Simulation-Based Analysis of Maintenance Strategies for Mechanized Tunneling Projects

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INTRODUCTION

In recent years, the development of tunnel boring machines has revolutionized the tunneling industry. The general structure of a tunnel boring machine (TBM) can be described as a multi-component system. To achieve high performance rates, machine elements have to perform reliably. Performance losses and interruptions of the construction process should be prevented or at least, reduced to a minimum. In order to achieve high advancing rates, cutting tools must be in good condition at any time. Furthermore, failure of individual tools might result in increased and faster wear of remaining structural components. For this reason, maintaining and replacing cutting tools is crucial to prevent project delays due to insufficient boring performance. Precise prognoses concerning the prevailing geology are infeasible and thus, efficient scheduling of maintenance actions is challenging. The intention of this work is to analyze different approaches of TBM maintenance in soft ground. Different strategies are analyzed by the use of a simulation approach. Cutting tool condition is regarded as performance limiting factor. The maximum operation time of the cutting tools is determined using the "Soil Abrasivity Index". A case study serves to show the effects of different maintenance strategies on total project duration.

SCHEDULING OF MAINTENANCE ACTIONS

Scheduling maintenance actions of single and multi-component systems concerns numerous fields of industrial production. Concentrating on mechanized tunneling in soft ground, cutting tool maintenance represents the most common reason for intermission of advance (Köppl 2014). In literature, time-based and condition-based maintaining techniques are widely discussed. The following section outlines the principles of time- and condition-based policies. Furthermore, examples for their applications in recent research are given.

Time-Based Maintenance

In general, the time-based maintenance approach assumes that the failure behavior of the system components is predictable. Maintenance actions are scheduled according to predefined intervals (e.g., hours, days, weeks). A detailed analysis of preventive repair times or interval forms the basis for maintenance decisions. For this approach, an adequate quantity and quality of data is fundamental. Numerous studies deal with the analysis of time-based maintenance for production equipment. In fields of mechanized tunneling, unplanned machine downtimes restrict the applicability of time-based maintenance approaches. Thus, this paper mainly focuses on condition-based maintenance.

Condition-Based Maintenance

Condition-based maintenance is the most discussed strategy in modern literature. It is often described as "predictive" policy. The basic assumption of this approach is that equipment failure can be predicted by certain signs, conditions or events. Condition-based maintenance decisions derive from information collected through a condition monitoring process (Jardine et al. 2006). It is assumed that system components deteriorate during operating time and negatively affect total performance. Core process of this strategy is monitoring of key factors which indicate that a failure is going to occur. Following this strategy, repair or replacement actions are only performed if necessary or just before breakdown (Andersen and Rasmussen 1999). Real-time assessment of equipment conditions serves to reduce unnecessary maintenance and related costs (Gupta and Lawsirirat 2006). If monitoring of the performance limiting factors is not possible, examinations of similar systems serve for predicting the system condition at a certain point of time. Condition-based maintenance is highly sensitive towards the monitoring procedure, as discussed in the next section in more detail.

Monitoring

Ahmad and Kamaruddin (2012) differentiate between two alternative monitoring techniques. On-line processing is carried out during the operating state of the system. On the contrary, off-line processing is performed when the equipment is inactive. Furthermore, monitoring can be scheduled into periodic intervals such as days, weeks or working shift end. The main challenge of periodic monitoring is an adequate planning of intervals to collect data. Important information of equipment failure between monitoring intervals must not be missed. Continuous monitoring is performed uninterruptedly and automatically using special measurement devices. This type of real-time assessment is expensive as special devices are required. On top of that, a continuous flow of data results in a high quantity of information that has to be processed immediately (Jardine et al. 2006). Due to immense progress concerning computer-based data processing within the last decades, this can be depicted as a minor problem nowadays.

