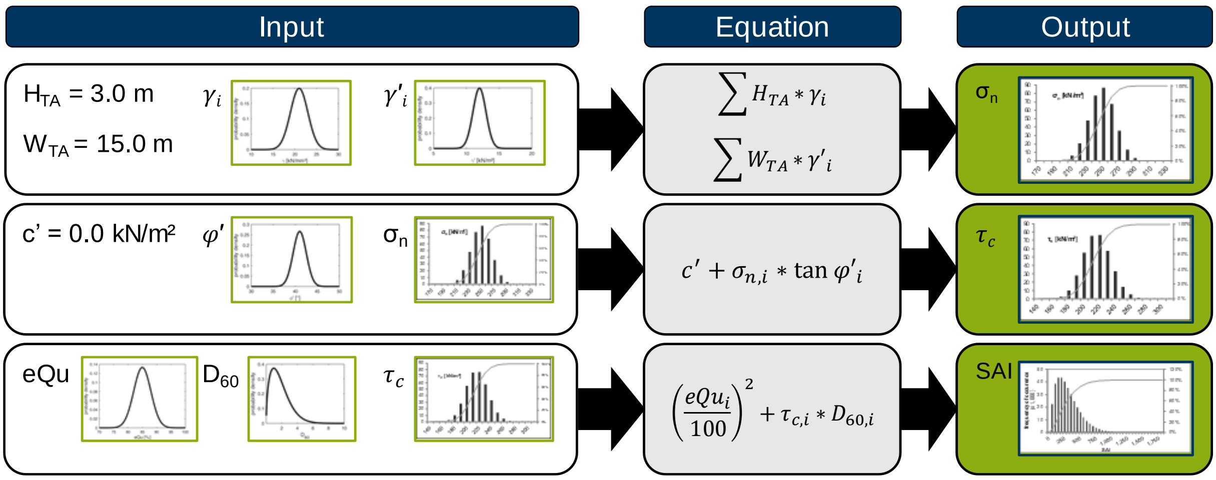


Figure 6-4: Calculation of the SAI value with the help of MCS.

The distribution of the resulting SAI values is presented in Figure 6-5. The resulting distribution is skewed to the left. The median of the SAI value lays at $SAI_m = 139.6$ and the 95 %-quantile $SAI_{95} = 375.6$ The 95 %-quantile gives the limit value that is only exceeded by 5 % of the calculated values. It is used for further analyses to reduce the risk of underestimating the SAI value. Using the maximum value would overestimate the SAI value, which results in a conservative and expensive maintenance schedule. The exact value for the used quantile value, can be adjusted according to the individual risk assessment.

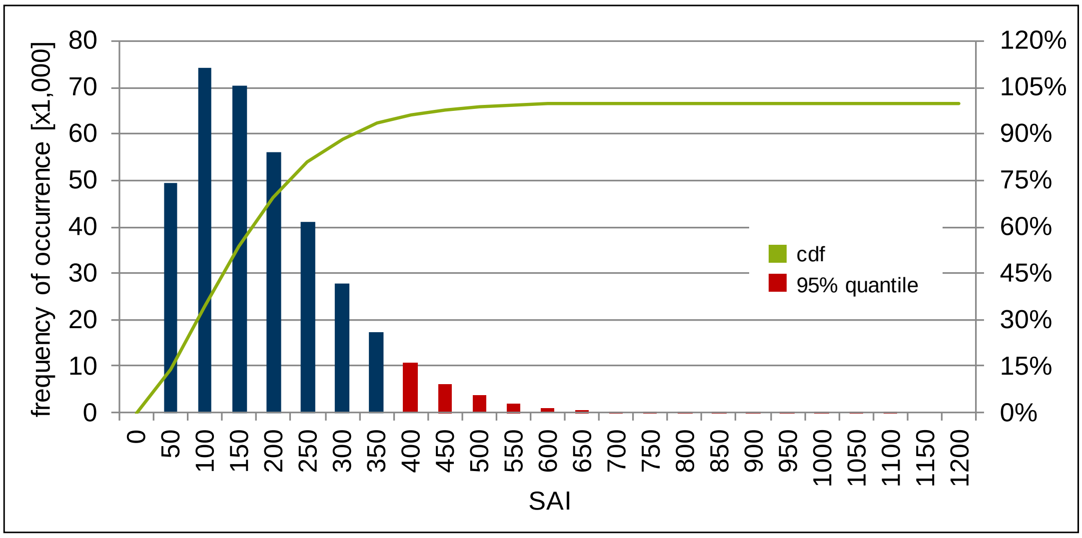


Figure 6-5: Histogram of the resulting SAI values of the MCS with 100,000 simulation runs.

Using this distributed SAI value and a distribution function for the penetration value, the deviation of the maximum cutting path can be evaluated. Figure 6-6 shows the propagation of the wear for one exemplary outer cutting tool. Two thousand simulation runs have been conducted, so that for each excavated ring the deviation of the tool condition can be regarded.

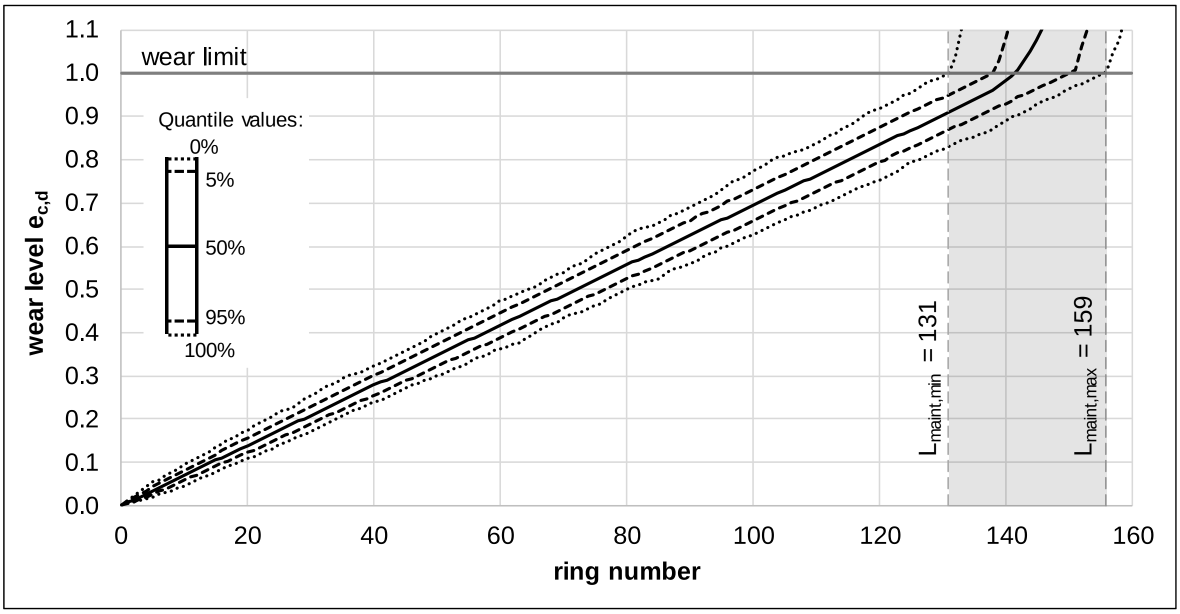


Figure 6-6: Confidence interval of tool condition for one exemplary tool and the corresponding maintenance interval L_{maint}.

Furthermore, the deviation of necessary maximum maintenance interval of the soil can be determined (Figure 6-7). Here, the length of the maintenance interval deviates from 131 to 159 excavated rings. Due to a ring length of 2.0 m, the maintenance interval deviates between 262-318 m.

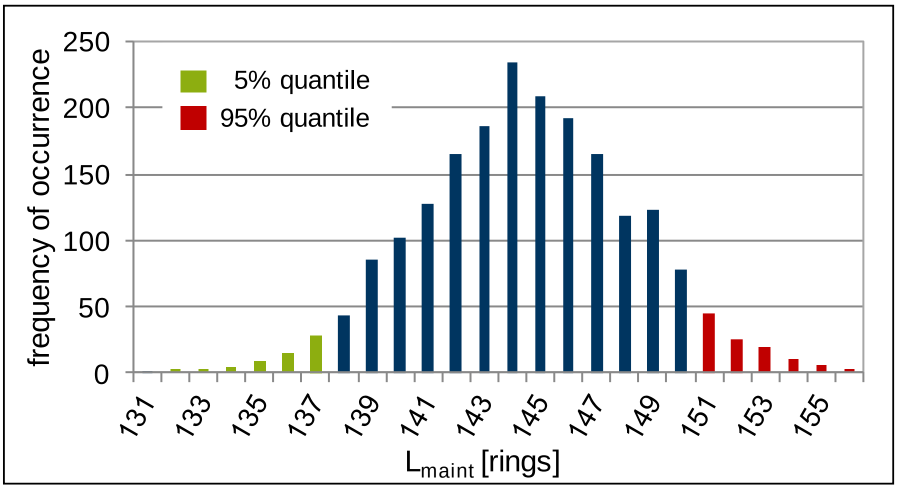


Figure 6-7: Histogram of the estimated maximum cutting path length

In order to avoid sever damages and unplanned maintenance stops, the lower limit value can be chosen. However, it may not be the economically optimal choice. Therefore, the deviation of the maintenance interval is analysed.

6.1.2 General sensitivity analysis

A global sensitivity analysis is conducted to gain a better comprehension of the system behaviour and dependencies of the input and output parameters. Therefore, PVS are performed, that vary chosen parameters within a given range and step size. The parameters and ranges are chosen according to the boundaries given by (Köppl et al. 2015b). The step size has been chosen in order to gain a wide variety of results, while also reducing the number of needed simulation runs. Table 6-3 presents all parameters used.

Table 6-3: Input parameters and ranges for PVS.

Parameter	**Min**	**Max**	**Step size**
SAI [-]	0	1,800	200
p_e [mm/rev]	5	45	5
p_{bar} [bar]	0.0	3.6	0.4
L_{maint} [rings]	44	164	8
D_{TBM} [m]	5.0	15.0	5.0
f_{prev} [-]	0.8	1.5	0.01

The following boundary conditions and input parameters are set and kept constant for the succeeding analyses:

- L_{tunnel} = 8.0 km
- U = 2.0 rev/min
- L_{seg} = 2.0 m

Furthermore, if the regarded input parameter are not suspect of the analyses and thus varied, they are kept constant at following values:

- L_{maint} = 50 rings ≙ 100.0 m
- SAI = 800
- p_e = 15 mm/rev
- p_{bar} =0.6 bar

The output parameter that has been evaluated are the resulting maintenance costs. In the following, relevant excerpts of the results are presented and discussed. For all input parameters, their influence on the maintenance costs for the regarded machine diameters are evaluated.

Support pressure for CA interventions p_{bar}

Regarding the support pressure during CA interventions it can be seen that due to the shorter working time allowed under compressed air, the maintenance cost increase when enhancing the pressure (Figure 6-8). This is due to the additional intervention processes that become necessary, when the tool replacement requires more time to be completed than the maximally allowed working time.

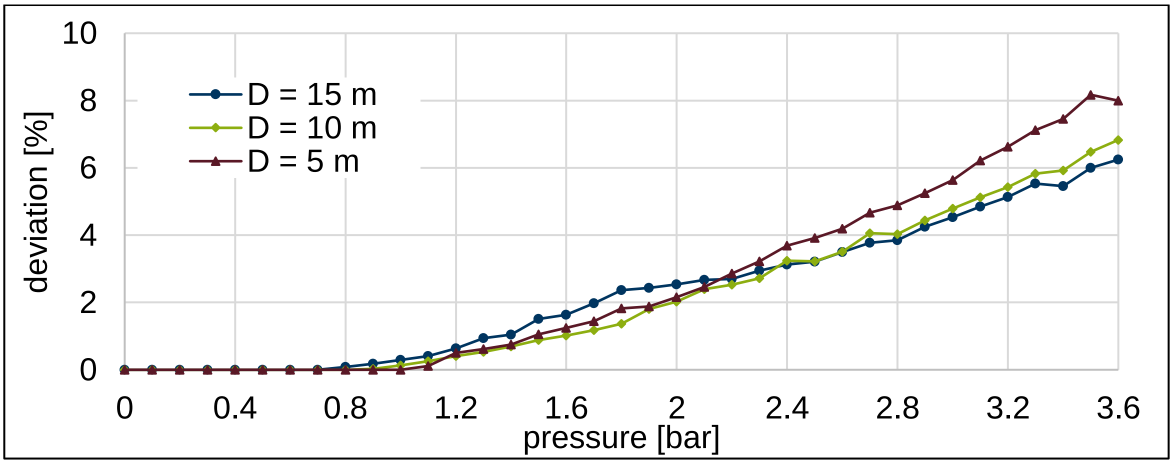


Figure 6-8: Influence of the face support pressure CA intervention on the deviation of maintenance cost for different machine diameter.

Length of maintenance interval L_{maint}

Figure 6-9 shows the influence of the maintenace interval on the costs. It can be seen that there is no linear dependency of the interval and costs. This is due to the non-linear number of maintenace stops and interventions during each stop. Furthermore, the number of replaced tools changes according to the maintenance interval. The red/ big points mark the determined maintenance interval using the wear prediction model. It can be seen that small increases of the the maintenance interval cause only small increases of costs for all machine diameter. However, if a cerrtain interval length is exceeded, additional corrective maintenance stops must be conducted which cause a sudden increase of costs.

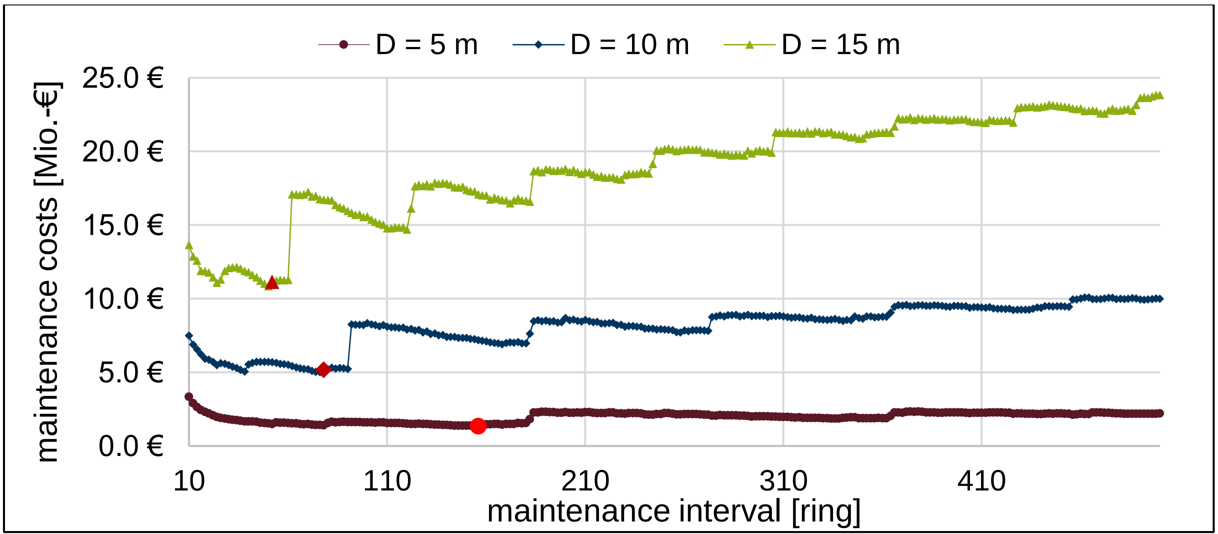


Figure 6-9: Influence of the maintenance interval on the costs for different machine diameters.

In general, increasing the number of maintenance stops decreases the cost that occur. Nevertheless, if the optimal number is reached, additional maintenance stops do not provide any further economical benefits, but result in expendable costs (Figure 6-10).

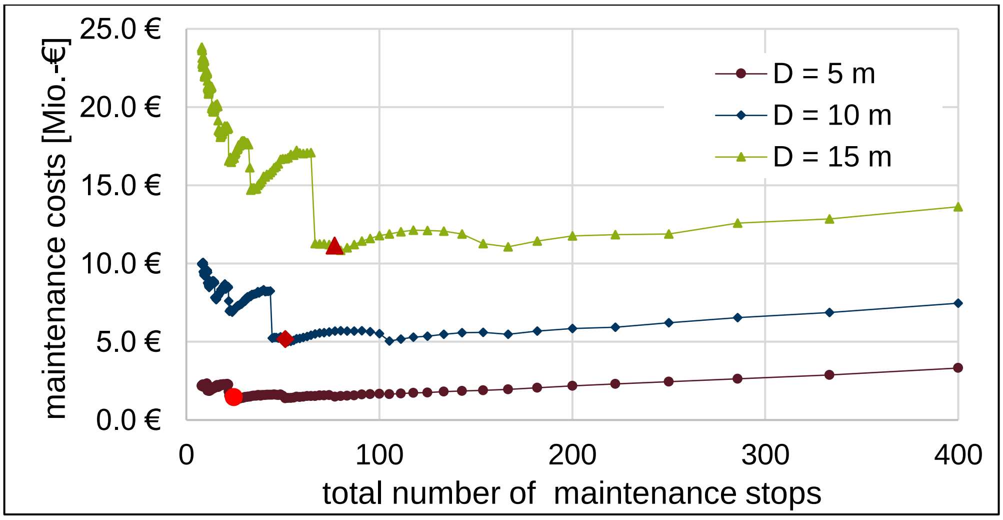


Figure 6-10: Influence of the number of maintenance stops on the costs for different machine diameters.

Penetration p_e

One of the indirect steering parameters of a tunnelling machine is the penetration of the cutting wheel. If the actual penetration is lower than the planned penetration, the cutting path of the tool per tunnel meter will increase. This leads to a reduced maintenance interval (Figure 6-11). When the scheduled maintenance stops are not adjusted accordingly, corrective maintenance work becomes necessary, increasing the maintenance costs.

