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SIMULATION OF MAINTENANCE STRATEGIES IN MECHANIZED TUNNELING

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ABSTRACT

Mechanized tunneling is one of the most common methods used for underground constructions for infrastructure systems. Since a tunnel boring machine (TBM) represents a non-redundant single machine system, the efficiency of maintenance work highly impacts the overall project performance. The wear and tear of cutting tools is a critical, but mostly unknown process. To plan the maintenance work of cutting tools efficiently, it is necessary to know the current tool conditions and adapt the planned maintenance strategies to the actual status accordingly. In this paper, an existing theoretical empiric surrogate model to describe cutting tool conditions will be used and implemented as a software component within a process simulation tool that manages TBM steering parameters. Further, different maintenance setups for TBM cutting tools are presented and evaluated. To prove the capability of the presented approach, a case study will show the effects that improved maintenance work can have on project performance.

1 INTRODUCTION

To comply with the constantly increasing requirements on the performance of infrastructure systems in urban areas, mechanized tunneling is one of the most common construction techniques for underground structures. The main advantage of using tunnel boring machines (TBMs) in subsurface construction projects is a generally high production performance by simultaneously minimizing disruption of existing surface structures and infrastructure systems. However, tunneling projects must always deal with many individual project specifications (e.g., the tunnel diameter or the available storage space) and uncertain or varying boundary conditions (e.g., ground conditions or process durations). Thus, mechanized tunneling projects are characterized as highly complex systems with sensitive process interactions and process dependencies (Maidl et al. 2012).

Each project setup and TBM design is unique and must be adjusted to the special project demands. A prediction of the TBM performance is indispensable for the project planning but, due to unknown project conditions, still a challenging task. For this reason, in many projects the given project performance does not match the planned project performance (Osborne et al. 2013). The production performance rate depends highly on the actual machine condition and, thus, is related to the quality of the maintenance work. Due to the comparatively long duration of the maintenance processes, detailed knowledge of the current condition of the TBM cutting tools is of crucial importance to achieve a high performance rate. Poorly planned maintenance strategies of the TBM cutting tools can also lead to lower advance rates and a decreased project performance. However, in general the planning of maintenance work is currently based mainly on experience or simplified static dimensioning (Köhler, Maidl, and Martak 2011).

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Wear and tear of the TBM cutting tools are highly related to the prevailing ground conditions (including earth pressure and abrasiveness) and machine steering parameters such as the face support pressure or the cutting wheel penetration rate. The wearing processes of cutting tools operating in hard rock conditions have been a strongly focused topic of researchers in the last few years (e.g., Wu et al. (2010); Schneider, Thuro, and Galler (2012); Wang et al. (2012)). Up to now, for soft ground conditions only few approaches predicting the wearing process of TBM cutting tools exist. As a consequence, for most projects in soft ground conditions periodic maintenance strategies based on pre-scheduled maintenance stops are applied. As a well-known fact, periodic maintenance ignores the current machine condition and can lead to undesirable and avoidable loss of production performance. A condition- based preventive maintenance strategy promises a greater efficiency of maintenance work and, consequently, a reduction of the project duration and potential costs for spare parts.

This paper shows the implementation of an empirical approach to forecast the condition of cutting tools of TBMs operating in soft ground conditions by creating a software component that is integrated within a simulation model. Varying ground conditions as well as different maintenance strategies are taken into account. The generated simulation model is used to optimize maintenance schedules for TBMs by varying maintenance parameters like the minimum average cutting tool condition. This generally leads to more efficient and robust maintenance schedules and can help improve the overall project performance.