In Jardine et al. (2006) it is stated that prognostics is superior to diagnostics. Prognostics can prevent unexpected failures resulting in a reduction of unplanned maintenance costs. With regard to condition-based maintenance, decision making (particularly in case of prognostic processes) can be achieved through equipment deterioration modelling. Ahmad and Kamaruddin (2012) name two methods of decision making: current condition evaluation-based (CCEB) and future condition prediction-based (FCPB). Following the CCEB method, the current equipment condition is monitored and forms the basis for maintenance decisions. The information collected in the monitoring process is used to estimate the actual system condition, which is then compared to a predefined failure limit. As soon as the condition level reaches or exceeds the limit, maintenance actions will be carried out. Following the CCEB method, the system state is usually checked by periodic monitoring.

Besides CCEB, Ahmad and Kamaruddin (2012) concentrate on the FCPB method which represents another CBM decision making method. This method is based on predicting the future trend of the equipment condition. If necessary, appropriate maintenance is planned and scheduled as in the CCEB approach.

Types of Maintenance Processes

Besides the strategies of scheduling maintenance actions, it can also be differentiated concerning the type of the maintenance process. Corrective maintenance is performed to correct a failure so that the affected component can be restored to an operational condition (United Air Lines Inc San Francisco CA 2011). As corrective maintenance actions are evoked by a defined system condition, this type of maintenance is condition-based. Preventive maintenance comprises time-based (e.g., maintenance after 24 operating hours) as well as condition based maintenance (e.g., maintenance in case of insufficient system performance). Following this approach, it is intended to reduce the probability of failure or the degradation of the functioning of a system component (Shaomin Wu and Zuo 2010). Regarding usually high expenditures caused by system failures, costs for preventive maintenance actions are usually lower than costs of corrective replacements. Additionally, unplanned system failures often lead to long production downtimes.

Effectiveness of Maintenance

Shaomin Wu and Zuo (2010) state that the effectiveness of maintenance can be classified into one of the three situations: perfect, minimal and imperfect. Perfect maintenance restores a system to be as good as new (AGAN), minimal restores it to the state just before the maintenance (as bad as old = ABAO) and imperfect maintenance brings a system to a condition between AGAN and ABAO. It has to be considered that only repairable system components can reach a condition between AGAN and ABAO. Using these categories to describe the effectiveness of maintenance, it is essential to exactly define the parameters describing the system state.

MAINTENANCE OF TUNNEL BORING MACHINES

TBM are multi-component systems. Although the interaction of the single machine elements plays a major role concerning the success of tunneling projects, this approach focuses on the cutting wheel as performance limiting factor. Thus, the multi-component system is reduced to a single-component system. Worn cutting tools are a major reason for maintenance stops of TBM. In many cases, the costs for inspecting and replacing tools exceed the material costs of the changed tools. As tunneling projects are influenced by varying and unstable boundary conditions, cutting tool performance prediction is difficult. The following section will explain the monitoring process of TBM cutting tools.

Equipment Condition

During the advance phase in soft ground, the cutting tools of the TBM continuously wear out, determined by a reduction of tool size. The rate of abrasion is mainly governed by the characteristics of the prevailing geology. As outworn cutting tools result in forced machine stops they have to be replaced if the remaining tool size drops below a defined level. The determination of this threshold depends on the person responsible for the project or on empirical values. To carry out maintenance actions on TBMs, the machine has to be stopped in order to access the tools. Accessing the tools is challenging as workers in many cases have to operate under hyperbaric conditions in soft ground conditions. Due to the mentioned working conditions, reducing the number of maintenance stops is intended.