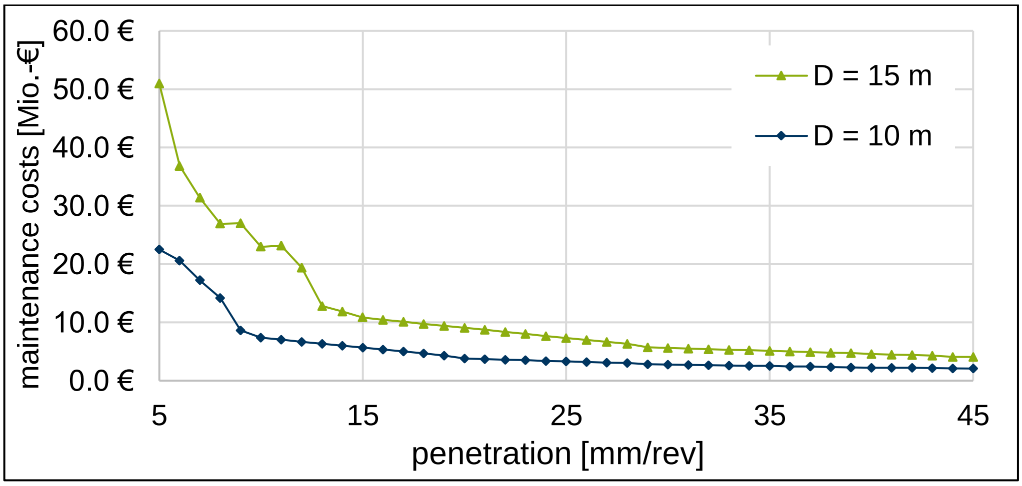


Figure 6-11: Influence of the penetration on the maintenance costs.

Soil Abrasivity Index SAI

The influence of the SAI-value corresponds to the relationship of the SAI to the length of the wear path, as shown in Figure 6-12. Above a certain value, there is no longer an increase of maintenance costs. Likewise, the maximum cutting path of the tools hardly decreases when exceeding a certain SAI value. Furthermore, it can be seen that outside the investigated range of SAI values (grey area) no valid statement can be made about the development of maintenance costs.

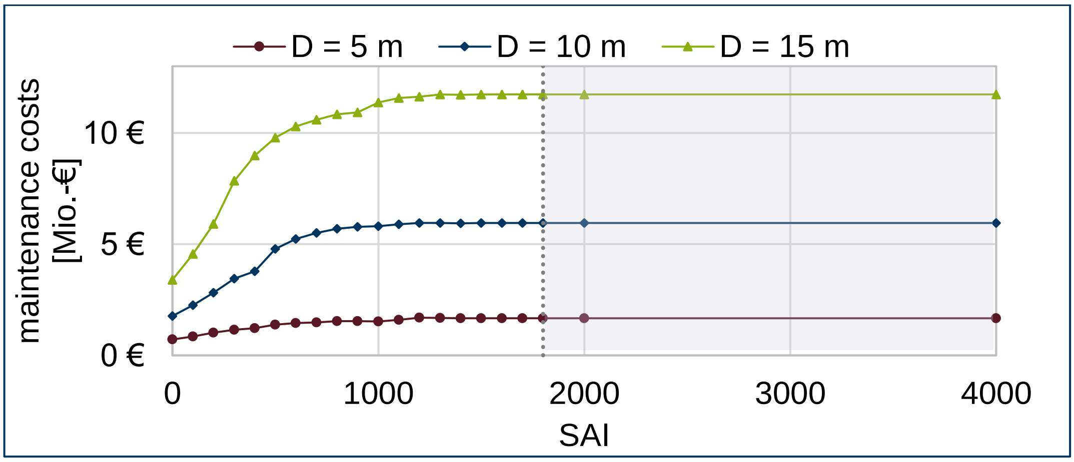


Figure 6-12: Influence of the SAI value on the maintenance costs.

Correction factor f_{prev}

The preventive replacement of cutting tools causes a lower utilization rate of the tools while increasing the reliability of the maintenance strategy by avoiding unplanned maintenance stops. Increasing the correction factor f_{prev}, the utilization of the tools increases so that the total number of replaced tools decreases. However, by increasing the limit value for preventive replacement of the tools the probability as well as frequency of unplanned maintenance stops and damaged tool holders increases, which leads again to higher maintenance costs (Figure 6-13).

Nonetheless, it has to be taken into account that for this PVS no uncertainties are considered, yet. Therefore, the influence of this factor when considering uncertainties are examined later on.

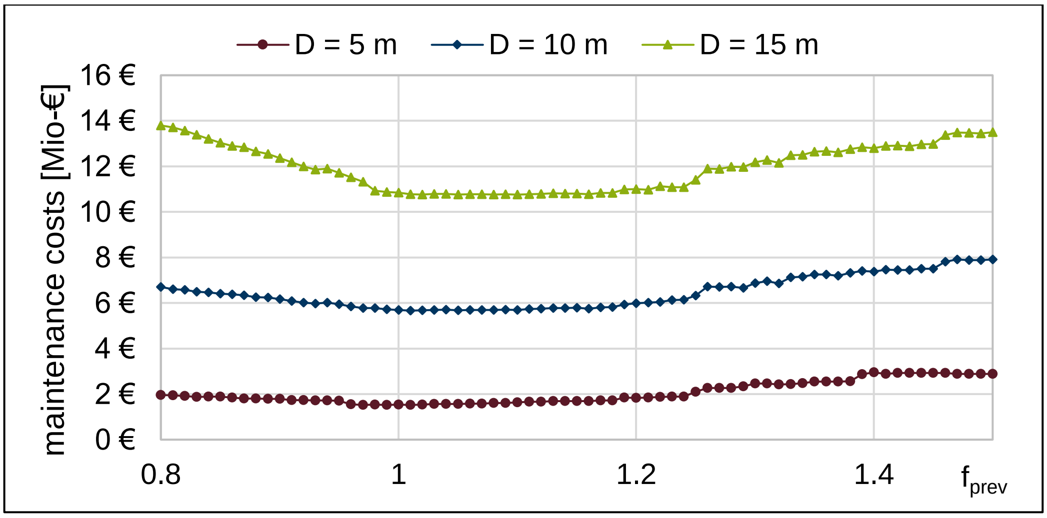


Figure 6-13: Influence of the correction factor f_{prev} on the maintenance costs

In Figure 6-14 and 6-15 plots are given that show the dependence of the maintenance cost on the relation between the length of the maintenance interval and the correction factor f_{prev} for two different machine diameters. It can be seen that the optimum of f_{prev} ranges between 1.0 and 1.2. Furthermore, it becomes apparent that preventive maintenance will not avoid corrective maintenance stops, if the maintenance interval is too large. However, reducing the preventive replacement of cutting tools will increase the need of corrective maintenance, thus the maintenance costs.

Nonetheless, regarding these two factors, considering uncertainties is mandatory to find a reliable and robust optimum. Concluding, an optimization of these two values, even without uncertainties, is a difficult task and is best performed using the PVS.

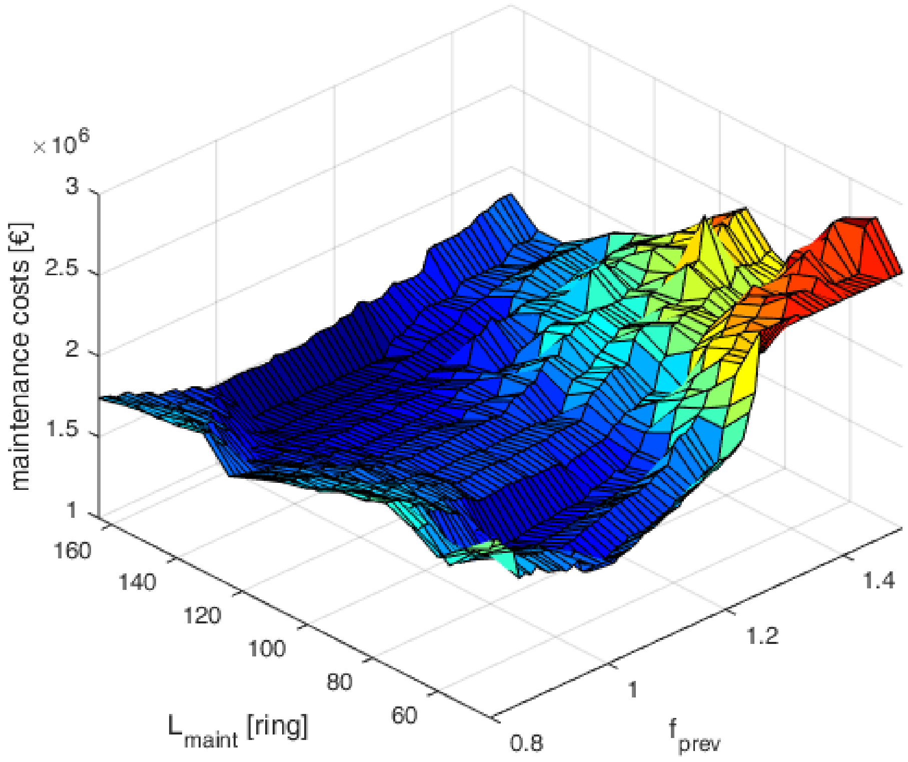


Figure 6-14: Surface plot of the maintenance costs in dependence of L_{maint} and f_{prev} for D_{TBM} = 5.0 m

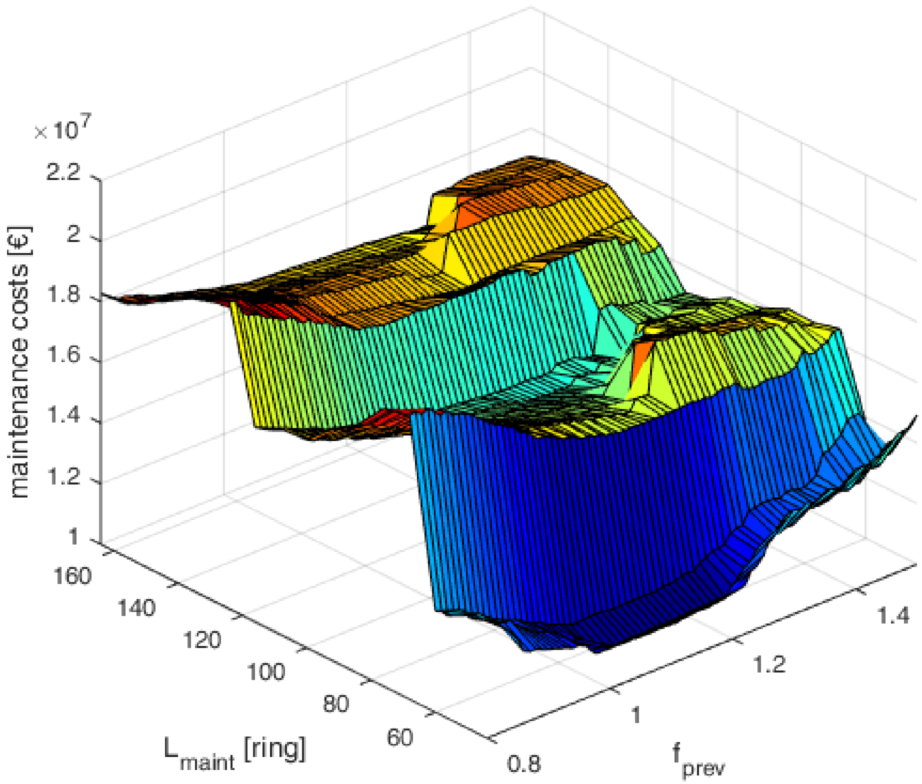


Figure 6-15: Surface plot of the maintenance costs in dependence of L_{maint} and f_{prev} for D_{TBM} = 15.0 m

6.1.3 Sensitivity of uncertainties

There are two types of uncertainties that have to be considered: the deviation of an input parameter and the probabilistic occurrence of an event. Here, the deviation of the parameters SAI and penetration are regarded using distribution functions. Furthermore, the sudden increases of the tool wear by surface spalling or breakage of the tool is analysed by considering the probabilities P_{major} and P_{minor}. The used boundaries for this investigation are:

- L_{tunnel} = 8.0 km
- L_{seg} = 2.0 m
- f_{prev} = 1.0
- D_{TBM} = 15.0 m
- p_{bar} = 0.6 bar
- U = 2.0 rev/min

In order to analyse the influence of the deviation of the SAI and penetration values, the distribution density functions given in Figure 6-16 are used. The values of these parameters are varied for every advance cycle. This way, the wear rate of the cutting tools fluctuates during the project execution.

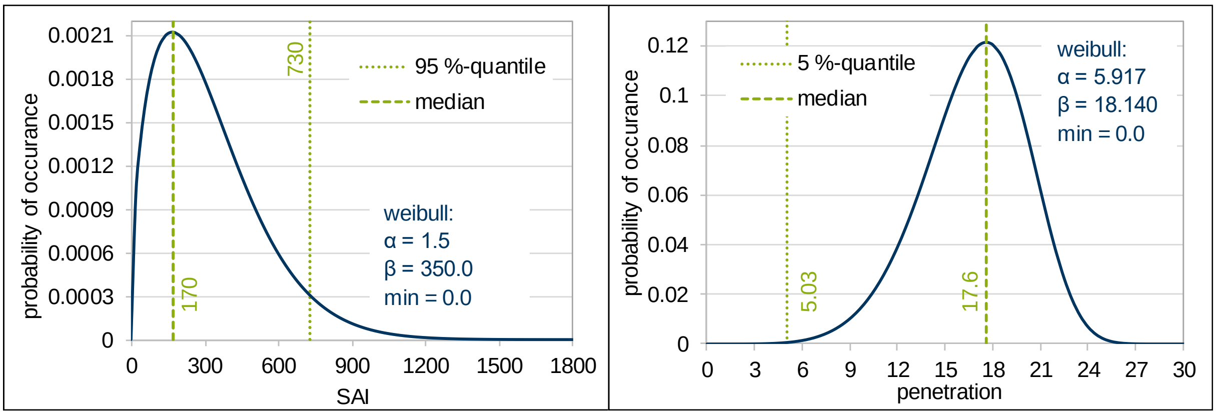


Figure 6-16: Distribution density functions of the SAI and penetration values.

MCS with 10,000 simulation runs each are performed to estimate the influence of the uncertainties. The SAI and penetration values are varied according to the distribution function. For the determination of preventive replacement, the 95 % and 5 %-quantile value of the parameters, $SAI_{95\%}$ = 730 and $p_{e,5\%}$ = 5.03 mm/rev, are used.

Two experiments have been conducted regarding different maintenance intervals. According to Section 3.2.3, the length of the maintenance interval has been calculated considering the uncertainties in SAI and p_e. For the first experiment, the resulting 5 %-quantile ($L_{maint,5\%}$ = 166 m ≙ 83 rings) for the maintenance interval has been used.

Even though this values already covers 95 % of the possible values, corrective maintenance occurred for all simulation runs. Therefore, Experiment 2 has been conducted, where the maintenance interval is chosen equal to the minimum value of the preliminary investigations $L_{maint,min}$ = 150 m ≙ 75 rings. This way the number of unplanned maintenance stops could be reduced. Nonetheless, the maintenance costs are higher than for Experiment 1, because of the additional planned maintenance stops. However, the deviation of the results from Experiment 2 are lower. The resulting amount and deviations of the maintenance costs are presented in Figure 6-17. These investigations show that further optimisation not only of the maintenance interval but also of the preventive replacement (f_{prev}) is mandatory to develop an economical but also robust maintenance schedule.

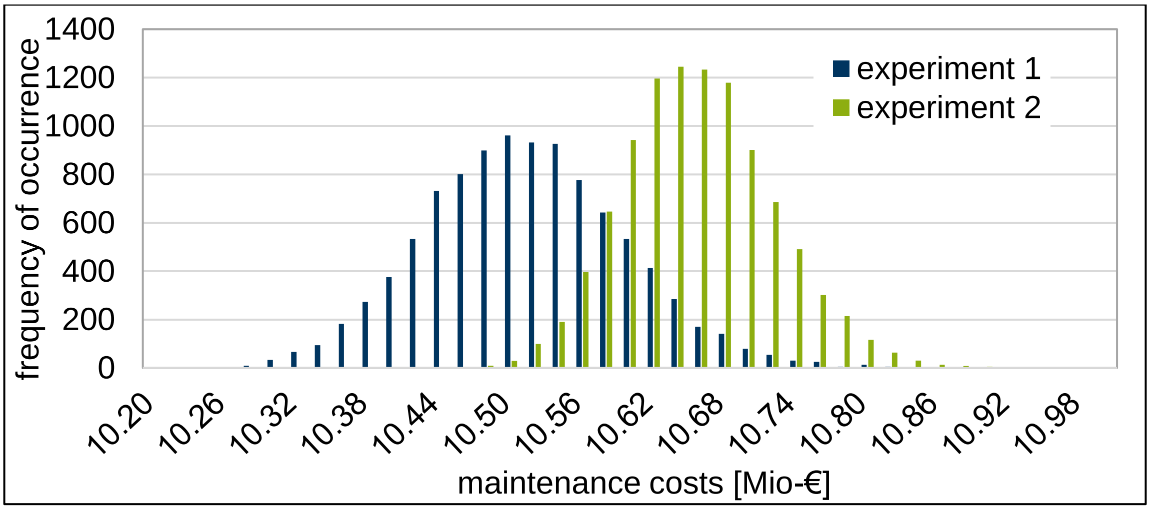


Figure 6-17: Histogram of the resulting maintenance costs for uncertain SAI and penetration

To analyse the effect on the chosen type of distribution function, the functions are replaced by simple triangular distributions, according to Figure 6-18. Triangular functions can be used if no sufficient data is available for distribution fitting. These distribution functions are used for Experiment 3.