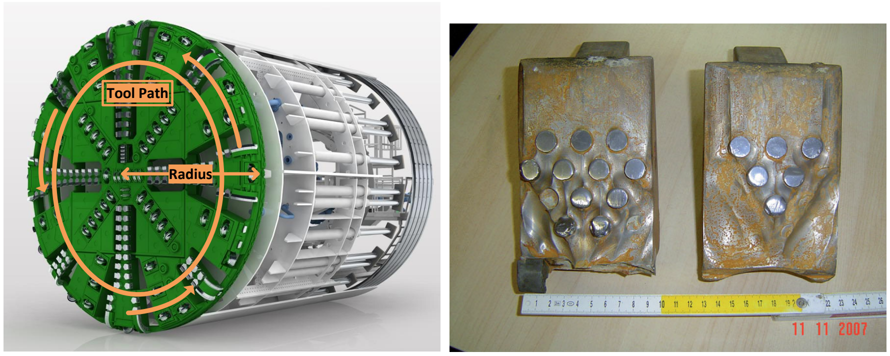
2 BACKGROUND

The planning of maintenance work for TBM cutting tools is a key factor for successful tunneling projects. However, maintenance scheduling for projects in soft ground conditions is mainly based on the experience of the project planners and finished projects often did not attain the expected performance. In the following, the necessity of maintenance work for TBMs is explained. Further, a prognosis model for the wear of cutting tools is presented and a short description of different maintenance concepts is listed.

To excavate the soil, a rotating cutting wheel is pressed against the tunnel face. Cutting tools are arranged on concentric tracks on the cutting wheel (as shown in Figure 1(a)) and in direct contact with the ground. Thus, cutting tools are subject to wear processes and have to be replaced in time (see Figure 1(b)). Replacing cutting tools is still a risky and time consuming process. Whenever a tool reaches a critical wear level and has to be replaced, most processes of the TBM have to stop in order to get access to the excavation chamber and to the cutting wheel. Unstable ground conditions require a pressurized excavation chamber to prevent a collapse of the tunnel face. Thus, releasing the support pressure and conducting maintenance work in an atmospheric pressure condition significantly increases the risk of surface settlements. In case of sensitive surface structures close to the tunnel alignment, this procedure should be avoided. However, when working under pressurized conditions, additional time is needed for workers to adapt to pressurized conditions.

During the advance phase, the cutting wheel is inaccessible. Consequently, observing the actual deterioration process is not possible. Due to a high number of unstable parameters that influence tool conditions, surrogate models for predicting tool conditions become necessary. Regarding the common practice of mechanized tunneling, electrical contacts, which are interrupted at a certain degree of deterioration, are used to check actual tool wear. Precise predictions of cutting tool abrasion is rather uncommon. In the last few years, several research projects focused on developing prediction models that can be applied in soft soils. Köppl, Thuro, and Thewes (2015a) concentrated on the identification and quantification of the main influencing factors that determine cutting tool conditions. Based on data from 18 tunneling projects, they developed an empiric prognosis model for predicting tool wear for soft ground TBMs. Wear level of cutting tools is described by their cutting path along the cutting wheel as shown in Figure 1(a).

The model can be used to estimate distances between maintenance stops under constant advance rate and deterministic values for soil conditions (Köppl and Thuro 2013). Additionally, the required amount of cutting tools to be changed can be determined. Köppl, Thuro, and Thewes (2015b) validated the prognosis model by examining original tunneling projects. In this paper, Köppl's approach is used as a surrogate



(a) Illustration of a TBM cutter head and the cutting tool path on the cutting wheel (Herrenknecht AG 2016)

(b) Wear to soft ground tools (Köhler, Maidl, and Martak 2011)

Figure 1: TBM cutter head and worn cutting tools

model for cutting tool conditions and is implemented within a simulation model to evaluate the performance of the following maintenance strategies.

Corrective maintenance is performed to remedy a malfunction so that the affected component can be restored to an operational condition. The occurrence of technical failures is subject to stochastic functions and disturbances may occur at any time. For this reason, corrective maintenance actions need to be taken into account regardless of the applied maintenance strategy.

Periodic maintenance describes a common maintenance strategy, which is performed regardless of the actual state of the cutting tools. It includes inspecting and maintaining the machine after a certain amount of time (e.g., a given number of operation hours) or at a certain level of production (e.g., after a set tunnel length). Because of the ongoing advance of the TBM, periodic stops are required in order to extend the TBM supply lines (e.g., electric supply or conveyor belt).

Preventive maintenance implies maintaining machine elements even if their condition is probably still satisfactory. This strategy is commonly used in case of critical sections where machine accessibility is known to be restricted. The aim of the preventive maintenance is to avoid production standstills with severe consequences within critical sections.

Application of these maintenance strategies can be linked in any combination to achieve a high quality of maintenance work.