The maximum productivity of cutting tools, described as m^3 of excavated soil per tool, is influenced by a variety of boundary conditions, such as the abrasivity and strength of the ground, the cutterhead rotation speed and the excavation speed. Observing the actual deterioration process is not possible as the excavation chamber cannot be entered while the wheel rotates. In the field of mechanized tunneling, a detailed geological data set is required to create reliable predictions on cutting tool deterioration. Recent studies mainly addressed prognosis models for cutting tool wear in hard rock (e.g. Cerchar Abrasivity Index). For the application of Slurry supported shield machines in soft ground, Köppl (2014) concentrates on the identification and quantification of the main influencing factors that determine cutting tool condition and on developing prognosis models for cutting tool wear. Köppl, F. and Thuro, K. (2013) develop an empirical model to estimate distances between maintenance stops. Additionally, the required amount of cutting tools to be changed can be estimated. The model is based on the new Soil Abrasivity Index (SAI) applicable in soft ground. By enabling foresighted planning, it is possible to avoid machine stops in critical areas. Köppl, Thuro and Thewes (2015) validate the prognosis model based on original reference projects. Accurate modeling results prove that the SAI can be used for predicting cutting tool wear.

Concerning the common standard of mechanized tunneling, actual tool wear is checked by electrical contacts which are interrupted at a certain degree of deterioration. Precise predictions of cutting tool abrasion is rather uncommon. To create a strong connection to realistic tunneling projects, this paper focuses on current condition evaluation-based (CCEB) maintenance decisions. As the cutting tools cannot be repaired, they are completely replaced during maintenance stops and their performance level is reset to "As Good As New" (AGAN).

CONCEPT

The intention of this work is to create a reliable but simplified simulation model of the mechanized tunneling procedure in order to examine possible maintenance strategies. As exact information on maintenance costs are internal knowledge of contractors and rarely are published, tunneling projects are examined with respect to their total project duration. Thus, the influence of a single maintenance strategy concerning overall project performance can be examined. Referring to industry, the results of this study may help to achieve high performance rates by supporting an efficient scheduling of maintenance actions.

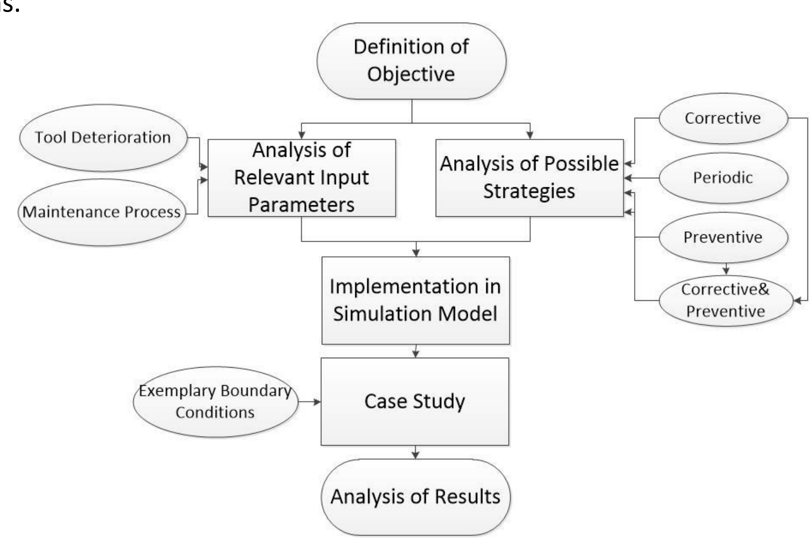

Figure 1: General proceeding

As the focus of this work lies on the TBM maintenance process, the general system had to be divided up into different elements according to their influence on the project's objective. The most important input parameters influencing cutting tool deterioration and maintenance actions were identified. They are explained more detailed in the following sections. In a second step, existing maintenance strategies were examined concerning their feasibility in mechanized tunneling projects. Three alternative strategies were implemented in a simulation model. A fourth strategy was created by combining the corrective and preventive approach. The influence of the chosen maintenance concept on total system performance was evaluated by a case study referring to total project duration. The mentioned approach is illustrated in Figure 1.