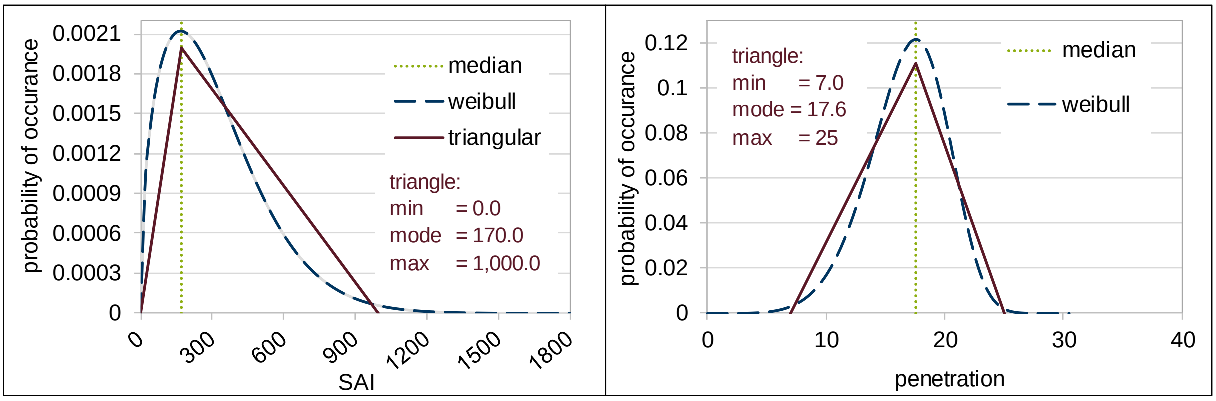


Figure 6-18: Comparison of distribution functions for SAI and penetration.

Figure 6-19 shows the resulting maintenance costs of Experiment 3 in comparison to Experiment 2. There is a significant difference in maintenance costs when using the same maintenance schedule as for Experiment 2. An increased number of unplanned maintenance stops and replaced cutting tools are resulting in higher maintenance costs.

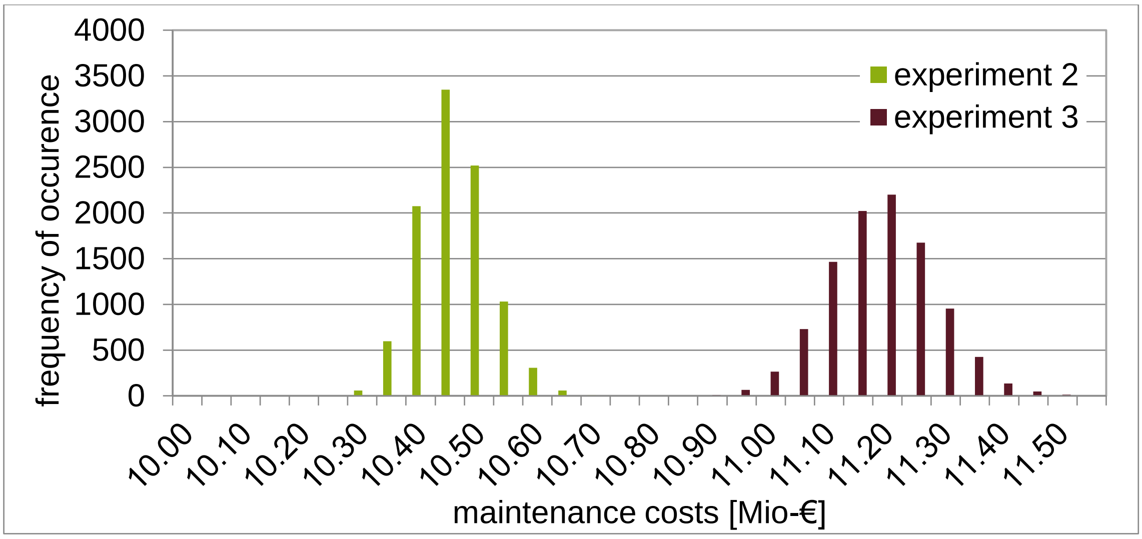


Figure 6-19: Histogram of maintenance costs for Weibull distributed penetration and SAI in comparison to triangular distributions

These differences can be explained by taking a closer look at the distribution functions of the SAI value. The Weibull-distribution leads to a higher frequency of small SAI values, while the triangle distribution leads to a higher frequency of higher SAI values (see Figure 6-20). Therefore, using the triangle distribution function changes the needed maintenance interval. It is reduced to $L_{maint,5\%}$ = 72 rings and $L_{maint,\ min}$ = 67 rings. This means a difference of 16-22 m. For the preventive replacement of cutting tools, the limit values SAI = 1,000 and p_e = 7.0 are used.

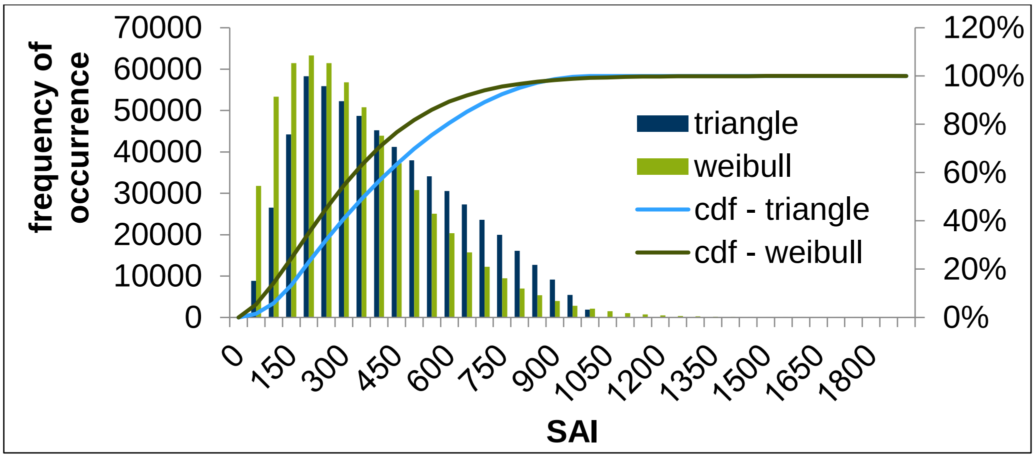


Figure 6-20: Comparison of frequency of occurrences of the SAI value.

This first estimation of the maintenance schedule already indicates how important the right choice of input data is. A continuous comparison of the assumed and the actual wear behaviour during project execution is therefore indispensable.

For the next experiment 4, probabilities for sudden damages of the cutting tool are added. The chosen probabilities are:

- P_{major} = 0.0001
- P_{minor} =0.002

The additional damage of the cutting tools and the random breakages of the tools cause higher maintenance costs and a greater deviation of results (Figure 6-21). Concluding, if surface spalling of the tools or sudden breakages are to expect, the maintenance schedule has to be adjusted accordingly.

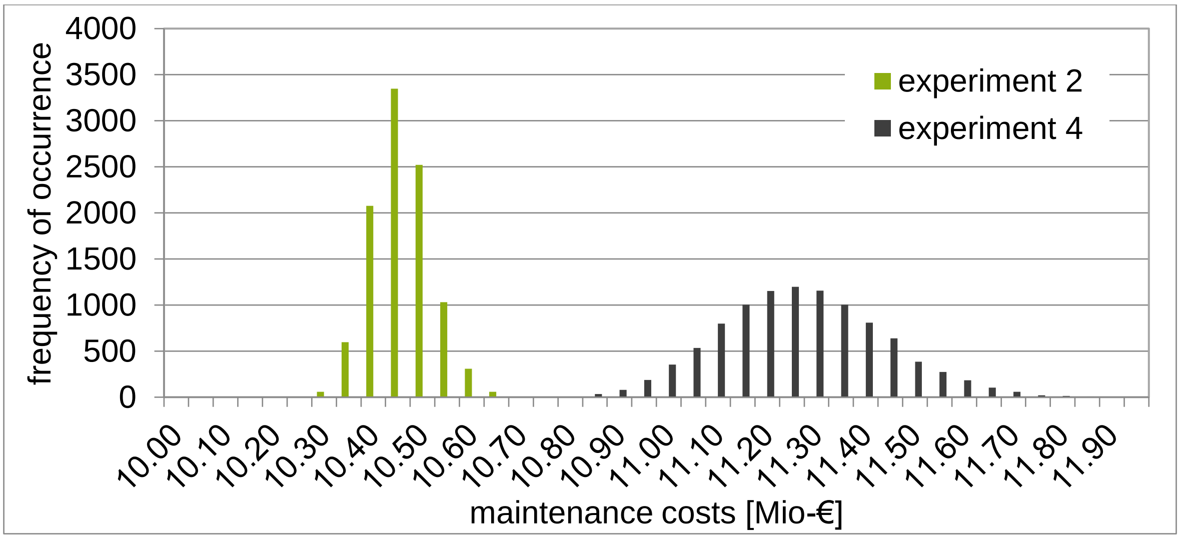


Figure 6-21: Histogram of the resulting maintenance costs with and without surface spalling and sudden breakages

6.1.4 Robust optimisation

The results of the preliminary investigations have shown that an optimisation of the maintenance schedule is mandatory, when considering uncertainties. Therefore, a parameter variation of L_{maint} and f_{prev} is conducted, considering uncertainties. Hence, for each parameter set a MCS with 1,000 simulation runs is performed. This analysis bases on the input parameters of experiment 4.

The resulting values for each parameter set are evaluated according to the robustness analyses presented in Section 4.4.2. The results of the preliminary experiments were symmetrically distributed. Therefore, the mean value and standard deviation are determined and used for the optimisation procedure. The results clearly show that the determined maintenance interval of 75 rings is not optimal regarding the maintenance costs. Due to the added sudden damages, a shorter maintenance interval is recommended. The maintenance interval L_{maint} = 65 rings with a correction factor f_{prev} results in the lowest maintenance costs with a mean value of μ_m = 9.57 Mio-€ and a standard deviation of approximately σ_s = 279,000 €.

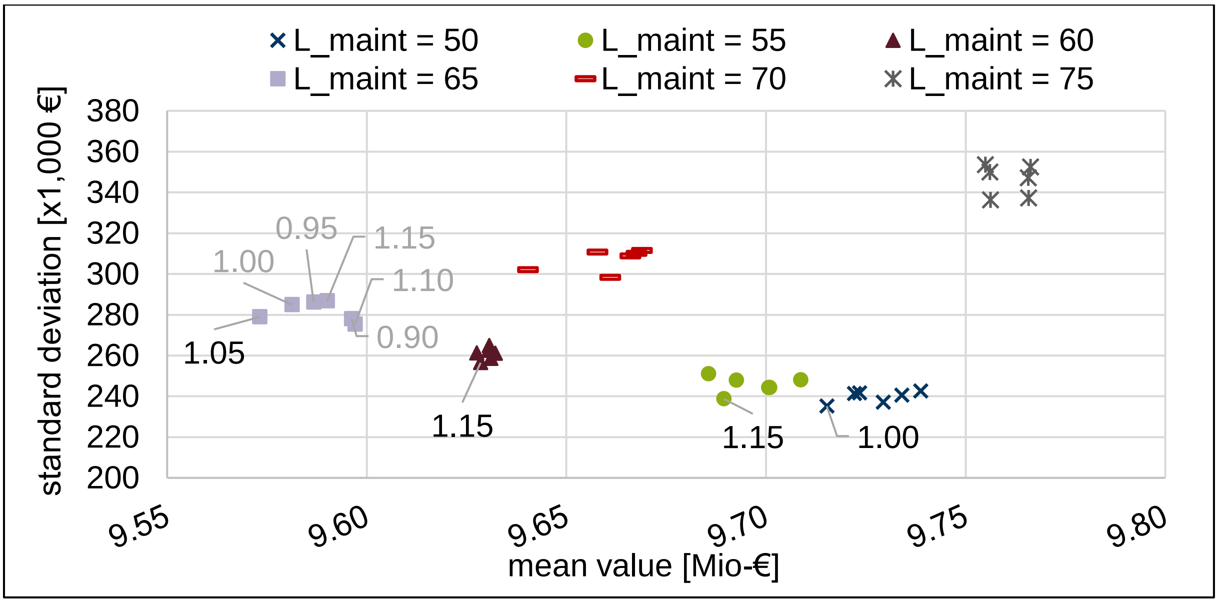


Figure 6-22: Scatter plot of standard deviation and the mean value of the different maintenance parameter sets

For the robust optimisation, the R-values of all parameters sets are determined. The weighting factor is varied to find all optimum values. These values are labelled in black in Figure 6-22 and their function of the robustness index is given in Figure 6-23. It can be seen that as soon as the standard deviation is taken into account, the aforementioned maintenance schedule is no longer the optimal choice. In general, it can be seen that a short maintenance interval reduces the deviation of the results. The mean costs are reduced when increasing the length of the maintenance interval until the optimum value is reached. If this length is exceeded, the maintenance costs will increase again.

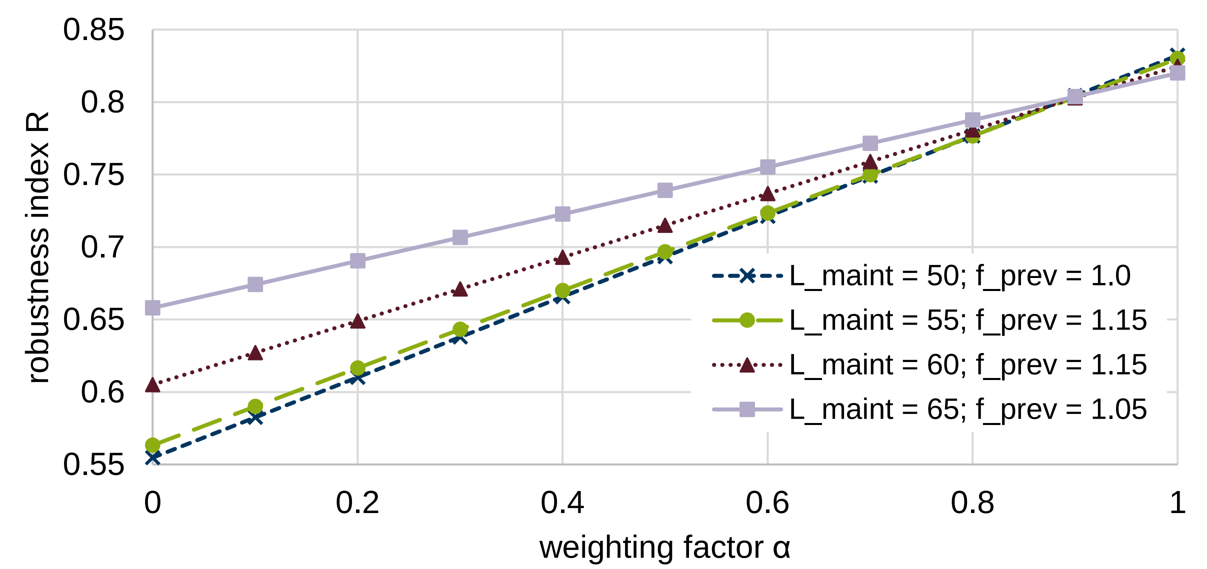


Figure 6-23: Target function R(α) for the chosen parameter sets.

However, it has to be considered that these results are gained by MCS with only 1,000 simulation runs. For a more valid conclusion, the number of simulation runs must be increased.

6.2 Case study

In the following, a fictive example project is analysed. Therefore, the project boundaries and input parameters are presented. Afterwards, a MCS simulation is performed to compare two project setups. Therefore, the resulting project costs are analysed and the robustness of the setup is evaluated. According to the PVS of the sensitivity analyses, the more advantageous setup is improved to reduce the amount and deviation of maintenance costs.

6.2.1 Project description

The following case study has been published similarly in Conrads et al. (2019). Two designs of an exemplarily metro tunnelling project are analysed. The first scenario A considers two single-track tubes. Therefore, two smaller tunnels are excavated. The other scenario B considers the excavation of one double-track tunnel with a lager diameter as shown in Figure 6-24.

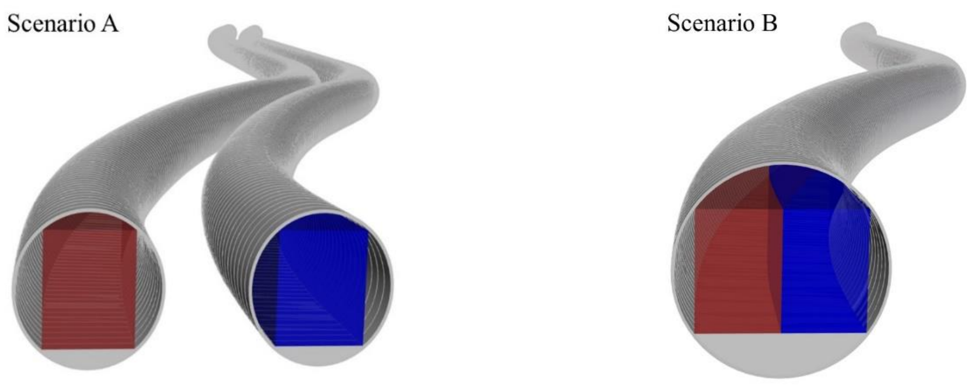


Figure 6-24: Layout of the two tunnel scenarios: A) two single-track tubes (D = 6.20 m); B) one double-track tube (D = 9.50 m) (Conrads et al. 2019).

The total length of the tunnel is 3,000 m, divided into three homogeneous sections with different values for soil properties. Between ring number 800 and 830 the tunnel passes under a river. Furthermore, at tunnel meter 2690-2713 there is a sensible surface structure. At both areas, a compressed air intervention should be avoided. The input data of the three homogeneous sections are summarised in Table 6-4.

Table 6-4: Input data for the soil properties of the homogeneous section.