3 LITERATURE REVIEW

Simulation models can significantly support the decision making process in highly complex projects and is well accepted in the construction industry. In general, to evaluate different project setups or maintenance strategies during project execution, monitoring variants of actual TBM operations in the field is often not possible or far too expensive. A digital representation of the real system provides these options and enables a comparison of different setups and evaluation criteria. In the case of mechanized tunneling, several approaches published in the last few years focus on different aspects of tunneling projects. The CYClic Operations NEtwork (CYCLONE) is one of the first approaches to simulate the construction processes, published by Halpin (1977) (see also Halpin and Riggs (1992)). Using the CYCLONE method, Hajjar and AbouRizk (1999) developed a user friendly simulation framework (SIMPHONY) in order to enable the quick and simple creation of special purpose simulations (SPS) (see also Hajjar and AbouRizk (2002)). The City of Edmonton successfully used SPS models based on the SIMPHONY framework for several existing tunneling projects (Ruwanpura and AbouRizk (2001); Fernando et al. (2003); Al-Battaineh et al. (2006); Ebrahimy et al. (2011)). Rahm et al. (2012) started from a process oriented point of view to describe the production processes of a TBM on an increasing level of detail. With a formal system description using the System Modeling Language (SysML) and the modeled process dependencies, the authors could show what impacts malfunctions of single system elements have on the whole production process. The results have been validated using real project data and published in Rahm et al. (2016). Summarizing, the use of simulation models for tunneling projects has already been shown and successfully applied in existing tunneling construction projects.

Concerning the analysis of maintenance processes, a distinction between planning the maintenance process itself and scheduling maintenance actions can be made. In the past decades, several research projects focused on simulation-based maintenance scheduling. Contreras, Modi, and Pennathur (2002) used a simulation model to compare the effectiveness of predictive maintenance with preventive maintenance actions for a distribution warehouse. The results of a case study showed that predictive maintenance reduced downtime by more than 50%. Altuger and Chassapis (2009) implemented a multi-criteria approach to select a preventive maintenance schedule which provides high utility and performance values for line fabrication. A concept to integrate maintenance strategies into a production planning approach using Discrete Event Simulation can be found in Gopalakrishnan, Skoogh, and Laroque (2013). The authors' objective was to investigate to what extent different maintenance strategies influence production performance and the overall robustness of production plans in the automotive industry. Their results show that introducing priority-based planning of maintenance activities has the potential to increase productivity by approximately 5%. In a subsequent work, they implemented the consideration that production bottlenecks may shift from time to time. Thus, they applied a dynamic approach to examine shifting priorities (Gopalakrishnan, Skoogh, and Laroque 2014). Sharda and Bury (2014) developed a Discrete Event Simulation representing a batch chemical production process. They evaluated the impact of changes in the renewal frequency on the total production capacity of the plant. By conducting a case study, they proved that a higher production capacity and reduced costs can be attained by longer maintenance intervals compared to the existing policy. Alabdulkarim and Ball (2014) rather focused on selecting appropriate product monitoring levels for maintenance actions for Product Service Systems (PSS). They applied Discrete Event Simulation for comparing the effect of different product monitoring levels on product availability. An industrial case study showed that higher monitoring levels do not automatically increase product availability, as different system constraints affect the maintenance operations.

So far, the published approaches of performance estimations for TBMs do not consider the impact of cutting tool wear and maintenance processes. However, detailed knowledge of current tool conditions is necessary for the efficient planning of a maintenance strategy.

4 PROBLEM STATEMENT

Inefficient maintenance work of TBM cutting tools increases the risk of accidents, generates avoidable time of standstill and decreases the machine utilization. Therefore, maintenance work should be kept to a minimum. However, maintenance work is also indispensable to facilitate high advance rates and should be extensively planned. Especially, the cutting tools of the TBM must be carefully maintained and spare parts are rather expensive. In short, the planning of maintenance work must consider partially contrary objectives in order to find good customized maintenance strategies:

- minimize the number of maintenance stops and replaced cutting tools,
- avoid maintenance work in positions with unfavorable ground conditions,
- maximize the TBM performance (minimize the project duration) and
- minimize project costs.

5 CONCEPT AND METHOLOGY

A simulation model representing production processes of TBMs and concerning the continuous wear of the TBM cutting tools promises significant improvements in the planning of maintenance works (Mattern et al. 2016). Thus, a multi-method simulation model has been developed, combining both aspects and enabling the evaluation of different maintenance strategies under varying boundary condition.