A simulation model is a simplified reproduction of a certain system. To guarantee reliable results the model's level of detail has to be chosen appropriately. In this project, the mechanized tunneling process is reduced to its two main operations phases: advance and ring building. Only disturbances caused by insufficient cutting tool performance are included. System performance is evaluated by total construction span of the single project. The analysis of costs caused by maintenance processes will be part of future studies. As the focus lies on effects of different maintenance approaches, the duration of advance and ring building are assumed to be stable.

As proposed by Köppl and Thuro (2013), the planned tunnel route is divided into homogeneous geotechnical sections. Each geological section is characterized by a certain Soil Abrasivity Index (SAI) directly influencing the maximum operation time of the single tool. It is assumed that within each geological section, the SAI remains constant. Boulders are not regarded explicitly and the prevailing water table is assumed to be constant. Tool wear is reduced to abrasion caused by direct contact between soil and tool irrespective of the rotation direction of the wheel.

Interaction between Geology and Cutting Tool Deterioration

Köppl (2014) developed the "Soil Abrasivity Index" (SAI) to describe the interaction between prevailing geology and maximum path of cutting tools. It is calculated according to Equation 1:

$$SAI = \left(\frac{equQuartz}{100}\right)^2 \cdot \tau \cdot D_{60} \quad [-]$$

Equation 1: Soil Abrasivity Index SAI

Köppl chose the following parameters to calculate the SAI of a geological section:

- $equQuartz$: equivalent Quartz content [%]
- τ: shear strength of the soil [kN/m²]
- D_{60}: grain diameter [mm]

Whereas Köppl developed approaches to calculate the maximum path of various types of cutting tools, this paper only refers to cutting scrapers. Each of those tools is studded with a cutting edge removing soil if the wheel rotates under pressure.

If necessary, the deterioration process of other tools can easily be introduced to the model by implementing a different equation. According to Köppl, the maximum path of a cutting scraper can be calculated by Equation 2 and is irrespective of the tool's radial position on the cutterhead. This position, however, determines the travelled distance of the tool per cutterhead revolution.

$s_c = 280.9 + \exp(-0.0050 \cdot (SAI - 1{,}300.7))$ [km]

Equation 2: Calculation of maximum cutting tool path

Equation 3 shows the calculation of the maximum length a tool can be used referring to actual tunnel length.

$L_{max} = \frac{s_c\, p\, 1000}{2\, \pi\, r_s}$ [m]

Equation 3: Maximum path of a tool referring to actual length

- s_c: maximum cutting tool path [km]
- p: penetration [mm/rotation]
- r_s : distance between tool and cutting tool center [mm]

The parameter *p* [mm/rotation] represents tool penetration and r_s [mm] indicates radial tool position on the cutting wheel. Tools placed on the outer tracks of the cutting wheel are characterized by a shorter operation time as their travelled length per rotation is high. A tool is damaged as soon L_{max} is exceeded.

According to Nilsen B., Dahl, F., Holzhauser, J., Raleigh, P. (2006), Scholz and Wendl (2010), Frenzel and Babendererde (2011), high wear levels result in increasing abrasion rates as TBM advance speed remains constant. Due to the fact that detailed approaches of load distribution on tools are rare, overall load increase is transferred to the single tools proportionally.

Calculation of the Maintenance Process Duration

TBM face stability is achieved by creating an adequate support pressure within the excavation chamber. According to the chosen machine type (e.g., EPB, Hydro-Shield), this pressure is achieved by different supporting media. During the operation phase, workers and machine components are effectively protected against earth and water pressure. In case of inspection or maintenance work, the supporting medium is (partly) removed from the excavation chamber and replaced by pressurized air. Thus, inspection and replacement work takes place under pressurized conditions.