Input	**Soil 1**	**Soil 2**	**Soil 3**
Start [m]	0	600	2100
End [m]	600	2100	3000
SAI	weibull min = 0.0, α = 1.5, β = 350.0	weibull min = 0.0, α = 1.8, β = 800.0	weibull min = 0.0, α = 1.5, β = 500.0
$SAI_{95\%}$	730	1470	1040
p_e [mm/rev]	weibull min = 2.0, α = 5.3, β = 23.0	weibull min = 0.0, α = 4.8, β = 25.0	weibull min = 0.0, α = 5.0, β = 20.0
$p_{e,5\%}$	13.1	13.5	11.0

Since there are no boulders or obstacles to expect, P_{major} is set equal to 0.0. However, probability of surface spalling is still set equal P_{minor} = 0.002. Furthermore, the air pressure inside the excavation chamber is set at 2.5 bar. Therefore, several accesses of the excavation chamber during one maintenance stop may become necessary.

6.2.1 Evaluation of maintenance schedule

The positions of the maintenance stops are determined using the wear prediction model for the outer cutting tools, since they will be worn out first. In order to estimate the position considering the uncertainties of the soil properties, a MCS has been conducted for each HGB and machine diameter. The resulting interval lengths are summarised in Table 6-5.

Table 6-5: Minimum length of the maintenance intervals L_{maint} [m] for Soil 1-3 and the resulting maintenance positions.

D_{TBM} [m]	Soil 1	Soil 2	Soil 3
Maintenance interval [m]			
6.2	486	374	356
9.5	308	240	228
Maintenance positions [m]			
6.2	[243; 443; 630; 817; 1004; 1184; 1362] n = 7		
9.5	[154; 306; 426; 546; 666; 786; 906; 1026; 1141; 1255; 1369;1483] n = 12		

Using these maintenance intervals, there are no interventions scheduled within the range of the critical areas.

6.2.2 Results

In Figure 6-25, the resulting distribution of the maintenance costs for the two machine diameters are presented. The total costs for Scenario A were double, since two tunnels have to be excavated, thus twice the maintenance work has to be carried out. It can be seen that the maintenance costs of Scenario B are significantly lower than for two tubes with a smaller diameter.

However, for scenario B there is a higher risk of unplanned maintenance stops. Especially the probability of no unplanned interventions is significantly lower for Scenario B ($P_{0,B}$ = 90/10,000 = 0.9 % and $P_{0,A}$ = 7,123/10,000 = 71.23 %). Furthermore, excavating the two tubes of Scenario A one after the other lowers the risk of unplanned maintenance even more. The actual geological conditions and wear behaviour of the tools are better known and more certain for the second tube. It shows that the bigger diameter machines are more sensitive to deviations of the soil properties. This behaviour can be explained by regarding the ratio of excavated tunnel meter to the cutting path of the tool. The ratio is significantly higher for large diameters causing a greater effect of the deviation in the wear amount.

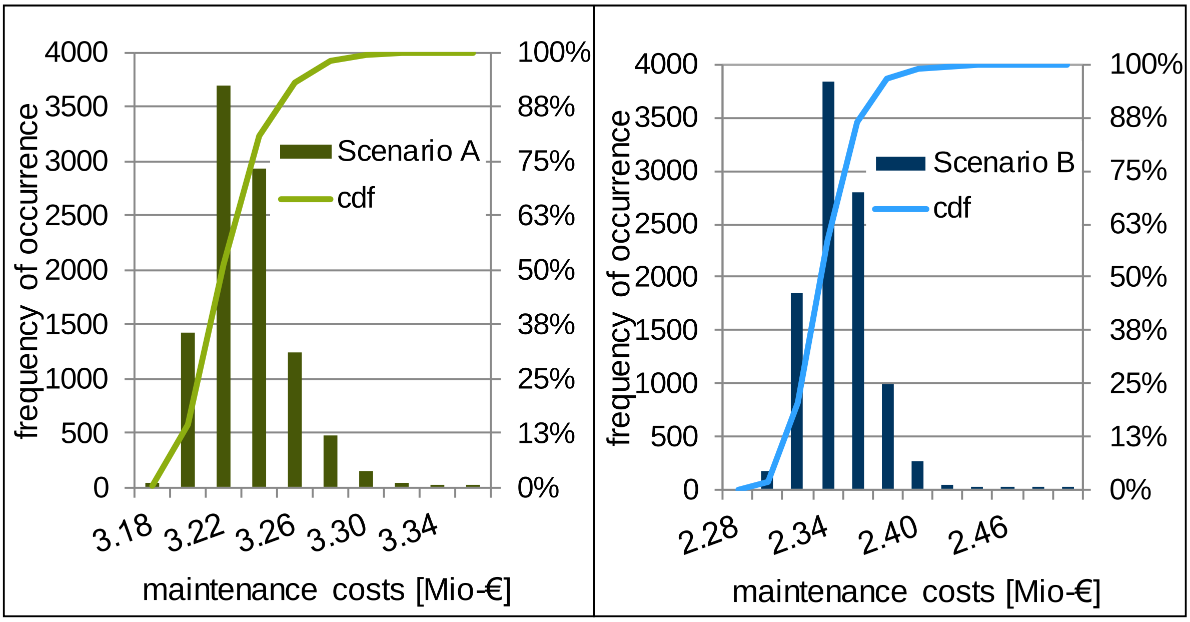


Figure 6-25: Histogram of the resulting maintenance cost for 10,000 simulation runs.

6.3 Verification and Validation

The verification of a simulation model is the proof that the implementation and calculations of the model work correctly. The validation proofs that the developed model is in accordance with the actual system. For the verification and validation (V&V) of a simulation model, several methods exist, thus suitable methods have to be chosen carefully. Rabe et al. (2008) and Sargent (2009) give a review of different methods that can be used for V&V of the simulation model. In the following, the described methods that are applicable for the presented simulation model are used for the V&V.

Conducting V&V it must be considered that the increase of the model confidence cause an increase in the V&V effort and may lead to high costs and/or long durations for the V&V procedure. The ratio between invested effort for V&V and increase of the model confidence to gain a higher value of the model is not proportional as shown in Figure 6-26. It can be seen, that by increasing the value of the model by conducting V&V, the costs, which are caused by conducting V&V, increase more rapidly to gain a very high confidence of the model. In most cases, conducting V&V to gain 100 % confidence leads to a disproportionate increase in costs.

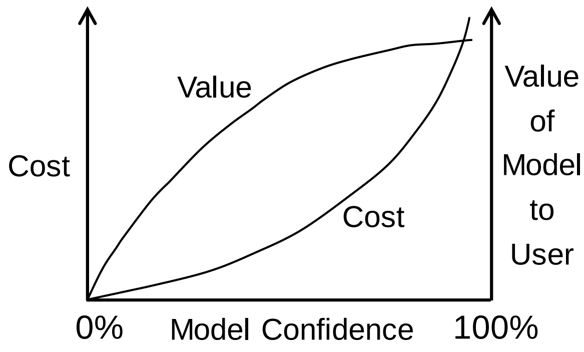


Figure 6-26: Model Confidence (Sargent (2009)).

6.3.1 Verification

For the verification of the presented model the following methods are used according to Rabe et al. (2008, pp. 95–112) and Sargent (2009):

- Submodel Testing
- Fixed Value Tests
- Statistical Techniques
- Operational Graphics

Submodel testing

Submodel Testing is an approach of analysing single elements of the system and it is not only used to verify the global output parameter “maintenance costs”, but also to verify the intermediate values. In general, it is recommended to verify single elements of the model before verifying or validating the whole model. Therefore, the following presented methods of verification are used on submodel level.

Fixed value test

Each function of all agents has been verified directly after their implementation. Therefore, *Fixed Value Tests* have been conducted. The principle of this method is to change the random model into a deterministic model. The distribution functions are exchanged with discrete input values, so that the resulting values from the model can be compared with manually calculated values. Similarly, if distribution functions shall be used for the input parameters, the determined input values have to be added to the output accordingly. This way, for each set of input values, the resulting output can be verified. In particular, the following parameters have been verified:

- Wear amount of each tool after one advance cycle
- Threshold for preventive tool replacement
- Duration of maintenance work and decompression time

However, this method only checks a few samples. In particular, more complicated operations or functions may not be fully verified by applying this method. In order to increase the reliability, PVS or sensitivity analyses can be conducted. This way, the number of checked samples increases and a greater range of values can be verified.

Statistical techniques

In order to verify the distribution function of the input parameters, *Statistical Techniques* can be used. However, these methods, e.g. Chi-Square Test or Kolmogorov-Smirnov Test, were already applied during distribution fitting (see Section 5.1.1). Therefore, the used distribution functions that base on a sufficient quantity of data can be considered as verified. The correct calculation of the random number have been checked graphically as presented in Figure 6-27. The resulting histogram of the calculated data follows the same shape as the implemented probability density function (pdf) of the input parameter.

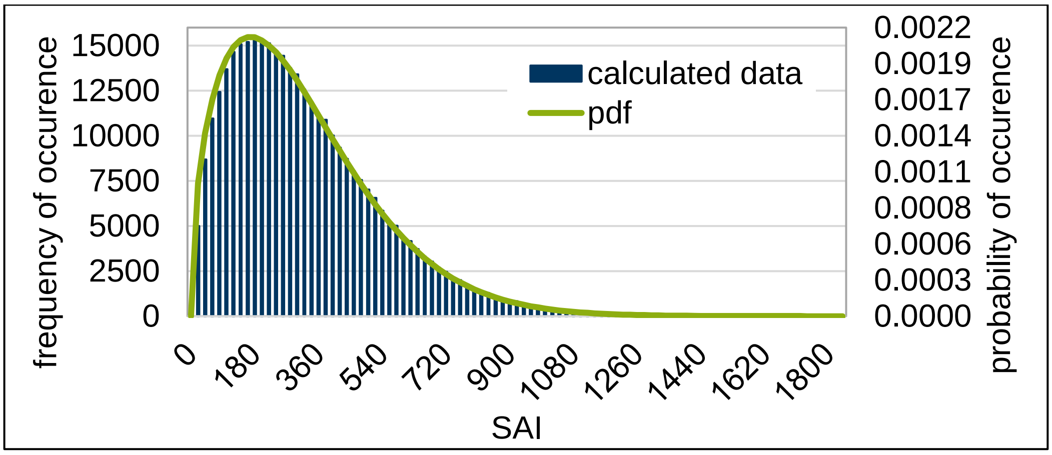


Figure 6-27: Comparison of calculated data with the defined probability density function (pdf).

The presented model includes physical parameters, which means that negative values must not occur. Therefore, the random value generation includes a query that stops the model and throws an error if the generated value is smaller than zero.

In order to prove that the chosen number of simulation runs of 10,000 is sufficient for the MCS, the resulting maintenance costs are divided into two data sets of 5,000 simulation runs each. Comparing the minimum, maximum and mean value of both datasets, there is only a deviation of less than 0.5 %. This shows, that even less simulation runs would be sufficient to evaluate the deviation of results.

Operational Graphics

Operational Graphics can be added to the graphical interface of the model. Therefore, values or state variables are displayed in graphs during the simulation. This way, the development of the variable over time can be observed. It is used to verify the wear behaviour of the cutting tools and to check the implemented rules for preventive tool replacement. Errors in tool replacement and wear calculations were detected and corrected.

During the implementation different small verifications, in particular *Fixed Value Tests*, have been applied to identify and erase possible errors. For example, it has been checked whether the correct decompression time has been chosen from the database according to the CA support pressure. Whenever the results did not fit the expected range of values and no explanation for the system behaviour could be found, further test have been conducted.

6.3.2 Validation

The validation of the model is a more complicated task than its verification, since the data of wear and maintenance is difficult to obtain. Furthermore, not all validation methods, which are proposed by Rabe et al. (2008, pp. 95–112) and Sargent (2009), are feasible. Here, three methods are chosen and discussed that could be used for the validation of the model:

- Face Validity
- Historical Data Validation
- Predictive Validation

Even with a small quantity of data, the model can be checked qualitatively. Therefore, the *Face Validity* method can be used to prove whether the model behaviour is realistic. It uses the knowledge of an expert in the field by discussing the model structure and the relation of the input and output data. This way, it is proved whether the model structure and implementation as well as its behaviour are reasonable. Here, this method has been applied in particular for the results of the sensitivity analysis. The system behaviour on changing input values has been analysed. If an unexpected behaviour occurred, theses have been formulated about either possible errors that have to be checked or explanations for the behaviour that had to be verified. The results have been discussed with two experts and the presented results of the analyses in Section 6.1 and 6.2 have been stated reasonable. This way, major errors could be detected and corrected. Furthermore, this procedure enabled a better understanding of the model and the system itself.

For the quantitative validation, the other two methods can be used for the validation of this model. The most common method is the *Historical Data Validation*. It contains the back analysis of historical project data and a comparison with the model output. Therefore, the necessary project-specific input parameters are used as input data for the simulation experiment. Considering uncertainties in the input parameters, a MCS has to be performed. The simulated results are then to be compared to the actual resulting values of the project. Figure 6-28 presents how the validity of results can be checked. The red line represents the resulting maintenance duration of a project. If this value lies within the deviation of the output data, as represented by the green output data, it can be proven valid for this project. The blue output data shows the case of invalid results.

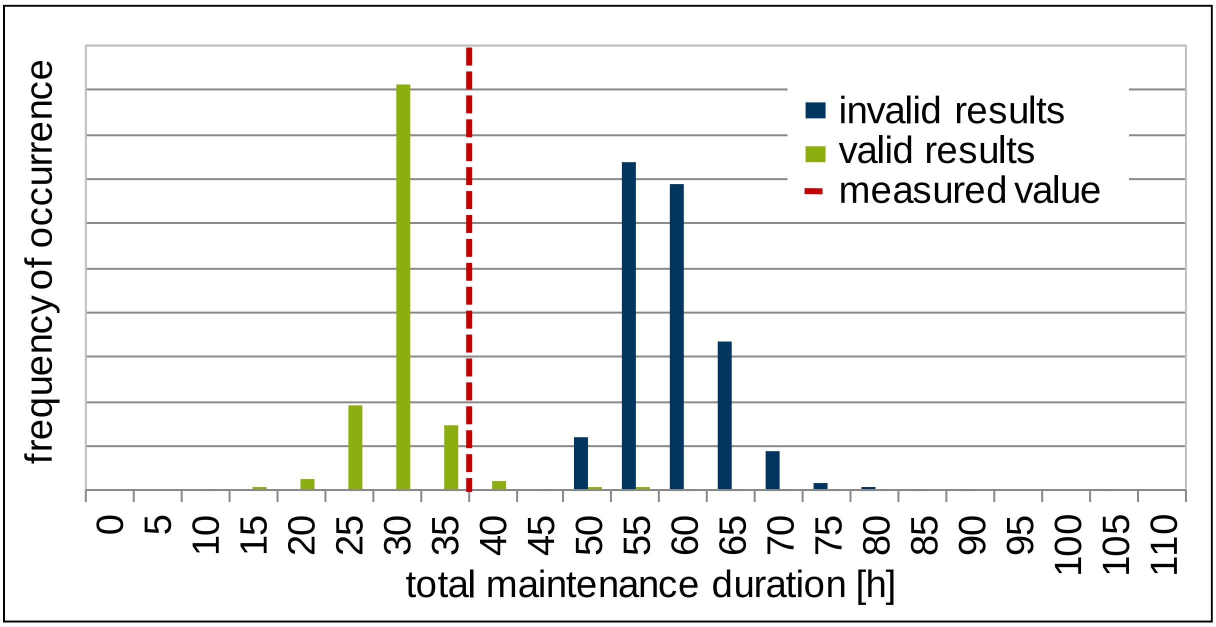


Figure 6-28: Exemplary comparison of calculated data of a simulation model with measured values of the analysed projects.

However, a 100 % validity of the model cannot be ensured, since only one case has been checked. Furthermore, this method requires a huge quantity and quality of data. The main disadvantage of this method is that the maintenance work of the historical data is highly affected by individual decision making processes. Only projects, which are scheduled based on the wear prediction method implemented in the simulation model, can be used for the validation. If there are other methods used for maintenance scheduling, the maintenance schedule of the project must be implemented directly into the model to gain comparable results. Using different maintenance strategies will lead to a varying number and positions of maintenance stops, which will lead to a deviation of the amount of replaced tools and thus of the duration and costs. Therefore, the maintenance-scheduling method cannot be validated this way. It could only be used for the validation of the wear prognosis. However, the wear prognosis model that is used in the simulation model has already been validated during the development (Köppl 2014). Hence, a validation of the wear behaviour is not mandatory.

In order to validate the output parameters, e.g. the number of maintenance stops, the duration of maintenance work or the number of changed tools, the *Predictive Validation* method is more suitable. Here, the simulation model is used to predict the behaviour of a system beforehand. After the execution of a project, the real data is compared to the forecast of the model. In order to use this method for the proposed model, the implemented wear prediction model is applied for maintenance scheduling of a project. During the project execution, the actual wear state of the tools has to be checked and compared to the predicted values. Therefore, the assumed input parameters have to be validated first. Consequently, in addition to the wear state of the tools, a good documentation of the soil and steering parameters is required. While the steering parameters can be easily assessed, thus are known for the driven tunnel section, the knowledge of the soil properties can only be increased using the observational method, but the data remains rather uncertain. If the actual parameters fit the assumed distributions, the tools replacement process can be compared to the prediction of the model for this maintenance stop. If the assumed wear rate of the tools fit the actual wear rate, there should not be any deviations of the number of replaced tools. However, since the wear measurement is subject to high uncertainties and deviations the actual number of replaced tools may differ from the calculated number basing on the actual wear state or the predicted number of the model. Furthermore, the responsible persons on site may decide to replace more or less tools, based on their experience. In general, it is recommended to consider expert knowledge at all points in time to prove, if the resulting schedule is reasonable, since the proposed model has not been fully validated. However, due to the lack of application possibilities, the *Predictive Validation* has not yet been conducted.