Köppl, Thuro, and Thewes (2015b) describe the lifetime of cutting tools by them maximum cutting path along the cutting wheel as already shown in Figure 1(a). Thus, the current wear level depends on the TBM advance speed and penetration rate. The penetration rate in [mm/rot] of a TBM is defined by the driven distance along the tunnel alignment during one rotation of the cutting wheel.

Due to the variability of the machine steering parameters and the project boundary conditions, data fitting methods are used to represent these uncertainties in the simulation model. For this reason, the mathematical surrogate model of cutting tools wear in soft ground conditions published by Köppl, Thuro, and Thewes (2015b) is extended by the use of probability functions for essential input parameters. Since the surrogate model for tool condition prediction is based on an empirical evaluation of over 4600 single cutting tools, possible variation of material quality is already considered in the mathematical formulation. The flowchart is shown in Figure 2, illustrating the concept of the simulation-based analysis of maintenance strategies.

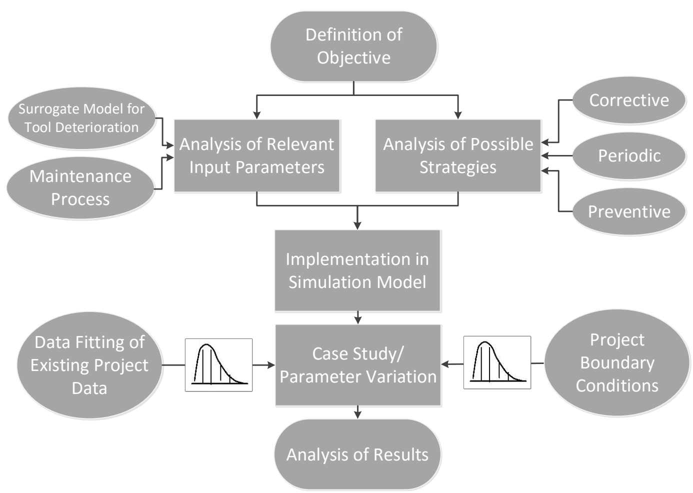


Figure 2: Flowchart of the concept to analyse maintenance strategies in mechanized tunneling.

To represent the production processes of a TBM, the Discrete Event Simulation (DES) method is used. The resulting state chart consists of the two operational states *advance* and *ringbuild*, which are alternately executed. Whenever a tool reaches the critical wear level, corrective maintenance work is conducted. All completely worn out tools should be replaced during this maintenance process. Additionally, a periodic maintenance state represents planned production stops due to, for example, the extension of TBM supply lines. These stops are defined by a maximum advance distance (*maxDistance*) between two periodic stops. During this stoppage, tools below a predefined wear level (*optWear*) should be replaced. To prevent unplanned corrective maintenance work, preventive maintenance is conducted whenever the average condition (*avgCondition*) of the cutting tools reaches a critical, predefined level (*optWear*). In this maintenance process, again all tools below the predefined wear level (*optWear*) are replaced. The formal description of the conceptual state machine is shown in Figure 3. It is visible that the TBM processes are highly simplified and only a part of the whole TBM, in this case the *advance* and *ringbuild* processes, are modeled.

Naturally, production and maintenance processes as well as TBM steering parameters are characterized by varying durations. Consequently, the application of a single, deterministic value to express a processs duration is not realistic. The application of stochastic parameters. Identifying appropriate distributions is normally performed by distribution fitting (or curve fitting) methods. Probability distributions are shaped closely to the histogram of a given data set by varying the parameters of the distribution adequately (Law 2014).

Possible distributions for the input parameters are derived from a database of completed projects and are implemented in the simulation model to generate the required random discrete values.

In case that two or more terms of maintenance processes are fulfilled, periodic or preventive maintenance is conducted. Within this maintenance, the worn out tools are replaced and corrective maintenance becomes needless. Further, periodic and preventive maintenance are planned maintenance stops with equal preparation time.

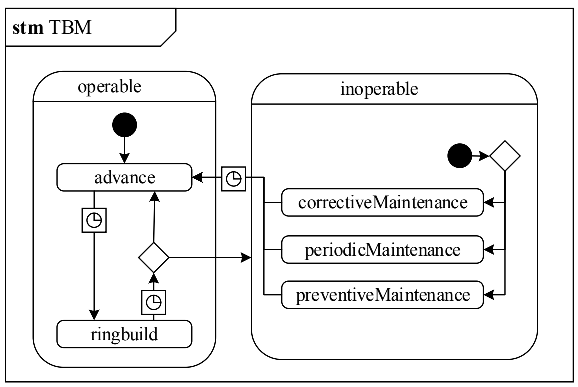


Figure 3: State machine representing the production and maintenance processes of a TBM.

