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UNCERTAINTY MODELING AND SIMULATION OF TOOL WEAR IN MECHANIZED TUNNELING

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ABSTRACT

The planning of mechanized tunneling projects requires the consideration of complex constraints and project objectives. Process simulation provides a tool to virtually evaluate different concepts in changing environmental conditions. The consideration of uncertain influences is an essential task within the development of a holistic simulation model. Some aspects (e.g. technical disturbances) can be considered by application of a probability function. However, geotechnical constraints feature a fuzzy nature not well suited for a probabilistic approach. The authors present an approach based on Fuzzy Logic to integrate the performance related influence of wear of cutting tools on the advance rate. The approach is described in detail and demonstrated by an artificial example. Simulation experiments were performed to illustrate the influence of wear on the advance rate in the context of disturbances. This innovative approach to consider such an essential performance factor is another step towards a holistic simulation model of mechanized tunneling projects.

1 INTRODUCTION

The planning of a tunnel project requires the consideration of manifold factors like dimensions of the structure, available space at the construction site, as well as hydrogeological and geotechnical conditions. Additionally the settlements evoked by the excavation process must remain as small as possible. Tunneling with a tunnel boring machine (TBM), including an active face support, is a very common construction method to achieve this goal (Maidl et al. 2012). But since interventions for tool change always increase the risk of settlements, planners try to plan them carefully considering expected wear. The individual project specifications must be considered in both the design and the construction of a TBM (Thewes 2007; Thewes 2010). The very high initial costs of tunneling projects primarily result from the combination of the described degree of individual requirements, the complexity of the TBM system, and the enormous dimensions. In case the anticipated production rate of a tunneling system cannot be sustained, either evoked by unforeseen ground situations or by deficiencies in logistical processes, very high follow-up costs might arise. In addition to that the compulsive sequence of excavation and installation of lining entails the issue that disturbances (i.e. technical failure or lack of required resources) of single machine elements can have significant influence on the performance of their successors. For this reason, failure of machine components, wear processes or organizational deficiencies can lead to significant delays. In case the impact of these disruptions exceeds an acceptable limit, late modifications of the tunneling system must be performed. This leads to the conclusion that the overall performance of a TBM project is not determined by a single process (i.e. speed of excavation or duration of segment installation) but rather by the coordinated interaction of production-related processes and their supply with required materials. Manufacturing quality, operational parameters and maintenance patterns also influence the total project duration significantly as many standstills can be traced back to these factors. This issue demands the thorough analysis of the tunneling process over the complete course of the project prior to the project implementation.

Process simulation has been proven to be an efficient tool for the virtual evaluation of an envisaged machine design and project concept. The simulation model presented in this publication is specified to the Earth Pressure Balance Shield machine (EPB-shield). This type of TBM is the most widely applied type in soft grounds with numerous recent innovations (Herrenknecht, Thewes, and Budach 2011). In order to provide flexibility and to reduce the modeling effort, the established model is based on distinctive simulation components. The occurrence and duration of a disturbance is uncertain, indifferent of the origin. The simulation of technical failure can be addressed with a stochastic approach. The evaluation of machine and project data provides estimations for the probability of occurrence and duration. However, this does not apply to the influence of geotechnical constraints and their influence on the cutting tools. A highly abrasive soil causes a lot of wear on the cutting tools. Obviously, worn tools have a poorer cutting performance than unworn tools. According to Hollmann et al. (2013), the speed of excavation is reduced due to worn cutting tools, in case the forward pressure cannot be increased any further. While the condition of the tools can be measured at least indirectly by observing the operating parameters, an exact statement as to how this affects the excavation is not possible. For this reason, the authors propose a concept based on Fuzzy Logic to integrate the influence of worn cutting tools on the advance rate. The approach influences a specific advance rate for the current ring under consideration of the wear-condition of the cutting tools and the advance rate of the last ring. Detailed information of the concept and the implementation are provided. A representative example demonstrates the concept. Further simulation experiments are executed to illustrate the impact of wear processes in the context of disturbances such as technical failure and logistical disturbances.