6.4 Discussion

Parameter variation studies have been conducted for a sensitivity analysis of the input parameters. This way, the behaviour of the system has been evaluated and the sensitivities have been assessed. It could be shown that the system is robust against minor deviations of the input values from the expected values. Concluding, the following findings of the PVS can be summarised:

6.4.1 *Sensitivity analyses (deterministic):*

Several parameters have been analysed deterministically to investigate their influence on the results of the maintenance scheduling model. In the following, the results for each parameters are summarised.

p_{bar}: The dependencies of the maintenance costs from the CA support pressure are as expected. An increase of maintenance cost can be observed simultaneously to increasing pressure. This is caused by the longer duration of decompression and shorter allowed working time under pressure.

p_e: The maintenance costs strongly increase if the penetration values become very small. Decreasing the penetration will significantly increase the cutting path of the outer cutting tools. This way, the maximum maintenance interval also decreases, which leads to corrective maintenance, if the maintenance interval is not adjusted according to the actual penetration value. Increasing the penetration value above the expected magnitude will reduce the maintenance cost. However, the reduction in costs is relatively small. Furthermore, it has to be considered that a higher penetration increases the probability of surface spalling and sever damages if boulders occur, due to the higher loadings applied on the tools. This would lead to an increase in costs.

SAI: The maintenance costs have a high sensitivity towards the area of small SAI values. For SAI values of above approximately 1000, there is a stagnation of maintenance costs. This relation is similar to the relation of the SAI value to the maximum cutting path of a tool, which also does not increase significantly after exceeding a SAI value above 1000. Concluding, the maintenance costs are anti-proportional to the maximum cutting path of the tools.

L_{maint}: A stepped increase of the maintenance costs occurs when the maintenance interval increases. This is due to additional unplanned maintenance stops, which occur when the maximum cutting path of the tools is exceeded and repair work becomes necessary. Smaller machine diameters lead to wider and less steps. If too small intervals are chosen, the maintenance costs also rise, but with a smaller magnitude. In this case, the additional unnecessary interventions cause an increase in costs.

f_{prev}: The minimum maintenance costs are achieved with a correction factor that lays approximately between 1.0-1.2. For this range of values the maintenance costs remain nearly constant for all combinations of L_{maint} and D_{TBM}. This proves the efficiency of preventive maintenance and that there are some tolerances in the determination of the replacement threshold.

6.4.2 Uncertainties and case study

The influence of the uncertainties in SAI and penetration have been analysed. It became clear how important the consideration of uncertainties during the maintenance scheduling is. Due to the lack of information and data for the soil properties, the distribution function for the SAI value is mostly assumed. Therefore, a deviation from the actual distribution is unavoidable. The results of Experiment 2 & 3 show that a deviation from the actual distribution may cause a significant change in the maximum allowed length of the maintenance interval. This reduction of L_{min} causes additional corrective maintenance if the maintenance schedule is not adapted to the changed conditions. Consequently, a continuous observation of the actual wear state and back analysis during the project execution is mandatory.

The abrasive wear mechanism leads to a constant wear of the tools. Including surface spalling and sudden tool breakages to the model with a probability of P_{minor} and P_{major}, the deviation of wear increases significantly. This leads to an increase in scale and deviation of the maintenance costs.

Furthermore, the optimisation of the maintenance schedule, consisting of L_{maint} and f_{prev}, is not a linear problem. Reducing the maintenance interval will reduce the deviation of the resulting maintenance costs, but at the same time, the magnitude of the values will increase (see experiment 1 & 2). Therefore, a robust optimisation has been conducted. The experiment combines a PVS with a MCS to estimate the maintenance costs for all reasonable maintenance strategies. The target values of the optimisation are minimum maintenance costs and minimum deviation of the results. This way, not only the costs are reduced, but also the dependability of the maintenance schedule will be increased. A large deviation is an indicator for a higher probability of corrective maintenance. In order to avoid unplanned maintenance stops, the deviation should be minimised. This way the reliability will be increased. However, considering the deviation may significantly influence the choice of the optimum maintenance strategy as shown in Section 6.1.4.

The presented case study showed how the model can be used to support the decision making process. Comparing the results of this problem statement to the results of Conrads et al. (2019), it can be seen that the same problem statement does not lead to the same conclusion if the input data and boundary conditions are different. Concluding, no general findings can be found for this problem statement. Instead, an analysis of the current project boundaries is necessary.

6.4.3 Verification and Validation

The Verification and Validation of a simulation model are very important but time-consuming tasks, due to the high number of parameters and dependencies as well as the interaction of the elements. The verification has been conducted mostly simultaneous to the implementation of the model, checking the newly implemented elements and functions. In order to cope with the uncertainties of the model, first verifications were performed for fixed values. Afterwards, the distribution functions have been added and random samples have been checked as well. This way major errors could be detected. However, a fully verification of all possible parameter combinations would cause an extreme number of calculations, leading to a great effort for a rather small benefit. Therefore, the results of the sensitivity analysis were carefully evaluated to identify errors in the results.

The results of the sensitivity analyses were further used for a first qualitative validation. The result have been discussed with experts to prove that the modelled system behaviour is reasonable. A higher reliability can be gained by adding more discussions with other experts.

The quantitative validation of the model has been discussed. Nonetheless, the quantitative validation could not be performed, yet, due to the lack of data. As discussed beforehand, even if data would have been available, the validation of the model is still limited, since the system state depends on the decision making of the scheduler and the executer. Therefore, only the wear prognosis can be validated and the assumptions made for the process durations, cost values and the threshold for corrective wear can be calibrated. However, these parameters are most likely to differ for each project, due to different boundary conditions and personnel on site. Furthermore, the actual soil properties are not completely known, even after the project execution, because the undisturbed ground is not accessible during the excavation. It is a complicated task to verify whether the deviations of results are due to an error in the model or due to the deviations of the assumed input parameters. Therefore, deviations from the prognosis are always to be expected.

6.4.4 Conclusion

The developed simulation model has been used to conduct several analyses. The performed sensitivity analyses support a better understanding of the dependencies of the parameters and system elements. The analyses of the uncertainties proves the importance to consider uncertain input data for a reliable maintenance scheduling. In general, the following findings can be stated:

- Considering uncertainties for determination of L_{maint} is mandatory but not sufficient for the scheduling of an efficient maintenance strategy.
- For the overall schedule, all tools have to be regarded and f_{prev} has to be determined.
- The simulation model is a sufficient tool to evaluate the necessary high number of elements and their dependencies as well as the uncertainties of the input data by enabling MCS.
- No linear dependency of the maintenance costs from the input parameters can be found. In particular, to evaluate the maintenance scheduling parameters L_{maint} and f_{prev} the simulation approach is needed for a comprehensible assessment of the system behaviour.
- The simulation models enables an efficient comparison of different maintenance strategies or project setups.
- Verification must be conducted during the development of the model and the evaluation of results.
- Validation is mandatory to provide reliable results. However, a complete validation of the model is not possible using a reasonable effort.

Based on the analysis, it is shown how the maintenance of the cutting tools can be planned under consideration of the uncertainties. Subsequently, the model can be used for an early adjustment of the maintenance stationing during tunnelling on the basis of the evaluated tunnelling data. Thus, an improved maintenance planning is possible under consideration of the project-specific conditions.

The developed simulation model can be used to conduct further analysis of different projects to gain a better understanding. Several parameter combinations have not been analysed yet. However, a complete evaluation of all parameter sets is connected with an enormous expenditure and could not be conducted completely for this thesis.

However, there are still some critical aspects remaining when regarding the validation of the model. In particular, the assumptions made during the model development have to be calibrated and validated before the model can be used in practice. Most of the increases in costs are caused by corrective maintenance. However, the threshold, which is used in the model, is assumed without any prevailing data. Furthermore, the limit to conduct corrective maintenance is dependent on the responsible personnel on site and on the interaction of the machine and the ground. Therefore, this value must be further analysed using project data.

Furthermore, the classification of the maintenance position needs to be included. Therefore, a risk assessment of additional costs caused by either additional measures of ground improvement or because of the consequential costs of a blow out or other collapse of the tunnel face. In general, the results must always be checked for their validity with the help of tunnelling experts.

7 Review and Recommendations

The scheduling of maintenance processes for cutting tools in mechanised tunnelling is an important task to ensure a high productivity of the tunnelling process. The wear behaviour of the tools is highly subject to uncertainties of the soil properties and steering parameters. Different wear prognosis models, which are mainly based on empirical data, were proposed in literature to improve the assessment of the maintenance effort and to support maintenance scheduling during the planning phase of a project. However, a detailed scheduling of the maintenance process, in particular for hydro shield tunnelling, is still not possible.

The presented simulation-based approach for maintenance scheduling adapts the empirical wear prognosis of Köppl (2014) and extends it with uncertain input data. The developed simulation model has been used to analyse the dependencies of the wear and maintenance processes and to evaluate the influence, which the uncertainties of the input parameters have on the efficiency of the maintenance schedule.

In the following, the presented model and the conducted analyses are reviewed and the main findings are summarised. Based on the results of the analyses, recommendations and findings for the construction management are given.

7.1 Review of the proposed model and analyses

A simulation-based approach for maintenance scheduling has been provided, which includes uncertain input data and considers the dependencies of all cutting tools. The presented simulation model has been used to perform several analyses, which support a better understanding of the system behaviour.

7.1.1 Simulation model

The proposed simulation model is hierarchically structured in order to implement all necessary elements separately while providing a clear and comprehensible interface. The chosen simulation software offers a multi-method modelling of the system. By including an empirical wear prediction model, the wear state of each cutting tool is simulated separately. This way, the maintenance decision is based on the individual condition of all cutting tools. Furthermore, uncertain input parameters are included in order to consider the unavoidable scattering of ground and steering parameters. The gained results support the decision-making process during maintenance scheduling.

The developed and analysed maintenance strategies are defined by the two parameters maintenance interval L_{maint} and the correction factor of preventive maintenance

f_{prev}. If uncertain input parameters are used to determine the maximum L_{maint}, the probability of corrective interventions can be significantly reduced. Similarly, the identification of the cutting tools, which have to be replaced preventively during a maintenance stop, has to be based on uncertain parameters. The correction factor f_{prev} offers an opportunity to adapt the preventive replacement according to the risk affinity of the scheduler.

In addition to the maintenance strategies, which solely base on the wear of cutting tools, a variety of boundary conditions of the individual projects have been discussed with respect to their influence on the chosen schedule.

However, it has to be considered that the model implies an accuracy that is hardly ever given in practice. The calculated maintenance costs are only a parameter for the evaluation of maintenance strategies and the comparison of variants. It does not represent the actual expected maintenance costs, yet. The used wear prediction model has been proven valid for an accuracy of ± 15 %. This deviation of the wear prediction itself has to be considered during the evaluation of the simulated results and especially when determining f_{prev}. Furthermore, the quality of the results strongly depends on the quality of the defined input parameters. Only if the input data fits the actual prevailing conditions of the project, valid results can be obtained. The assumptions made for the corrective maintenance do not base on any actual data. Corrective interventions occurring during the simulation of a project have to be carefully evaluated.

Nonetheless, considering the mentioned critical aspects, the model can be used to analyse and evaluate maintenance strategies for hydro shield tunnelling projects.

7.1.2 Findings of the analyses

In order to gain a more detailed knowledge about the behaviour of the modelled system, in a first step, deterministic sensitivity analyses have been conducted. The influence of several parameters on the maintenance schedule and on the resulting maintenance costs has been investigated. For some parameters, e.g. the CA support pressure, the dependencies showed the expected behaviour, thus no new insights could be gained. However, other parameters showed an unsteady or unpredicted dependency of the maintenance costs from the specific value. This emphasises the importance of the detailed evaluation gained from the simulation model. It is significant to further analyse the sensitivities of the model against the deviation of the various input parameters.

Subsequently, it has been investigated, how the uncertainties influence the system behaviour. Therefore, a combined PVS and MCS have been conducted. The results of the analyses underline the importance of correct input data. If the actual values deviate in an unexpected magnitude, the maintenance schedule will be under or over estimated. Even a merely different form of the distribution function, as evaluated in Section 6.4.2 Experiment 2 and 3, can lead to a significant increase of maintenance costs.

The PVS of L_{maint} and f_{prev} has been conducted in order to analyse the possibilities to optimise the maintenance schedule. The results showed that no clear dependence of those two parameters and the optimum maintenance costs could be found. Therefore, a detailed analyses of the maintenance strategy is mandatory, in order to identify the most economic and reliable solution. For this analyses the proposed simulation model is an efficient tool. The implemented model reduces the required effort and time for an overall evaluation of the system and simultaneously offers a comprehensible structure and evaluation of results.

With the proposed simulation model, a method has been developed that supports the maintenance scheduling of cutting tools under consideration of uncertainties of the wear prediction and the multitude of project-specific boundary conditions.

7.2 Recommendations for the Construction Management

Maintenance scheduling is a complex but important task for the efficiency of a tunnelling project. A simulation-based approach has been presented, which supports the evaluation of maintenance schedules during the planning phase of a hydro shield tunnelling project. In order to successfully apply the proposed approach in the construction management, the following restrictions must be considered:

- Only projects within the boundary conditions given by Köppl can be analysed with this model.
- The chosen input data as well as the results of the simulation experiments must always be evaluated by an experienced engineer in order to ensure a reliable maintenance schedule.
- The validation of the simulation model must be extended using *Historical Data Validation* or *Predictive Validation*.
- Currently, the model can only be used to compare and evaluate different strategies until it is fully validated and calibrated.

In general, it is recommended to improve the documentation of the maintenance processes and tool wear as well as ground properties and steering parameters during project execution. A detailed post-processing of project data will lead to an increased knowledge about the system's dependencies and helps to improve wear prediction and maintenance scheduling of future projects.

Even an exact wear prognosis model needs a high level of information about the soil properties. If the ground remains nearly unknown, no proper maintenance schedule can be found. There will always be an over- or underestimation of the tool wear. Consequently, a 100% reliable maintenance schedule will never be found, because the soil properties are never completely known and always bear the risk of unexpected characteristics, thus wear behaviour.

However, the presented model offers the opportunity to consider these unavoidable uncertainties. This way, a robust maintenance schedule can be determined and the risk of the deviation of input parameters can be evaluated. Basing on the mentioned findings, the procedure presented in Figure 7-1 is recommended for maintenance scheduling.

Even though the simulation model is not fully validated yet, it offers an efficient method to evaluate and compare different maintenance schedules and project set-ups. Furthermore, the proposed simulation-based method helps to decrease the time and money spent on maintenance scheduling and execution.

If process simulation cannot be used due to missing software or knowledge a simplified analysis using a calculation tool, e.g. Excel, to conduct a MCS for the determination of the maximum maintenance interval of each tool. This way a first estimation of the necessary number and position of maintenance stops is possible. Furthermore, preventive maintenance of the cutting tools can be determined manually. However, this method is less flexible and detailed than using a simulation model. The gained results also have to be validated during project execution after each inspection of the cutter head.

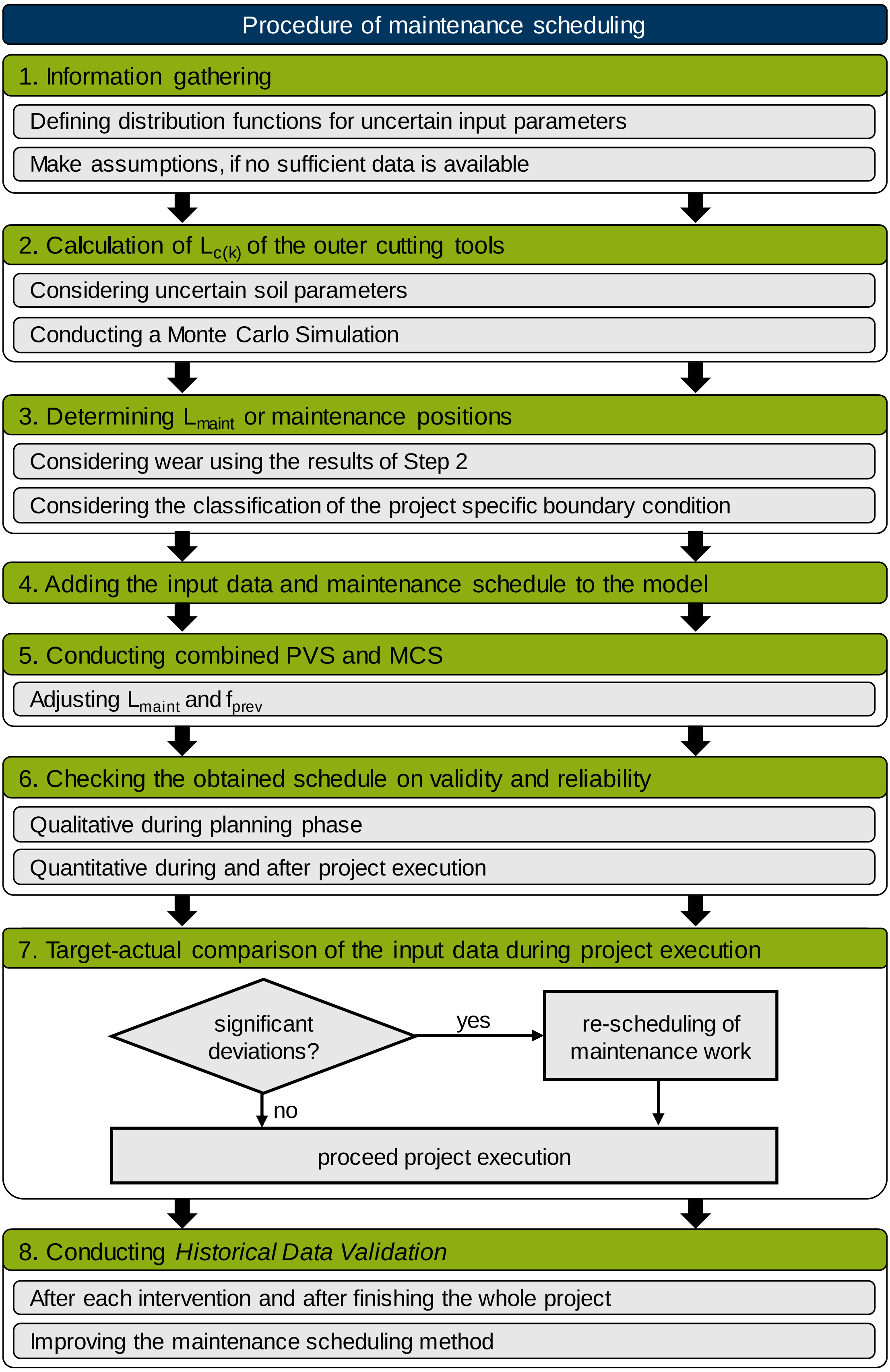


Figure 7-1: Proposed procedure for the application of the presented model in the construction management.