Data: Signal.Maintenance
Corrective Maintenance
if *wear level of one tool* $\geq$ *minToolCondition* **then**
| replace this tool
end
Periodic Maintenance
if *TBM reached maxDistance* **then**
| replace all tools $\leq$ *optCondition*
end
Preventive Maintenance
if *average condition* $\leq$ *minAverageCondition* **then**
| replace all tools $\leq$ *optCondition*
end

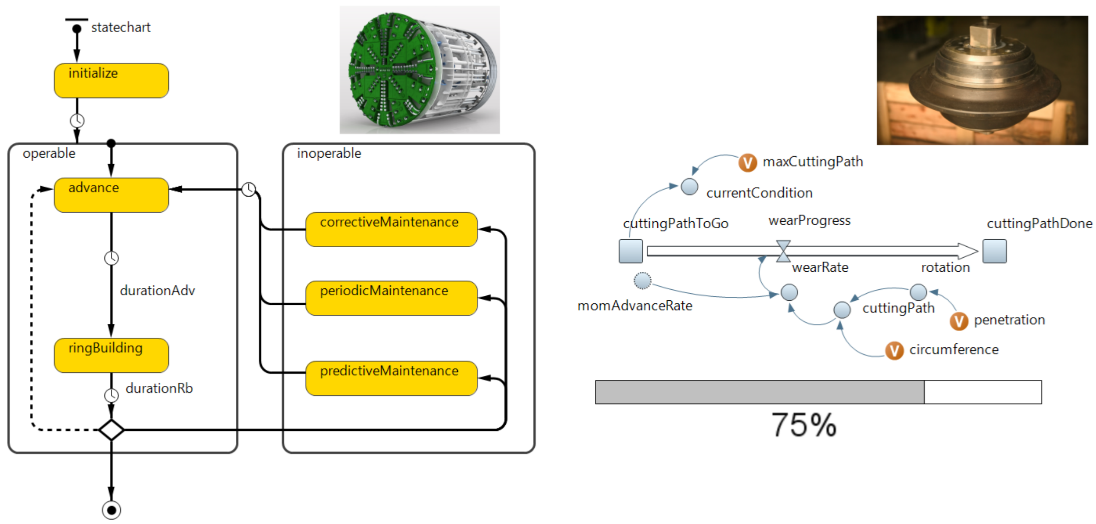
Algorithm 1: maintenanceWork()

As proposed by Köppl, Thuro, and Thewes (2015b), the planned tunnel route should be divided into homogeneous geotechnical sections. Each geological section is characterized by a certain Soil Abrasivity Index (SAI) which directly influences the maximum operation time of a single tool. It is assumed that within each geological section, the SAI remains constant. High SAI values represent high abrasivity and thus an increased wearing of the cutting tools. Detailed explanations for the SAI can be found in the given literature.

6 IMPLEMENTATION

The developed simulation model is closely related to the formal description shown in Figure 3 and represents a simplified process model of a TBM. To evaluate different maintenance strategies, the adjustable simulation parameters *optWear* and *avgCondition* control whether maintenance work is necessary or not. A cutting tool with a wear level which exceeds the defined value *minToolCondition* is regarded as worn out and triggers a corrective maintenance process immediately after the next ringbuild is completed. The duration of the maintenance work depends on the support pressure to allow for adaption to pressurized conditions. The duration further depends on the time for replacing one cutting tool multiplied with the number of tools to be changed and a variable risk index ($rI \geq 1.0$). The risk index also depends on the required support pressure (sP) inside the excavation chamber and includes a safety factor for sensitive surface structures. This risk index is unique for every project and has to be estimated by the project engineers.

The wear of cutting tools is modeled using the System Dynamic (SD) method. All input parameters are taken into account to enable the continuous evaluation of each single cutting tool condition. The DES state chart is connected to the SD wear model to control whenever the machine is advancing and tool degeneration starts. Vice versa, during ringbuild process the tool condition stays constant. Soil parameters and the corresponding SAI, as well as the machine steering parameters are recalculated for every advance cycle and thus directly affect the current wear rate. Variation of *maxDistance*, *minAverageCondition*, *optCondition* and *minToolCondition* enables the evaluation of a single maintenance strategy or any combination of possible



(a) Discrete event model for production and maintenance processes (b) System dynamics model for wear of cutting tools

Figure 4: Screenshots of the implemented model in AnyLogic (7.3.1).

maintenance strategies. In Table 1, value ranges for these parameters and the resulting maintenance strategies are shown.