In this work, time spent on cutting tool maintenance is considered as performance limiting factor. The duration of a maintenance process depends on the number of the changed tools, the time for the change process and the time needed to adapt to pressurized conditions. Figure 2 shows the maximum possible working time under pressurized conditions and the time needed to adapt to atmospheric conditions after having accessed the excavation chamber (Regulations on Work in Compressed Air (DruckLV)). Under unfavorable conditions, the time needed to replace damaged and worn tools may exceed the maximum time that can be spent in the excavation chamber. In this case, two or more accesses of the excavation chamber become necessary. For this study, it is assumed that maintenance work is possible irrespective of the current machine position.

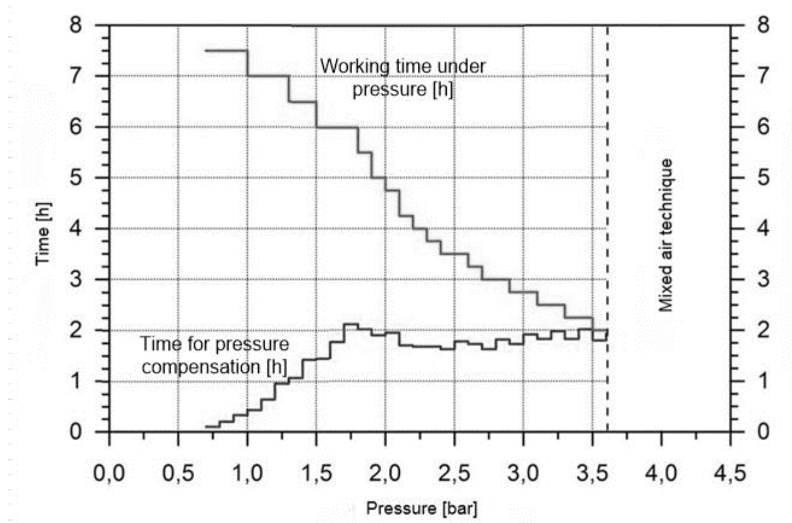

Figure 2: Maximum working time and time required time for pressure compensation according to DruckLV

MAINTENANCE STRATEGIES

The following section describes the different maintenance strategies to be analyzed in this study.

Strategy 1: Corrective

This strategy comprises running the TBM until the first tool exceeds its maximum operation time. As a consequence, the TBM has to be stopped. Continuing the boring process without cutting tool replacement is not possible. Within this strategy, there are only unplanned machine stops.

Strategy 2: Periodic

Strategy 2 includes replacing the cutting tools after a certain number of ring building phases (*periodicInt*). For this reason, the amount of completed operation cycles since the last maintenance stop is counted. The parameter *optWear* serves to define at which wear level cutting tools are replaced. In case of inappropriate replacing interval, breakdowns caused by inefficient cutting tools are still possible. Thus, planned and unplanned machine stops may occur. Average tool condition or prevailing support pressure do not influence the decision making process.

Strategy 3: Preventive

A preventive strategy implies replacing worn cutting tools in case of favorable working conditions indicated by low support pressure. The parameter *avgCond* defines the average machine performance below which maintenance is appropriate. Unplanned breakdowns caused by inefficient cutting tools are still possible if the parameters for decision making are chosen inappropriately.

Strategy 4: Corrective and Preventive

Strategy 4 represents a combination of corrective and preventive replacement. Maintenance actions are performed in case the average tool condition falls below a defined level. The machine is stopped and damaged tools are replaced. Depending on prevailing support pressure, the current machine position is classified in a category (green, yellow or red). Those categories indicate whether the current maintenance conditions is favorable or not. Following strategy 4, only unplanned stops may occur.