8 Conclusion

The maintenance of cutting tools in mechanised tunnelling is important to ensure an efficient performance of the whole system. In particular, hydro shield machines require a reliable maintenance schedule to guarantee a high utilisation of the machine. In the following, a conclusion of the developed model is drawn. Therefore, the outline and results are summarised. Afterwards, an outlook is given, where further research is proposed.

8.1 Summary

The goal of the presented thesis is to provide a method to improve the maintenance schedule for the replacement strategy of cutting tools in mechanised tunnelling. This method shall consider uncertainties in order to increase the reliability of the maintenance schedule. This way, the utilisation and performance of a tunnelling machine shall be improved to increase the economic benefit.

In a first step, the processes that influence the productivity of the tunnelling project are analysed and are grouped into production processes and support processes. Maintenance work is one of the auxiliary production processes, since it is not directly producing the tunnel construction, but is mandatory to conduct the main production processes and lead to unavoidable downtime.

Process simulation is identified as being a useful method to analyse processes and to evaluate and improve the productivity of a complex system. It can be used to analyse and evaluate the wear and maintenance of cutting tools. In order to develop a simulation model, detailed information and data of the system are required. Therefore, the state of the art of the process controlling and data documentation of tunnelling projects in general are reviewed.

Furthermore, a focus of the literature review is set on the wear prediction of the cutting tools and the maintenance processes that are required for the replacement of the tools. The wear of cutting tools is a widely discussed topic. Several index tests exist, which are analysing the abrasiveness of the ground. However, the focus of this thesis lays within the maintenance of cutting tools of hydro shield machines. For hydro shield machines, a wear prediction model of Köppl (2014) is chosen, because it allows a quantitative and individual wear prediction of all tools. This way, not only the amount of used cutting tools, but also the maintenance positions can be determined.

In order to evaluate and adjust the maintenance schedule obtained from the wear prediction, the maintenance processes are reviewed in more detail. Maintenance processes can be categorised into mobilisation, tool replacement and demobilisation. For each sub-process, a duration can be set. The decisive process durations are the tool replacement, whose duration depends on the number of replaced tools and the decompression of the worker if compressed air interventions are required. In general, the maintenance of cutting tools uses a predictive schedule. However, preventive tool replacements are required in order to obtain an efficient schedule. Furthermore, due to the unavoidable uncertainties, corrective maintenance must be considered.

In order to develop a model to analyse and evaluate maintenance schedules, the analysed system is structured and all elements and processes are implemented in a simulation model. The individual modelling of all cutting tools enables an evaluation of preventive maintenance. Different maintenance strategies can be implemented and evaluated. The structured implementation supports a comprehensible evaluation of the results. Uncertain input data is considered performing MCS. Furthermore, an improved maintenance strategy can be obtained performing a combined PVS with MCS. In order to evaluate the regarded maintenance schedule, the evaluation criteria are summarised by monetarisation, determining the maintenance costs.

The developed model is used to perform several analyses. In a first step, discrete sensitivity analyses are conducted in order to analyse the dependencies of the system and to gain a better knowledge of the system behaviour. Furthermore, the influence of uncertain input data is assessed. The analyses emphasise the importance of suitable input data. Even small deviations of the assumed input and the actual conditions may lead to a significant increase in costs and downtime caused by corrective maintenance. In addition, a comparison of variants is presented, in order to show how the developed model supports the decision making process during the planning phase of a project. The results of the analyses are used for verification and a first qualitative validation of the model.

Based on the analyses and model evaluations, a procedure for the scheduling of maintenance of the cutting tools is recommended for the construction management. The first five steps presented in Figure 7-1 are needed in order to determine and evaluate a robust maintenance schedule including the maintenance interval L_{maint} and the correction factor for preventive tool replacement f_{prev}. The next three steps are necessary to increase the validity and reliability of the model and of the obtained results. A detailed documentation during project execution and a continuous comparison of actual data with the assumptions of the model and the determined results helps to improve the model, thus the determined maintenance schedule of future projects.

8.2 Further research

In this thesis, a simulation-based method for maintenance scheduling has been presented and discussed. However, based on the discussion of the model and analysis made, further problem statements and research goals could be identified. In the following, an outlook on further research is given.

Two aspects should be added to the presented research. The validation of the model is mandatory to obtain reliable results. Therefore, as much data as possible must be gathered for a more thorough validation of the model using *Historical Data Validation*. If no sufficient data is available, *Predictive Validation* can be conducted with the help of future projects. For both methods a good documentation and processing of the data is required in order to conduct a sufficient validation. Furthermore, the assumptions made during the implementation of the model must be calibrated using the obtained data.

Detailed documented and processed data can be further used to improve or extend the given wear prediction models. This way, the uncertainties might be reduced and the application field of the model can be increased. Combining a database of wear data with the process controlling of a TBM, real-time adaption of the wear prognosis can be conducted in order to improve the maintenance schedule during project execution. This way, an early warning system can be implemented using actual-target comparisons to notify bigger deviations from the prognosis that possibly lead to a failure of the system.

The second aspect that can be extended is the evaluation of the classification of the maintenance position based on the project specific boundary conditions. The proposed classifications in Section 5.1.2 are only qualitative. In order to gain a comprehensible and reproducible method, a fuzzy decision model is recommended as shown in Figure 8-1. Thereby, the discrete values of the classification are fuzzified using membership functions in order to gain uncertain values. Afterwards, rules are defined, which are used for the combination of several classification values. In the end, the output is defuzzified, so that a discrete value for the overall classification is obtained.

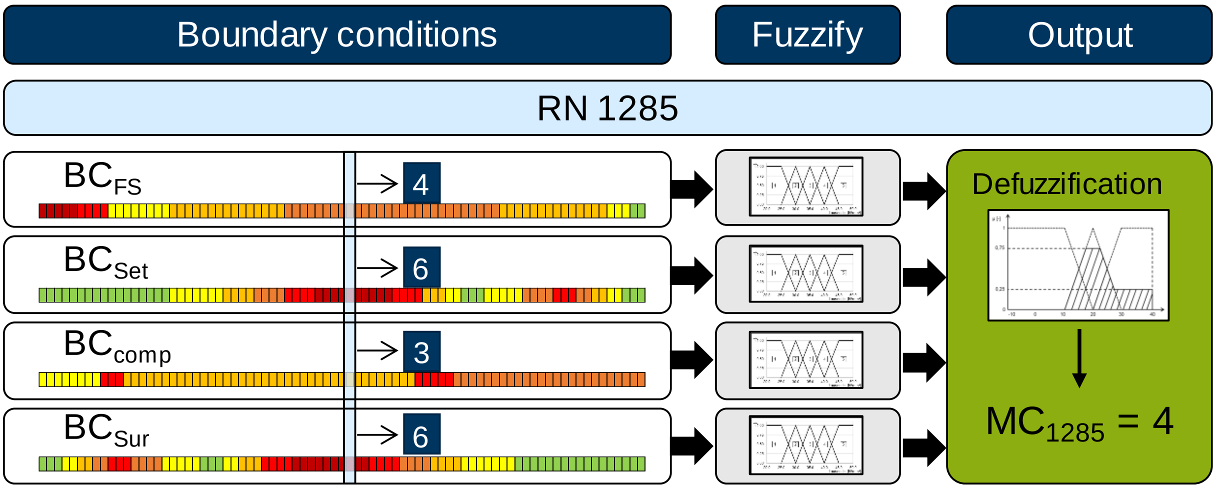


Figure 8-1: Exemplary concept for a fuzzy classification of a maintenance position.

Another approach is a risk assessment of the maintenance position. Therefore, possible threads of a CA intervention have to be identified. For each threat, the follow up costs in case of an occurrence have to be determined. In addition, the probability of occurrence must be determined to evaluate the risk of the threat. Furthermore, the decrease of the risk conducting counter measures, e.g. ground improvement, can be evaluated as well. The determined probability density function of the follow up costs for the analysed maintenance position can then be added to the maintenance-scheduling model.

Furthermore, the implemented model can be included in one of the simulation models that are used for the overall analyses of production processes and the supply chain presented by Rahm (2017) and Duhme (2018). By doing this, the influence of the maintenance work on the overall productivity can be evaluated. Furthermore, the model can be extended by implementing additional wear prediction models. This way, an analysis of different machine types and ground conditions becomes possible.

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Appendix A

Table A-1: Review of the influencing ground properties for hard rock abrasive wear.

Parameter	Values	References
Hard rock TBM		
abrasiveness	CAI,	(Büchi et al. 1995); (Galler et al. 2014); (Thuro and Käsling 2011)
	LAC,	(Büchi et al. 1995); (Galler et al. 2014); (Thuro and Käsling 2011)
	AV / AVS,	(Bruland 2000a)
	SJ	(Bruland 2000a)
mineralogy	eQu	(Galler et al. 2014); (Schimazek et al. 1976); (Thuro 2002); (Thuro and Käsling 2011)
rock strength, resistance	UCS,	(Büchi et al. 1995); (Galler et al. 2014); (Hassanpour et al. 2014) ; (Thuro 2002); (Thuro and Käsling 2011)
	BTS,	(Büchi et al. 1995); (Galler et al. 2014); (Thuro and Käsling 2011); (Schimazek et al. 1976)
	VHNR	(Hassanpour et al. 2014)
Micro-structure of the rock	particle size	(Büchi et al. 1995); (Schimazek et al. 1976)
	particle shape	(Büchi et al. 1995);
	quality of the binder	(Thuro 2002)
	homogeneity	(Thuro and Käsling 2011)
	degree of weathering	(Thuro 2002)

CAI: Cerchar Abrasivity Index
LAC: LCPC Abrasivity Coefficient
AV/AVS: Abrasion Value (Steel)
SJ: Sievers' J-value
eQu: equivalent quartz content
UCS: uniaxial compressive strength
BTS: Brasilian Tensile Strength
VHNR: Vicker's hardness number of rock

Appendix B: Questionnaires - Maintenance Processes

Drucklufteinstiege im Rahmen von Hydroschildvortrieben

Die vorliegenden Fragen beziehen sich alle auf Drucklufteinstiege zur Werkzeugkontrolle bzw. zum Werkzeugwechsel im Rahmen von Hydroschildvortrieben im Lockergestein.

1) Im Vergleich zum dafür eingeplanten Zeitraum. Wie viel Zeit haben die Drucklufteinstiege, an denen Sie beteiligt waren, zum Großteil in Anspruch genommen?

   ☒ länger als geplant (50%)

   ☐ kürzer als geplant

   ☒ genauso lange wie geplant (50%)

2) Falls der Drucklufteinstieg länger gedauert hat als geplant, was waren möglicherweise die Gründe dafür?

   ☐ zu wenig Personal

   ☒ höherer Verschleiß als erwartet, daher mehr Werkzeugwechsel als geplant

   ☒ Schwierigkeiten beim Aus- bzw. Einbau der Werkzeuge

   ☐ andere: DL-Verlust -> Auffüllen -> Bildung neuer Filterkuchen

3) Welche Arbeiten sind auf der Baustelle für einen Drucklufteinstieg notwendig? Wie viel Zeit nehmen diese in etwa in Anspruch? Wann werden Sie durchgeführt?

   (s. Anlage 1-3: vorbereitende Arbeiten, Werkzeugwechsel und nachbereitende Arbeiten)

   nur wenn möglich beantworten

4) Welche Personen sind zwingend an einem Drucklufteinstieg beteiligt?

   2-4 Mann Abbaukammer (G31 notwendig); Schleusenwärter, DL-Befähigter (nur vor Ort notwendig), DL-Arzt (nur > 2 bar)

5) Wie viele Personen werden zum Wechsel eines Werkzeuges benötigt?

   Abbaukammer: 2-4 Mann
   atmosph.: 1x Schleusenwärter; 1x Materialschleuse
   2x Logistik (Transporte)

6) Wer definiert die Verschleißgrenze, ab der ein Werkzeug gewechselt werden soll?

   Disken: Lieferant
   Schälwerkzeuge: nach Erfahrungswerte; abhängig von Referenzstrecke

Figure B-1: Interview 1, page 1.

7) Werden diese Verschleißgrenzen vorher definiert oder entscheidet man letztendlich erst während der Wartung ob ein Werkzeug gewechselt werden soll oder nicht?

Disken werden v. definiert. Wird aber auch abhängig von noch zu fahrender Strecke bzw. Situation ab! Schälwerkzeuge: vor Ort

8) Welche Informationen werden beim Wechsel eines Werkzeuges dokumentiert?

- [x] Datum
- [x] Vortriebsstationierung (Ringnummer, Vortriebsstand [m])
- [ ] Bearbeiter
- [x] Werkzeugtyp
- [x] Werkzeug ID-Nummer (Schneidrollen) (Hartgestein, EPB ja, Hydro bei Bedarf)
- [x] Spur-Nr.
- [x] Arm Nr. (Schälmesser und Räumer)
- [ ] Drehrichtung (Schälmesser und Räumer)
- [x] Zustand des Abbauwerkzeuges bei Ausbau
- [x] Wechselgrund
- [x] Fotodokumentation (teilweise) (exemplarisch)

9) Wie werden diese Informationen dokumentiert?

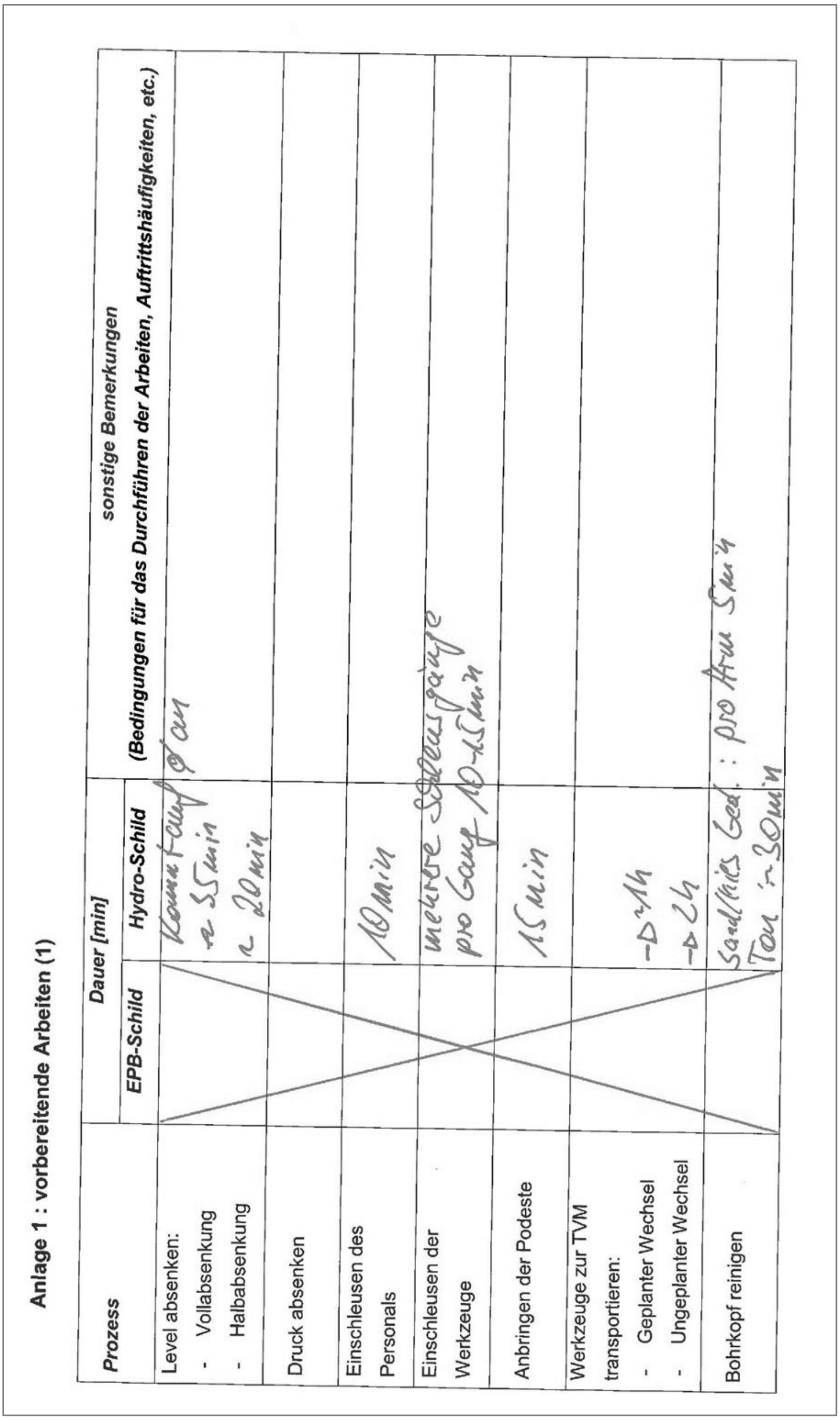
- [x] direkt in der Kammer
- [ ] per Funk nach draußen
- [ ] andere: ______

9) Falls nicht alle Informationen dokumentiert werden. Woran liegt das?

- [ ] hohe Luftfeuchtigkeit erschwert Dokumentation in der Kammer
- [ ] zu wenig Zeit
- [ ] andere: ______

* wird immer dokumentiert, wenn auch in der Kammer etwas „spartanischer" –> wird dann atmosph. sauber geschrieben u. übertragen.