7 CASE STUDY

To demonstrate the feasibility of the presented approach, a case study was carried out. Doing this, the maintenance strategies for a TBM with a diameter of 10 meter in strongly abrasive geology was evaluated. The tunnel length is assumed to be 2,700 meter with six different types of soil to drive through. Probability functions of the advance speed and penetration rate for the different soil conditions and duration for the ringbuild are identified using data fitting methods on project data of finished projects. Parameters of the suitable probability distribution functions for the advance speed, penetration rate and ringbuild duration for each geological section are shown in Table 2. The duration shows the probability distribution for the assembly of one segment of the tunnel ring and is valid for all geological sections. A tunnel ring consists of seven segments, each with a width of 1.5 meter.

The TBM cutting wheel is equipped with 50 cutting tools arranged on 10 different concentric tracks with a radius between 500 mm and 5000 mm. Thus, each concentric tool track of the cutting wheel is

Table 1: Simulating different maintenance strategies by varying corresponding model parameters.

Parameter				Maintenance Strategy		
maxDistance [m]	minAverageC. [%]	optCondition [%]	minToolC. [%]	corrective	periodic	preventive
infinity	0	0	-	-	-	-
infinity	0	0	[0-100]	×	-	-
$\leq$ tunnel length	0	0	[0-100]	×	×	-
$\leq$ tunnel length	[0-100]	[0-100]	[0-100]	×	×	×
$\leq$ tunnel length	[0-100]	[0-100]	-	-	×	×
infinity	[0-100]	[0-100]	-	-	-	×

Table 2: Probability distribution functions to model TBM advance speed and penetration rate.

Section [-]	Chainage [m]	Advance speed [mm/min]	Penetration rate [mm/rot]	Ringbuild time [min/pcs]
1	500	Weibull-Distribution a = 3.79; b= 39.85; loc= 0	Beta-Distribution p = 3.16; q = 1.10; min = 1.45; max = 21.85	Weibull-Distr. a = 6.67; b = 42.60; loc= 0
2	1100	Weibull-Distribution a = 6.67; b = 42.60; loc= 0	Beta-Distribution p = 3.81; q = 2.64; min = 10.56; max = 21.48	
3	1400	Inverse-Weibull-Distribution a = 2.55; b = 0.06; loc = 0	Beta-Distribution p = 3.09; q = 1.01; min = 0.02; max = 20.04	
4	1700	Weibull-Distribution a = 3.80; b = 28.71; loc = 0	Beta-Distribution p = 3.18; q = 1.44; min = 0.85; max = 18.80	
5	2500	Weibull-Distribution a = 9.64; b = 40.13; loc = 0	Weibull-Distribution a = 12.05; b = 17.34; loc = 0	
6	2700	Weibull-Distribution a = 4.01; b = 18.93; loc = 0	Weibull-Distribution a = 8.34; b = 18.93; loc = 0	

equipped with 5 cutting tools. The six different soil sections and geological conditions are illustrated in Figure 5.

Project performance is measured by the overall project duration and the number of replaced cutting tools. These parameters have a strong influence on the project cost and, thus, should be minimized as already mentioned in Section 4.

It is assumed that the electric supply lines of the TBM is extended every 150 meters. Thus, the *maximumDistance* parameter in this example is fixed to 150 meters or 100 advance cycles. Corrective maintenance is executed as soon as one tool reaches a wear level of 95%. In order to find the optimized conditions where preventive maintenance should be executed, a parameter variation experiment of *minAverageCondition* and *optCondition* within a value range of [0-90]% in steps of 5% was performed.

Since we use probability distributions for each pair of values, multiple simulation runs are necessary. To eliminate misinterpretations caused by possible freak values, we conducted 100 simulation runs per pair of values.