IMPLEMENTATION

The different maintenance strategies were analyzed by expanding an existing simulation model representing the TBM operation. This model was established for TBM performance prediction (König et al. 2014) for evaluating disturbances in mechanized tunneling (Rahm et al. 2015), (Scheffer et al. 2015) and for efficient planning of TBM jobsite logistics (Scheffer et al. 2014). System elements, interdependencies and processes relevant for cutting tool deterioration were added using the discrete-event simulation (DES) approach (Figure 3). DES is a common way to analyze systems which can be depicted as networks of queues and activities where state changes occur at discrete points of time (Antuela A. Tako and Stewart Robinson 2012). Thus, DES is highly appropriate for representing the cyclic operation method of TBMs. In contrast to DES, System Dynamics (SD) is a common technique to represent a system as a set of stocks and flows in which state changes occur continuously over time (Brailsford and Hilton, 2001). This simulation approach is suitable to represent the continuous deterioration of the cutting tools. The commercial simulation software AnyLogic 7.2 enables DES and SD modeling and was used to implement and expand the existing model. The *Cutting Wheel* of the existing model was modified and the *Cutting Tools* were realized as additional simulation components. As system parts are implemented following a flexible structure, cutting wheels of different designs can be analyzed.

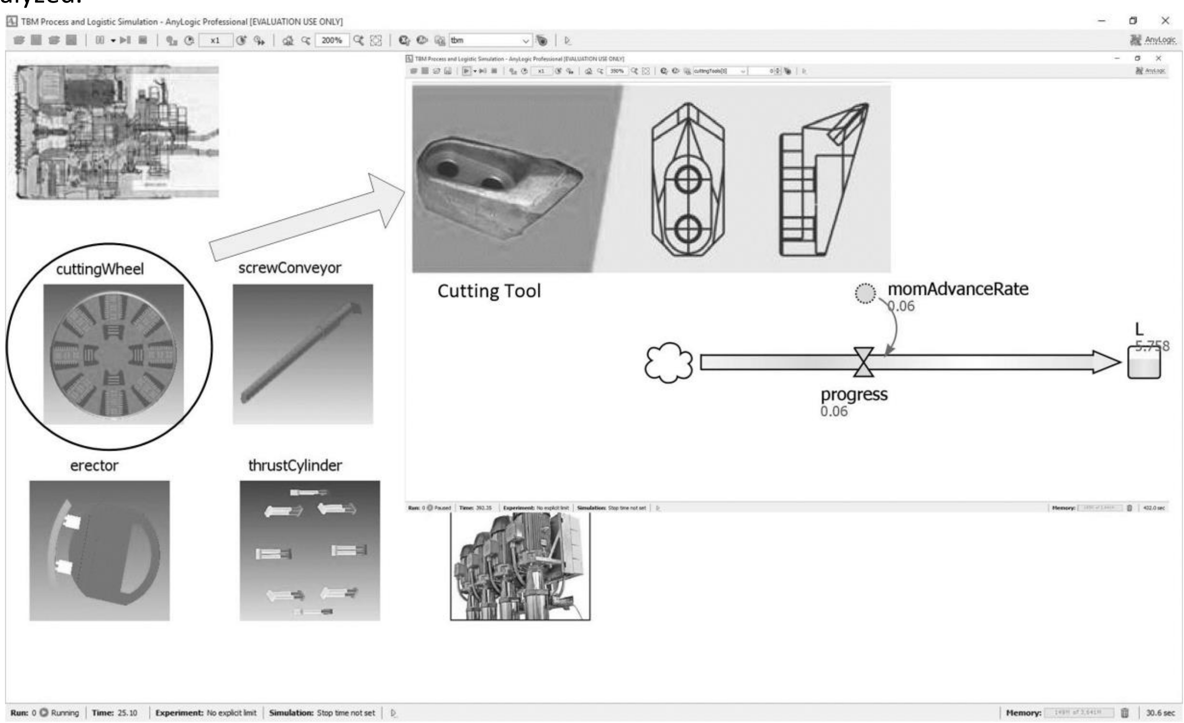

Figure 3: Expansion and modification of existing simulation model

CASE STUDY

The following case study is conducted to test the applicability of the developed model for comparing the performance of four different maintenance concepts. The effects of different maintenance strategies on total TBM performance are measured by total project duration. A TBM expanded tunnel of 3500 meter length was used for the simulation. Table 1 shows the input parameters of the simulation. A probability function was applied to reproduce fluctuations concerning replacement duration of the tools (Table 1).