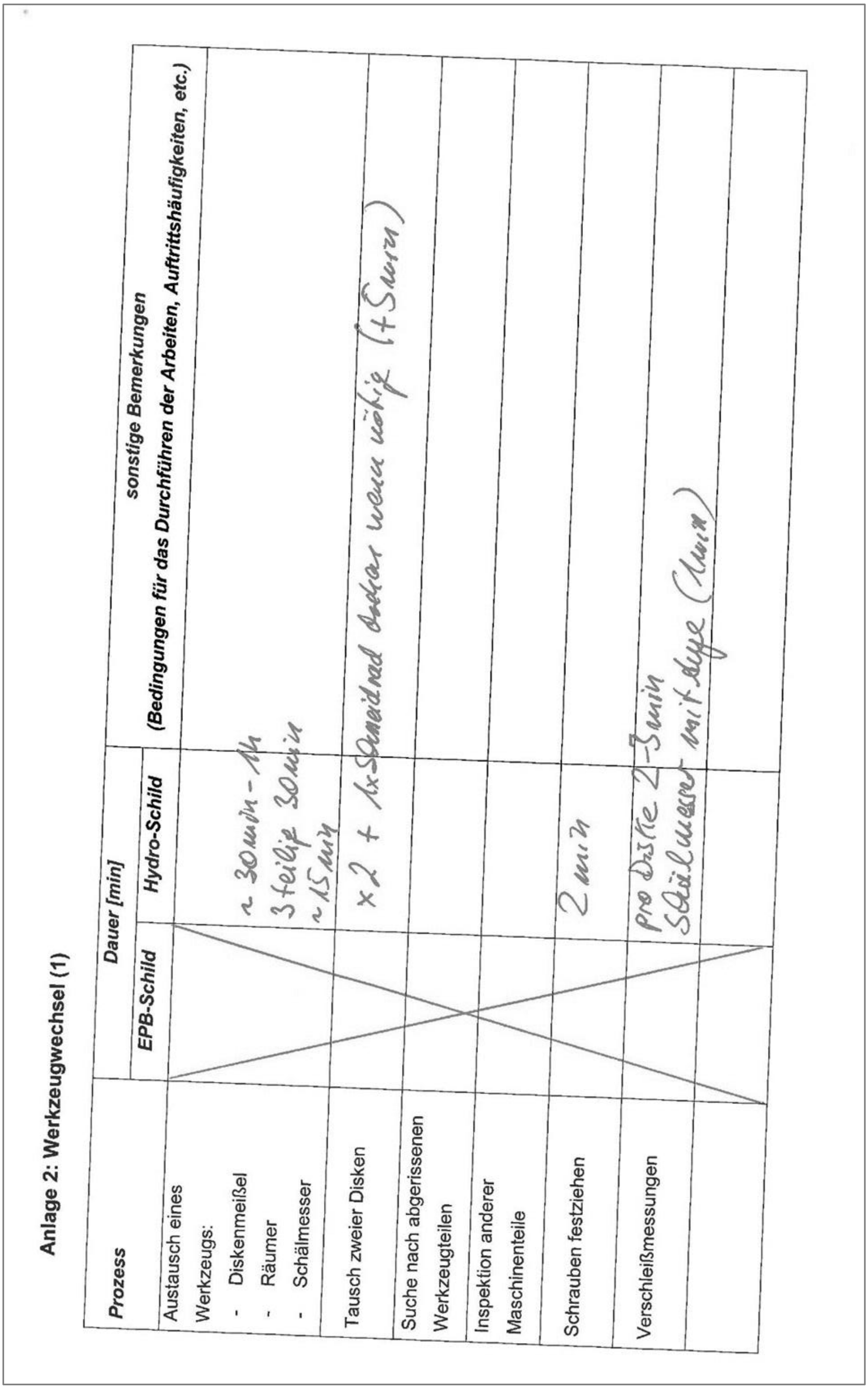
Figure B-2: Interview 1, page 2.



Anlage 1 : vorbereitende Arbeiten (1)

Prozess	*Dauer [min]*		*sonstige Bemerkungen*
	EPB-Schild	*Hydro-Schild*	*(Bedingungen für das Durchführen der Arbeiten, Auftrittshäufigkeiten, etc.)*
Level absenken: - Vollabsenkung - Halbabsenkung		Kommt auf Ø an ≈ 35 min ≈ 20 min	
Druck absenken			
Einschleusen des Personals		10 min	
Einschleusen der Werkzeuge		mehrere Schleusgänge pro Gang 10-15 min	
Anbringen der Podeste		15 min	
Werkzeuge zur TVM transportieren: - Geplanter Wechsel - Ungeplanter Wechsel		 → ~1h → 2h	
Bohrkopf reinigen		Sand/Kies Ged.: pro Arm 5 min Ton ≈ 30 min	

Figure B-3: Interview 1, page 3.



Anlage 2: Werkzeugwechsel (1)

Prozess	Dauer [min]		sonstige Bemerkungen
	EPB-Schild	Hydro-Schild	(Bedingungen für das Durchführen der Arbeiten, Auftrittshäufigkeiten, etc.)
Austausch eines Werkzeugs: - Diskenmeißel - Räumer - Schälmesser		~ 30min - 1h 3 teilig 30min ~15min	
Tausch zweier Disken		x2 + 1x Schneidrad [illegible] wenn nötig (+5min)	
Suche nach abgerissenen Werkzeugteilen			
Inspektion anderer Maschinenteile			
Schrauben festziehen		2min	
Verschleißmessungen		pro Diske 2-3min Schälmesser mit Lupe (1min)	

Figure B-4: Interview 1, page 4.

Anlage 3: nachbereitende Arbeiten (1)

Prozess	*Dauer [min]*		*sonstige Bemerkungen*
	EPB-Schild	*Hydro-Schild*	*(Bedingungen für das Durchführen der Arbeiten, Auftrittshäufigkeiten, etc.)*
Ausschleusen	Druck-LV	Druck-LV je nach Druckstufe	Druck-LV
Demontieren der Podeste		15-20min	
Auffüllen der Abbaukammer		15-20min	(abhängig vom Ø)
Druck erhöhen		5min	

Figure B-5: Interview 1, page 5.

Drucklufteinstiege im Rahmen von Hydroschildvortrieben

Die vorliegenden Fragen beziehen sich alle auf Drucklufteinstiege zur Werkzeugkontrolle bzw. zum Werkzeugwechsel im Rahmen von Hydroschildvortrieben im Lockergestein.

1) Im Vergleich zum dafür eingeplanten Zeitraum. Wie viel Zeit haben die Drucklufteinstiege, an denen Sie beteiligt waren, zum Großteil in Anspruch genommen?

   □ **x** länger als geplant

   □ kürzer als geplant

   □ genauso lange wie geplant

2) Falls der Drucklufteinstieg länger gedauert hat als geplant, was waren möglicherweise die Gründe dafür?

   □ zu wenig Personal

   □ höherer Verschleiß als erwartet, daher mehr Werkzeugwechsel als geplant

   □**x** Schwierigkeiten beim Aus- bzw. Einbau der Werkzeuge

   □ andere:____

3) Welche Arbeiten sind auf der Baustelle für einen Drucklufteinstieg notwendig? Wie viel Zeit nehmen diese in etwa in Anspruch? Wann werden Sie durchgeführt?

   (s. Anlage 1-3: vorbereitende Arbeiten, Werkzeugwechsel und nachbereitende Arbeiten)

4) Welche Personen sind zwingend an einem Drucklufteinstieg beteiligt?

   ____Schicht Ingenieur, Schleuse wächter, TBM Fahrer__________

5) Wie viele Positionen werden zum Wechsel eines Werkzeuges benötigt?

   ____?____

6) Wer definiert die Verschleißgrenze, ab der ein Werkzeug gewechselt werden soll?

   _____TBM Lieferant, Tunnel Manager._____________

Figure B-6: Interview 2, page 1.

7) Werden diese Verschleißgrenzen vorher definiert oder entscheidet man letztendlich erst während der Wartung ob ein Werkzeug gewechselt werden soll oder nicht?

________Vorher definiert____________

____

____

8) Welche Informationen werden beim Wechsel eines Werkzeuges dokumentiert?

Siehe HK Dokumentation.

□ x Datum

□ x Vortriebsstationierung (Ringnummer, Vortriebsstand [m])

□ x Bearbeiter

□ x Werkzeugtyp

□ x Werkzeug ID-Nummer (Schneidrollen)

□ x Spur-Nr.

□ x Arm Nr. (Schälmesser und Räumer)

□ x Drehrichtung (Schälmesser und Räumer)

□ x Zustand des Abbauwerkzeuges bei Ausbau

□ x Wechselgrund

□ x Fotodokumentation

Figure B-7: Interview 2, page 2.

Anlage 1 : vorbereitende Arbeiten (1)

Prozess	***Dauer [min]***		***sonstige Bemerkungen (Bedingungen für das Durchführen der Arbeiten, Auftrittshäufigkeiten, etc.)***
	EPB-Schild	***Hydro-Schild***	
Level absenken: - Vollabsenkung - Halbabsenkung	Zwischen 15 min bis 120 min	Zwischen 15 min bis 120 min	Je nach Geologie, je nachdem ob Filterkuchen notwendig
Druck absenken	10 bis 20 min	10 bis 20 min	Wird in verschiedene Stufe gemacht, je nach Geologie und Druck
Einschleusen des Personals	5 min	5 min	
Einschleusen der Werkzeuge	1 min	1 min	Durch Material Schleuse
Anbringen der Podeste	5 min	5 min	Je nach TBM Durchmesser, Beispiel für Ø7m Nicht alle Podeste werden montiert
Werkzeuge zur TVM transportieren: - Geplanter Wechsel - Ungeplanter Wechsel	Geplanter und ungeplanter: laufen parallel mit die Vorbereitungsarbeiten	Geplanter und ungeplanter: laufen parallel mit die Vorbereitungsarbeiten	Werden mit dem Zug in Boxen auf der Maschine gebracht. Segment Kran transportiert die Disken in eine Transport Wanne auf dem Segment Feeder. Erektor hebt die Disken zu die Material Schleuse

Figure B-8: Interview 2, page 3.

Bohrkopf reinigen	1 min bis 20 min pro Arm	1 min bis 20 min pro Arm	In kohäsive Geologie oder mit kompaktiertes Material sehr lang. Hochdruck reiniger manchmal notwendig.
Temperatur runterkühlen	1 Std bis 24 Std	Mit Mix shield, die T° sind nicht so hoch. 1 Std bis 6 Std.	Je nach Normen. 28°C in Singapur.

Anlage 1: vorbereitende Arbeiten (2)

Figure B-9: Interview 2, page 4.

Anlage 2: Werkzeugwechsel (1)

Prozess	*Dauer [min]*		*sonstige Bemerkungen*
	EPB-Schild	*Hydro-Schild*	*(Bedingungen für das Durchführen der Arbeiten, Auftrittshäufigkeiten, etc.)*
Austausch eines Werkzeugs: - Diskenmeißel - Räumer - Schälmesser	- 30 min bis 1 Std - 20 min - 10 min	- 30 min bis 1 Std - 20 min - 10 min	Unterschied zwischen 17" und 19"
Tausch zweier Disken	1 Std bis 1 1/2 Std	1 Std bis 1 1/2 Std	
Suche nach abgerissenen Werkzeugteilen	10 min.	10 min	Falls teilen zu klein, werden nicht gesucht.
Inspektion anderer Maschinenteile			? Stein brecher für Mix shield, 5 min check
Schrauben festziehen	1 min pro Disk	1 min pro Disk	
Verschleißmessungen	20 min	20min	Für ca. 40 Disken

Anlage 2: Werkzeugwechsel (2)

Figure B-10: Interview 2, page 5.

Anlage 3: nachbereitende Arbeiten (1)

Prozess	***Dauer [min]***		***sonstige Bemerkungen*** ***(Bedingungen für das Durchführen der Arbeiten, Auftrittshäufigkeiten, etc.)***
	EPB-Schild	***Hydro-Schild***	
Ausschleusen	Druck-LV	Druck-LV	Druck-LV
Demontieren der Podeste	5 min	5 min	Je nach TBM Durchmesser, Beispiel für Ø7m Nicht alle Podeste werden montiert
Auffüllen der Abbaukammer	10 min	10 min	
Druck erhöhen	2 min	2 min	

Anlage 3: nachbereitende Arbeiten (2)

Figure B-11: Interview 2, page 6.

Planung von Werkzeugwechseln/Wartungsstopps

1) In welcher Projektphase werden die Wartungspositionen für Werkzeugwechsel geplant?

☐ Entwurfsplanung
☐ Ausführungsplanung
☒ andere: AV Vortrieb des AN, dann ggf. Abstimmung und Genehmigung AG

2) Wer legt die Wartungspositionen fest?

☐ AG
☒ AN
☐ AG + AN gemeinschaftlich
☐ AG legt feste Einstiegspositionen vor, welche vom AN nach eigenem Ermessen ergänzt werden können
☒ andere: Mitwirkung ggf. AG samt Tunnelbausachverständige des AG

3) Werden vom AN zusätzlich festgelegte Wartungspositionen vom AG vergütet?

☐ Ja
☒ Nein
☒ andere: ggf. nur bei Vertragsabweichungen "geänderte Geologie"

4) Was steht bei der Planung der Werkzeugwechsel im Vordergrund bzw. was ist der „erste Schritt" der Planung?

☐ Bestimmung des Laufweges der Abbauwerkzeuge
☒ Bestimmung der Besonderheiten im Trassenverlauf, z.B. Flussunterquerungen, in in denen Einstiege zwingend vermieden werden sollen
☒ Festlegung der Einstiege in etwa gleichem Abstand, d.h. periodische Wartung
☐ andere:

5) Worauf basiert die Einschätzung des Laufweges der Abbauwerkzeuge?

☒ Erfahrungswerte
☐ Rechnungen basierend auf der Abrasivität des Bodens/Lockergesteins
☐ andere:

6) Ist es wichtiger möglichst wenige Einstiege durchzuführen oder stehen die Werkzeugkosten im Vordergrund, d.h. die Werkzeuge sollen erst getauscht werden wenn deren Verschleißgrenze erreicht ist?

☒ möglichst wenige Einstiege
☐ Werkzeugtausch erst bei Erreichen der Verschleißgrenze
☒ andere: ganzheitliche Risikominimierung des Vortriebs

Figure B-12: Interview 3, page 1.

7) Erfolgt während des Vortriebs eine planmäßige Anpassung der Wartungsplanung, um die Parameter zu überprüfen, die im Rahmen der Planung angenommen wurden?

☒ Ja
☐ Nein
☒ andere: wenn erforderlich, z.B. abweichendem Verschleiß

8) Wird im Rahmen der Planung mit korrektiven Wartungsstopps gerechnet, weil der tatsächliche Werkzeugverschleiß im Vorhinein nicht zu bestimmen ist?

☒ Ja
☐ Nein
☐ andere:

9) Woran lässt sich – außer an der automatischen Verschleißerkennung – ohne Einstieg erkennen, dass Werkzeuge verschlissen sind?

☒ verminderte Penetration
☒ erhöhte Vortriebskraft
☒ andere: verminderte Auffahrfähigkeit von Hindernissen

10) Ist es üblich Werkzeuge von inneren Spuren auf äußere Spuren zu versetzen?

☐ Ja
☒ Nein
☐ nur in Ausnahmefällen, z.B.:
☒ andere: Komplettausch, ggf. längere Laufzeiten der inneren Spuren, also keine Wechsel

Maschinenplanung

1) Zu welchem Zeitpunkt wird die Auslegung der TVM festgelegt, d.h. Werkzeugbesatz, Öffnungsverhältnis etc.?

☐ Entwurfsplanung
☐ Ausführungsplanung
☒ andere: Maschinenkonzept im Zuge der bestellung der TVM des AN

2) Wer legt die Auslegung der TVM fest?

☐ AG
☒ AN
☐ AG + AN
☐ Maschinenhersteller
☒ andere: Abstimmung mit Taunnelbausachverständigen des AG und AG

3) Ist die Auslegung der TVM zum Zeitpunkt der Wartungsplanung schon bekannt?

☒ Ja
☐ Nein

Figure B-13: Interview 3, page 2.

☐ andere:

Verbesserung der Wartungsplanung

1) Wo liegt das Problem der korrekten Einschätzung der Wartungspositionen?

☒ Abrasivität des Bodens ist nicht klar
☒ Laufweg der Werkzeuge ist nicht bestimmbar
☐ andere:

2) Falls dies der Fall ist, warum lässt sich die Abrasivität des Bodens nicht gut einschätzen?

☒ fehlende Angaben im Baugrundgutachten
☒ andere: QAndere Einflüsse unbekannt, Hindernisse, Verbauwände etc..

3) Wird zur Bestimmung des Laufweges eine Methode eingesetzt?

☐ Ja
☒ Nein, reine Einschätzung auf Basis von Erfahrungswerten
☐ andere:

4) Würde die genaue Bestimmung des Laufweges bei der Wartungsplanung helfen oder werden ohnehin viele Werkzeuge präventiv gewechselt, um Einstiege in ungünstigen Bereichen zu vermeiden?

☒ genaue Bestimmung des Laufweges wäre hilfreich
☐ viele Werkzeuge werden ohnehin präventiv gewechselt
☒ andere: Berücksichtigung der Materialeigenschfaten (Härte) der Werkzeuge

5) Haben Sie Vorschläge, welche Angaben o.ä. für eine bessere Bestimmung der Wartungspositionen hilfreich wären?

☐ Nein
☒ Ja, folgende: Bestimmung des Laufweges in Abhängigkeit des geologischen Längsschnittes und Bestimmung ewaiger Wartungspositionen mit minimalem Einstiegsrisiko

Figure B-14: Interview 3, page 3.

Planung von Werkzeugwechseln/Wartungsstopps

1) In welcher Projektphase werden die Wartungspositionen für Werkzeugwechsel geplant?

☒ Entwurfsplanung
☒ Ausführungsplanung
☐ andere:

> Je nach Projekterfordernis gibt der AG in der Entwurfsphase bereits Wartungspositionen vor, um die (DL-) Intervention in einem sicheren Bereich durchzuführen und vor Unterfahrung von sensiblen Bereichen.