In Figure 6, the average values of the project duration and number of replaced cutting tools of the 100 conducted simulation runs are shown. Conventional project setup with periodic maintenance stops every 150 meter and a corrective policy to replace tools when reaching a wear level of 95% gives a project duration of 163.9 days while changing 515 cutting tools. The shortest project duration of 139.8 days was achieved with a combination of corrective, periodic and preventive maintenance. An exemplary simulation result for one simulation run with is shown in Figure 7. In case of preventive maintenance, the average tool condition triggering preventive maintenance work is set to 50%. In this scenario, when preventive and periodic work is performed, tools with a remaining cutting path below 55% are replaced

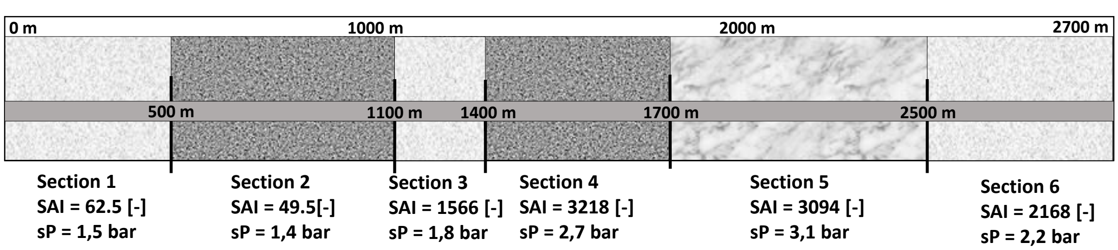


Figure 5: Soil sections and geological conditions.

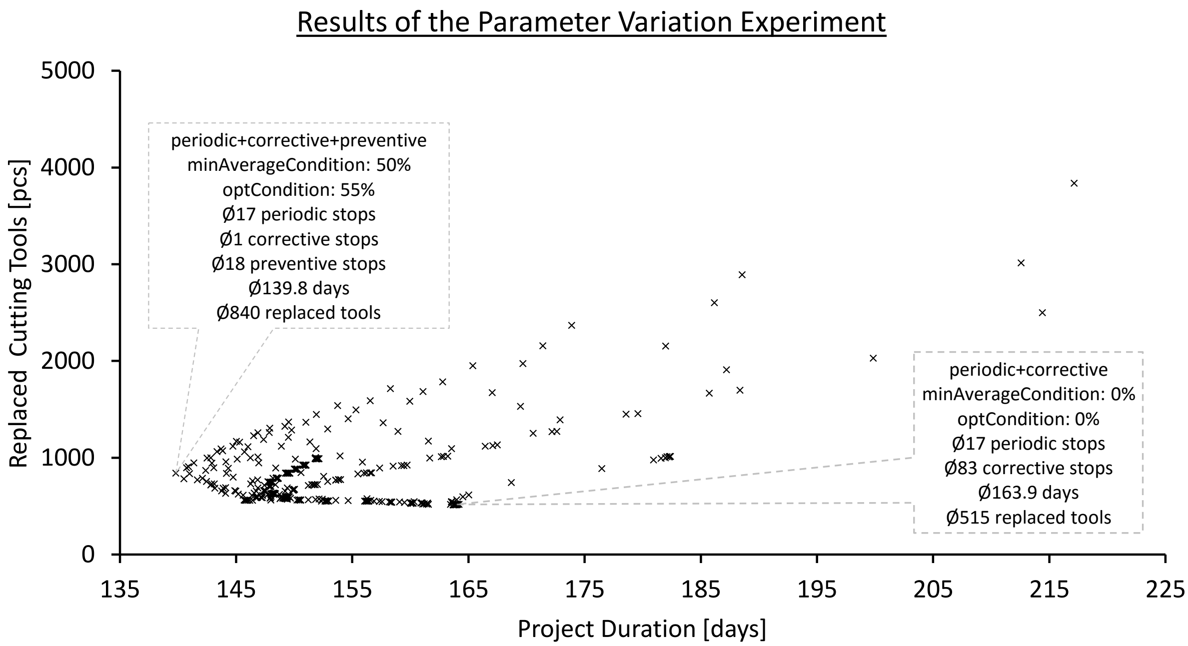


Figure 6: Simulation results of the parameter variation experiment.