Table 1: Parameters of the case study

Parameters influencing scheduling of maintenance strategies (case study)			
Parameter	**Strategy**	**Explanation**	**Value**
timePerTool	1-4	Time needed to exchange one tool [min]	Normal(45, 0.5)
critWear	1-4	Wear level to determined tool failure [%]	100
optWear	2-3	Wear level at which tools are replaced preventively [%]	30
optAvgCondition	3	Average condition of all cutting tools at which preventive maintenance actions take place [%}	50
optSupportPressure	3	Support pressure which is assumed to be favorable to conduct maintenance [bar]	2.8
periodicInt	2	Number of rings after which periodic maintenance is conducted [pcs]	50
optWearGreen	4	Level of wear at which tools are replaced under “green” conditions (low support pressure) [%]	40
optWearYellow	4	Level of wear at which tools are replaced under “yellow” conditions (moderate support pressure) [%]	50
optWearRed	4	Level of wear at which tools are replaced under “red” conditions (high support pressure) [%]	60

To achieve comparable results, the strategies are tested on the same geological profile. SAI and support pressure of the exemplary geology are presented in Figure 4. Parameters for calculating the SAI are chosen in accordance with real tunneling projects documented in Köppl (2014).

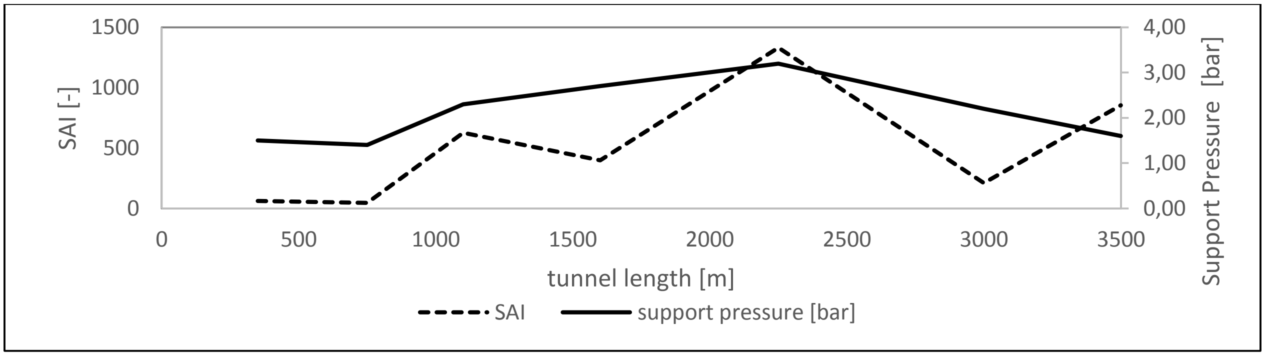

Figure 4: Geological profile of the case study

Results

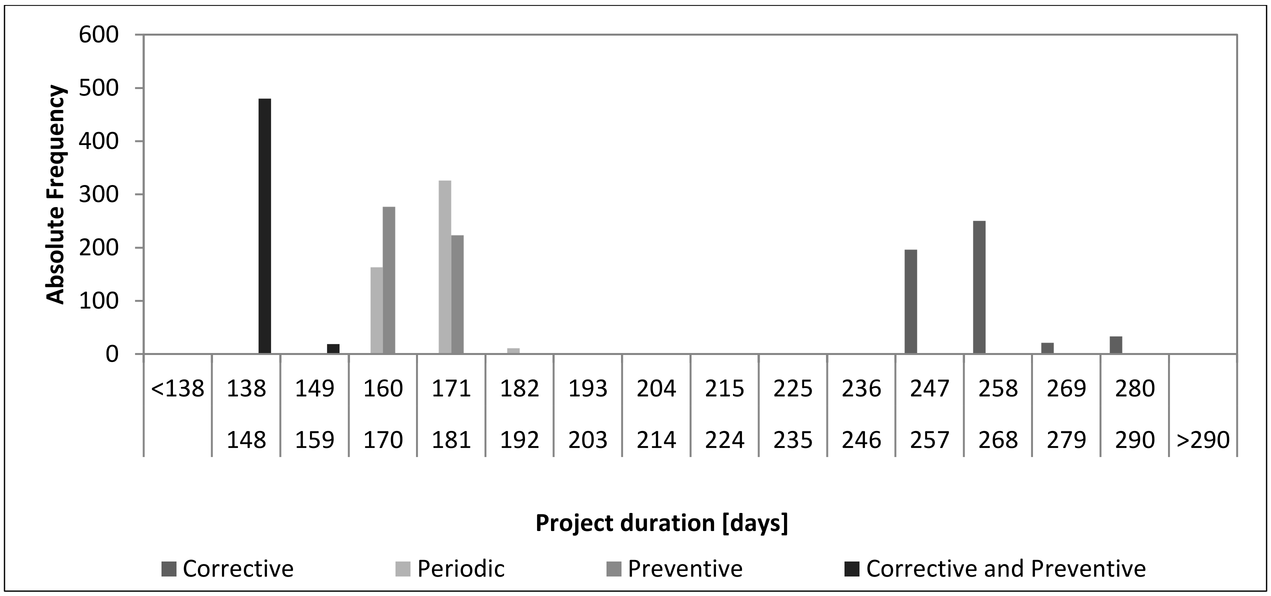

Figure 5: Total project duration of 500 simulation runs for the different strategies

Figure 5 shows the decisive influence of different maintenance strategies concerning total project duration. Following the corrective maintenance approach, project duration accounts for about 260 days. Replacing the tools every 50 rings leads to an average make span of about 173 days and by applying the preventive approach, project duration can be reduced to 170 days. Combining corrective and preventive approach, total make span accounts for 142 days. The case study shows that an effective maintenance scheduling may reduce total tunnel construction span by 118 days. Considering the high correlation between project duration and project costs, the results confirm an immense potential of preventing additional costs by effective maintenance decisions. In future studies, adjustable parameters should be optimized to achieve further performance improvements.