2) Wer legt die Wartungspositionen fest?

☒ AG
☐ AN
☐ AG + AN gemeinschaftlich
☒ AG legt feste Einstiegspositionen vor, welche vom AN nach eigenem Ermessen ergänzt werden können `s. 1)`
☐ andere:

3) Werden vom AN zusätzlich festgelegte Wartungspositionen vom AG vergütet?

☐ Ja
☒ Nein
☐ andere:

> Eine zusätzliche Vergütung erfolgt i.d.R. nur, wenn die Projektrandbedingungen von der Prognose (Abrasivität des Baugrunds) abweichen. Der AN hat auf Basis der Ausschreibungsunterlagen sämtliche Maßnahmen umzusetzen (Schneidraddesign, Werkzeugbesatz, Spülströme etc.), die einen Verschleiß minimieren.

4) Was steht bei der Planung der Werkzeugwechsel im Vordergrund bzw. was ist der „erste Schritt" der Planung?

☐ Bestimmung des Laufweges der Abbauwerkzeuge
☒ Bestimm… …ngen, in
in denen…
☐ Festlegu… …ung
☐ andere:

> Sofern der AG Vorgaben für Inspektionen und Wartung macht, stehen die Trassenspezifika im Vordergrund (Flussunterquerung, geringe Überdeckung, sensible Unterfahrungsbereiche wie z.B. Bahntrassen od. Versorungsleitungen). Die neusten Erkenntnisse zur Optimierung der Standzeit bzw. der Wartungsaufwands empfehlen regelmäßige Wartungen, um nicht den Grenzverschleiß zu erreichen und damit den maximalen Instandsetzungsaufwand und -kosten zu provozieren.

5) Worauf basiert die Einschätzung des Laufweges der Abbauwerkzeuge?

☒ Erfahrungswerte
☒ Rechnungen basierend auf der Abrasivität des Bodens/Lockergesteins
☐ andere:

> Überwiegend auf Basis von Erfahrungswerten. Neuere Erkentnisse (F. Köppl, 2014) liefern erste praktikable Prognosemodelle.

6) Ist es wichtiger möglichst wenige Einstiege durchzuführen oder stehen die Werkzeugkosten im Vordergrund, d.h. die Werkzeuge sollen erst getauscht werden wenn deren Verschleißgrenze erreicht ist?

☐ möglichst wenige Einstiege
☐ Werkzeugtausch erst bei Erreichen der Verschleißgrenze
☒ andere:

> Unterschiedlich, da die Kosten für die Wechselarbeiten auch maßgeblich mit der Druckhöhe der notwendigen Druckluft und damit mit dem Ein- und Ausschleusaufwand (längere Stillstandzeiten, erhöhter Personalaufwand, erhöhtes Risiko) korrelieren.

Figure B-15: Interview 4, page 1.

7) Erfolgt während des Vortriebs eine planmäßige Anpassung der Wartungsplanung, um die Parameter zu überprüfen, die im Rahmen der Planung angenommen wurden?

- ☐ Ja
- ☒ Nein
- ☐ andere:

8) Wird im Rahmen der Planung mit korrektiven Wartungsstopps gerechnet, weil der tatsächliche Werkzeugverschleiß im Vorhinein nicht zu bestimmen ist?

- ☒ Ja
- ☐ Nein
- ☐ andere:

9) Woran lässt sich – außer an der automatischen Verschleißerkennung – ohne Einstieg erkennen, dass Werkzeuge verschlissen sind?

- ☐ verminderte Penetration
- ☒ erhöhte Vortriebskraft
- ☒ andere: Tendenziell verminderter Ringspaltmörtelverbrauch, jedoch schwierig in der Feststellung, da auch geologische Aspekte zu reduzierten Mengen führen können (Konvergenz des Ausbruchrands, reduzierte Penetration in die Porenräume). Anstieg der Schneidradkontaktkraft Netto-Anpresskraft Schneidrad ohne Anteil Stützdruck) und Drehmomente.

10) Ist es üblich Werkzeuge von inneren Spuren auf äußere Spuren zu versetzen?

- ☐ Ja
- ☐ Nein
- ☒ nur in Ausnahmefällen, z.B.:
- ☐ andere: Sofern der Werkzeugbesatz der inneren Spur auch gewechselt werden soll und z.B. der Kaliberbereich mit "verschlissenen" Disken (geringerer Überschnitt) bestückt werden soll.

Maschinenplanung

1) Zu welchem Zeitpunkt wird die Auslegung der TVM festgelegt, d.h. Werkzeugbesatz, Öffnungsverhältnis etc.?

- ☒ Entwurfsplanung Grundlagen
- ☒ Ausführungsplanung
- ☐ andere:

2) Wer legt die Auslegung der TVM fest?

- ☐ AG
- ☐ AN
- ☒ AG + AN
- ☐ Maschinenhersteller
- ☐ andere:

AG: Stellt in der Entwurfs- bis Ausschreibungsplanung grundlegende Anforderungen an die Vortriebsmaschine auf.
AN: Muss ein geschlossenes Lösungskonzept zur Erfüllung des Anforderungsprofils mit Störfallszenarien erarbeiten. Der Werkzeugbesatz, das Schneidraddesign, die Spülströme etc. liegen in der Sphäre des AN. Der Maschinenhersteller berät und konzipiert die TVM mit den AN zusammen.

3) Ist die Auslegung der TVM zum Zeitpunkt der Wartungsplanung schon bekannt?

- ☒ Ja
- ☐ Nein
- ☐ andere:

Figure B-16: Interview 4, page 2.

Verbesserung der Wartungsplanung

1) Wo liegt das Problem der korrekten Einschätzung der Wartungspositionen?

☐ Abrasivität des Bodens ist nicht klar
☐ Laufweg der Werkzeuge ist nicht bestimmbar
☒ andere: Abweichungen von der Prognose sind möglich, der theoretische Laufweg ist in einer Spannweite bestimmbar. Die Steuerung des Abbauprozesses (Drehzahl, Vortriebsgeschwindigkeit, Penetration) und die Aufladung der Förder-suspension haben einen maßgeblichen Einfluss auf den Werkzeugverschleiß.

2) Falls dies der Fall ist, warum lässt sich die Abrasivität des Bodens nicht gut einschätzen?

☐ fehlende Angaben im Baugrundgutachten
☒ andere: Mit der Durchführung von Abrasivitätsuntersuchungen (z.B. LCPC) in geeignetem Umfang kann eine ausreichende Prognose aufgestellt werden.

3) Wird zur Bestimmung des Laufweges eine Methode eingesetzt?

☐ Ja
☒ Nein, reine Einschätzung auf Basis von Erfahrungswerten
☐ andere:

4) Würde die genaue Bestimmung des Laufweges bei der Wartungsplanung helfen oder werden ohnehin viele Werkzeuge präventiv gewechselt, um Einstiege in ungünstigen Bereichen zu vermeiden?

☒ genaue Bestimmung des Laufweges wäre hilfreich
☐ viele Werkzeuge werden ohnehin präventiv gewechselt
☒ andere: Sofern der tatsächliche Laufweg bekannt wäre, könnte eine Abstimmung mit den Wartungsstopps erfolgen.

5) Haben Sie Vorschläge, welche Angaben o.ä. für eine bessere Bestimmung der Wartungspositionen hilfreich wären?

☒ Nein
☐ Ja, folgende:

Figure B-17: Interview 4, page 3.

Planung von Werkzeugwechseln/Wartungsstopps

1) In welcher Projektphase werden die Wartungspositionen für Werkzeugwechsel geplant?

☐ Entwurfsplanung
☒ Ausführungsplanung
☐ andere:

2) Wer legt die Wartungspositionen fest?

☐ AG
☒ AN
☐ AG + AN gemeinschaftlich
☐ AG legt feste Einstiegspositionen vor, welche vom AN nach eigenem Ermessen ergänzt werden können
☐ andere:

3) Werden vom AN zusätzlich festgelegte Wartungspositionen vom AG vergütet?

☐ Ja
☒ Nein
☐ andere:

4) Was steht bei der Planung der Werkzeugwechsel im Vordergrund bzw. was ist der „erste Schritt“ der Planung?

☐ Bestimmung des Laufweges der Abbauwerkzeuge
☒ Bestimmung der Besonderheiten im Trassenverlauf, z.B. Flussunterquerungen, in in denen Einstiege zwingend vermieden werden sollen
☐ Festlegung der Einstiege in etwa gleichem Abstand, d.h. periodische Wartung
☐ andere:

5) Worauf basiert die Einschätzung des Laufweges der Abbauwerkzeuge?

☐ Erfahrungswerte
☐ Rechnungen basierend auf der Abrasivität des Bodens/Lockergesteins
☒ andere: Erfahrungswerte basierend auf der Abrasivität des Bodens/Lockergestein

6) Ist es wichtiger möglichst wenige Einstiege durchzuführen oder stehen die Werkzeugkosten im Vordergrund, d.h. die Werkzeuge sollen erst getauscht werden wenn deren Verschleißgrenze erreicht ist?

☐ möglichst wenige Einstiege
☐ Werkzeugtausch erst bei Erreichen der Verschleißgrenze
☒ andere: möglichst wenig Einstiege unter Ausnutzung des max. Verschleiß (abzgl. Reserve)

Figure B-18: Interview 5, page 1.

7) Erfolgt während des Vortriebs eine planmäßige Anpassung der Wartungsplanung, um die Parameter zu überprüfen, die im Rahmen der Planung angenommen wurden?

☒ Ja
☐ Nein
☐ andere:

8) Wird im Rahmen der Planung mit korrektiven Wartungsstopps gerechnet, weil der tatsächliche Werkzeugverschleiß im Vorhinein nicht zu bestimmen ist?

☒ Ja
☐ Nein
☐ andere:

9) Woran lässt sich – außer an der automatischen Verschleißerkennung – ohne Einstieg erkennen, dass Werkzeuge verschlissen sind?

☐ verminderte Penetration
☒ erhöhte Vortriebskraft
☒ andere: hohe Anpresskraft SR bei niedriger Penetration, Drehmoment SR

10) Ist es üblich Werkzeuge von inneren Spuren auf äußere Spuren zu versetzen?

☐ Ja
☒ Nein
☐ nur in Ausnahmefällen, z.B.:
☐ andere:

Maschinenplanung

1) Zu welchem Zeitpunkt wird die Auslegung der TVM festgelegt, d.h. Werkzeugbesatz, Öffnungsverhältnis etc.?

☐ Entwurfsplanung
☒ Ausführungsplanung
☐ andere:

2) Wer legt die Auslegung der TVM fest?

☐ AG
☒ AN
☐ AG + AN
☒ Maschinenhersteller
☐ andere:

3) Ist die Auslegung der TVM zum Zeitpunkt der Wartungsplanung schon bekannt?

☐ Ja
☐ Nein
☒ andere: Ja, für den AN

Figure B-19: Interview 5, page 2.

Verbesserung der Wartungsplanung

1) Wo liegt das Problem der korrekten Einschätzung der Wartungspositionen?

☐ Abrasivität des Bodens ist nicht klar
☐ Laufweg der Werkzeuge ist nicht bestimmbar
☒ andere: Abrasivität nicht erschöpfend beschrieben, Inhomogenitäten im Baugrund, Laufweg Meissel max. Abschätzung, Abbauverhalten Boden nicht bekannt bzw. max. Erfahrungswerte

2) Falls dies der Fall ist, warum lässt sich die Abrasivität des Bodens nicht gut einschätzen?

☐ fehlende Angaben im Baugrundgutachten
☐ andere:

3) Wird zur Bestimmung des Laufweges eine Methode eingesetzt?

☐ Ja
☒ Nein, reine Einschätzung auf Basis von Erfahrungswerten
☐ andere:

4) Würde die genaue Bestimmung des Laufweges bei der Wartungsplanung helfen oder werden ohnehin viele Werkzeuge präventiv gewechselt, um Einstiege in ungünstigen Bereichen zu vermeiden?

☐ genaue Bestimmung des Laufweges wäre hilfreich
☐ viele Werkzeuge werden ohnehin präventiv gewechselt
☒ andere: bei Hydroschilden wird eher präventiv gewechselt, bei EBP oder offenen Schilden wäre die Bestimmung des Laufweges hilfreich.

5) Haben Sie Vorschläge, welche Angaben o.ä. für eine bessere Bestimmung der Wartungspositionen hilfreich wären?

☐ Nein
☒ Ja, folgende: Datenbank aufgefahrener Projekte mit Angaben/Anzahl gewechselter Meissel (normaler Verschleiß / Blockierer / Sonstige) und Angabe des Wechselgrundes sortiert nach TVM-Typ und Gesteinsformationen mit Quarzgehalt

Figure B-20: Interview 5, page 3.

Planung von Werkzeugwechseln/Wartungsstopps

1) In welcher Projektphase werden die Wartungspositionen für Werkzeugwechsel geplant?

☐ Entwurfsplanung
☒ Ausführungsplanung
☐ andere:

Die HOCHBAHN hat bei der Ausschreibung der U4 keine Wartungspositionen festgelegt.

2) Wer legt die Wartungspositionen fest?

☐ AG
☒ AN
☒ AG + AN gemeinschaftlich
☐ AG legt feste Einstiegspositionen vor, welche vom AN nach eigenem Ermessen ergänzt werden können
☐ andere:

von AN vorgegeben oder dann gemeinsam festgelegt

3) Werden vom AN zusätzlich festgelegte Wartungspositionen vom AG vergütet?

☐ Ja
☒ Nein

Es sei denn, der AN kann darlegen, dass entgegen der ausgeschriebenen Geologie, diese nicht zu erwarten waren.

4) Was steht bei der Planung der Werkzeugwechsel im Vordergrund bzw. was ist der „erste Schritt" der Planung?

☐ Bestimmung des Laufweges der Abbauwerkzeuge (Geologie)
☒ Bestimmung der Besonderheiten im Trassenverlauf, z.B. Flussunterquerungen, in in denen Einstiege zwingend vermieden werden sollen
☐ Festlegung der Einstiege in etwa gleichem Abstand, d.h. periodische Wartung
☐ andere:

5) Worauf basiert die Einschätzung des Laufweges der Abbauwerkzeuge?

☒ Erfahrungswerte
☒ Rechnungen basierend auf der Abrasivität des Bodens/Lockergesteins
☐ andere:

Kombination aus beiden

6) Ist es wichtiger möglichst wenige Einstiege durchzuführen oder stehen die Werkzeugkosten im Vordergrund, d.h. die Werkzeuge sollen erst getauscht werden wenn deren Verschleißgrenze erreicht ist?

☐ möglichst wenige Einstiege
☒ Werkzeugtausch erst bei Erreichen der Verschleißgrenze
☐ andere:

bzw. nach Trassenverlauf, lieber in „sicherer" Parkposition als unter Gebäude

Figure B-21: Interview 6, page 1.

7) Erfolgt während des Vortriebs eine planmäßige Anpassung der Wartungsplanung aufgrund von Maschinenparametern o.ä., die im Vorhinein im Rahmen der Planung anders angenommen wurden?

☐ Ja
☒ Nein
☐ andere:

8) Wird im Rahmen der Planung mit korrektiven Wartungsstopps gerechnet, weil der tatsächliche Werkzeugverschleiß im Vorhinein nicht zu bestimmen ist?

☒ Ja — ggf. nach Geologie
☐ Nein

9) Woran lässt sich ohne Einstieg erkennen, dass Werkzeuge verschlissen sind?

☐ verminderte Penetration (ggf. kann aber auch Verklebungen hindeuten)
☐ erhöhte Vortriebskraft
☐ andere: Verschleißmesseinrichtungen (Öldruckdose in der Spur)

10) Ist es üblich Werkzeuge von inneren Spuren auf äußere Spuren zu versetzen?

☐ Ja
☐ Nein
☒ nur in Ausnahmefällen, z.B.: falls keine neuen Werkzeuge verfügbar
☐ andere:

Maschinenplanung

1) Zu welchem Zeitpunkt wird die Auslegung der TVM festgelegt, d.h. Werkzeugbesatz, Öffnungsverhältnis etc.?

☐ Entwurfsplanung
☒ Ausführungsplanung (Bsp. U4 HOCHBAHN)
☐ andere:

2) Wer legt die Auslegung der TVM fest?

☐ AG
☒ AN
☐ AG + AN
☐ Maschinenhersteller
☐ andere:

3) Ist die Auslegung der TVM zum Zeitpunkt der Wartungsplanung schon bekannt?

☐ Ja
☒ Nein

Figure B-22: Interview 6, page 2.

Verbesserung der Wartungsplanung

1) Wo liegt das Problem der korrekten Einschätzung der Wartungspositionen?

☒ Abrasivität des Bodens ist nicht klar
☒ Laufweg der Werkzeuge ist nicht bestimmbar
☐ andere:

} Kombination

2) Falls dies der Fall ist, warum lässt sich die Abrasivität des Bodens nicht gut einschätzen?

☐ fehlende Angaben im Baugrundgutachten
☒ andere: fehlende Erfahrungswerte (ggf. Unklarheit über Findlinge, etc)

3) Wird zur Bestimmung des Laufweges eine Methode eingesetzt?

☐ Ja (nicht bekannt)
☐ Nein, reine Einschätzung auf Basis von Erfahrungswerten
☐ andere:

4) Würde die genaue Bestimmung des Laufweges bei der Wartungsplanung helfen oder werden ohnehin viele Werkzeuge präventiv gewechselt, um Einstiege in ungünstigen Bereichen zu vermeiden?

☐ genaue Bestimmung des Laufweges wäre hilfreich
☒ viele Werkzeuge werden ohnehin präventiv gewechselt
☐ andere:

(könnte helfen, aber meistens kommt es eher auf die sichere Einstiegsposition an)

5) Haben Sie Vorschläge, welche Angaben o.ä. für eine bessere Bestimmung der Wartungspositionen hilfreich wären?

☒ Nein
☐ Ja, folgende:

TB7 Göhring

Figure B-23: Interview 6, page 3.