(*minAverageCondition* = 50%, *optCondition* = 55%) and results in 840 replaced cutting tools during the project progress. This performance is achieved with a fixed number of 17 periodic and on average 18 preventive and one corrective maintenance stop. It becomes visible that, due to the fixed minimum average condition, preventive maintenance can occur near to planned periodic planned stops. For that case, project planners must decide if a stop is non-essential. To prevent the occurrence of corrective maintenance stops, preventive maintenance should be done whenever the average tool condition is below 60%. This leads to 895 (+6.5%) replaced cutting tools and increases the project duration to 141.3 days (+1.1%). A poorly planned maintenance strategy easily increases the project duration by up to 55% and also significantly the number of required substitutes. However, supporting this multi-criteria decision making, a pareto-optimal solution can be found using the presented simulation model.

8 CONCLUSION AND OUTLOOK

To overcome the limitation in the currently applied maintenance planning methods, a simulation model analyzing the effects of different maintenance strategies to the project performance is presented. An existing theoretical empiric surrogate model to describe cutting tool conditions is implemented in a simulation model and extended by the use of probability distribution functions. Essential soil parameters with a significant influence on the wear of cutting tools are used to predict the tool condition. Production and maintenance processes of a TBM are represented by state charts. By varying maintenance parameters, like the minimum average tool condition, different maintenance strategies are executed and evaluated concerning the influences on the project duration and the amount of replaced cutting tools. For multi-criteria decision problems like the maintenance planning of TBMs, no single optimal solution exists. Thus, the project duration and number of replaced cutting tools must be weighted by the project engineers with respect to project conditions. Doing so, an optimized maintenance strategy for a specific project can be found. The applicability of the approach is shown in a theoretical case study executed with probability distribution gathered from data of finished projects. It is apparent that maintenance strategies significantly affect the project performance.

The implemented TBM processes are highly simplified and further TBM element (e.g. Erector or Grout

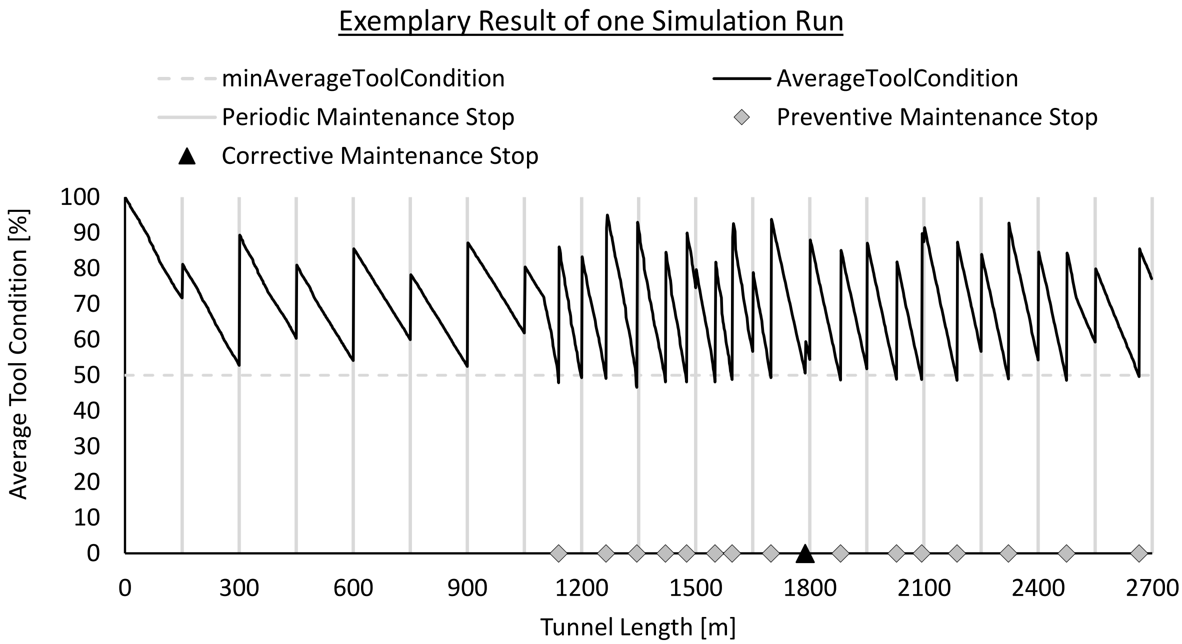


Figure 7: Simulation run with parameter combination: *minAverageCondition*: 50%, *optCondition*: 55%.

Pump) are not considered. Thus, further work should increase the level of detail of the TBM model and possible combination of different maintenance strategies for miscellaneous machine elements.

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