SUMMARY AND CONCLUSION

In mechanized tunneling, expenditures on high safety demands, staff employment or losses due to machine downtime often overweigh actual costs for tool maintenance. For this reason, this paper addresses the influence of different maintenance strategies on project performance. After the expansion and modification of an existing simulation model that displays the basic functioning of a TBM, four different maintenance strategies were analyzed by conducting a case study. Comparing these strategies it becomes evident that the minimum project duration was achieved by preventive and corrective maintenance considering the current position of the TBM and the duration needed for maintenance. The reliability of the model could be increased by adding further system components and by using input parameters deriving from realistic data. Due to the limited data basis concerning maintenance processes, verification and validation of the created model will be part of future studies. Furthermore, future studies should include cost calculation in order to enable an efficient decision making process.

The findings of the conducted case study have to be analyzed critically as many input parameters are based on assumptions or on a sparse data basis. Further investigations have to be made concerning the interaction between soil and cutting tools. In this work, the deterioration of the cutting tool is only influenced by the Soil Abrasivity Index (SAI) of the prevailing geology. The effect of further input parameters (e.g., ground water table, boring speed) should to be examined in more detail by in-situ investigations. Further investigations have to be made to define the risk of entering the excavation chamber realistically. Consequences of running the machine despite use of ineffective cutting tools have to be analyzed explicitly as that might result in an increased rate of failure. To increase the reliability of future simulations, more data on maintenance actions are necessary (e.g., time for exchange process, "penalty" for unplanned stops). The possibility of combining maintenance actions with other actions as shift changes or inspection of other machine parts could also be included.

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