2 BACKGROUND

The application of discrete-event simulation to analyze projects in civil engineering is increasing. The first approaches were presented by Halpin (1977) and Tommelein et al. (1994). The scope towards mechanized tunneling was introduced by Ruwanpura, AbouRizk, and Fernando (2001). The authors developed a special purpose simulation tool to analyze tunneling projects and the associated costs. Additional simulation models concentrate on the prediction of the advance rate in varying or uncertain soil conditions (Alvarez Grima, Bruines, and Verhoef. 2000; Chung, Mohamed, and AbouRizk 2006; Likhitruangsilp and Ioannou 2003; Ourdev, AbouRizk, and Al-Battaineh 2007). Shaheen, Fayek, and AbouRizk (2009) published a concept to calculate the advance rate of a specific TBM, considering various influences. They defined a catalogue of eleven aspects comprising influences from soil, TBM, operator experience and shift organisation. The influences are evaluated with a fuzzy logic expert system to predict the advance rate of a TBM project. However, dependencies to the supply chain and required materials are not addressed. Leitner and Schneider (2005) developed an approach to easily foresee the duration of the excavation considering standstills for maintenance and change of the excavation tools. A simulation model for hard rock tunnelling was presented by Donghai, Yunqing, and Jiao (2010). The model considers dependencies to fundamental processes of the supply chain (e.g. muck handling). However, the approaches developed so far, regard mechanized tunneling as a construction method with only one performance determining aspect, namely the speed of excavation. This is partly due to the high modeling effort for the required level of detail and the individual reasons for component failures. Even once modeled, there is little statistical information available for this level of detail as it is not automatically collected by the TBM operator. However, mechanized tunneling is a complex system characterized by manifold interactions and dependencies. The execution of the core processes depends on the timely disposability of required materials. In addition to that, a particular disturbance might affect the execution of another process which might finally again result in a disruption of the progress. For this reason, all performance related disruptions must be modeled in detail.

3 MACHINE TECHNOLOGY

Tunneling in soft ground conditions requires constant counterbalancing of the excavation face to avoid the formation of sinkholes or settlements. Earth pressure balance (EPB) shield machines utilize the excavated soil to transfer the support pressure onto the face. In order to control the pressure at the desired level, advance rate and muck removal rate from the excavation chamber are balanced with each other. Although a good support pressure control already greatly reduces the extent to which settlements occur, there are always some long term settlements to be expected due to the ground disturbance. This process can be partly compensated by the ring gap backfilling at the end of the machine. A slight overcompensation of the gap may counter anticipated mid-term settlements. EPBs are typically used in clayey and silty grounds which have good plastic properties (Maidl et al. 2012). For less cohesive ground conditions it is possible to treat the soil with conditioning agents such as foam, bentonite or polymers in order to extend the EPBs application range. This also reduces wear, clogging and required torque (Budach and Thewes 2010). Looking at the operation of EPB shields, the two core processes *advance* and *ringbuilding* are forming a repetitive production cycle. Both processes rely on a number of logistical processes which ensure sufficient supply with segments, grout and grease as well as constant muck removal. In many projects it is these supporting processes and not the raw drilling speed which limit the total performance of the tunneling system. Therefore a ringbuilding cycle can only be performed when the segments have been delivered and excavation can only be made when muck removal by vehicle or belt conveyor is ensured and enough grout is available. In case there is not enough of any required material at the TBM, the core processes need to slow down or wait for supplies. Another aspect that slows down the advance is the wearout of the tools. Time consuming tool replacements cause the machine standing still and worn tools slow down the excavation process. Therefore a good tool maintenance strategy is very important for the success of a project.

4 PROBLEM STATEMENT

From a general project management point of view on the construction of a tunnel the expected project duration is of enormous interest. Especially for tunnels built by TBMs, the high investment necessary for the related equipment requires precise planning. Experience shows that the actual project duration is greatly influenced by the rate and duration of work interruptions. These can either be caused by technical difficulties, problems within the jobsites internal and external supply chains or maintenance works. Due to the various relations and dependencies between the involved work processes, singular disturbances have different cascading effects on the whole system. Conducting simulation studies prior to project execution allows planners to analyze the effects of different events on the project duration and to adapt the technical system according to their results. In order to gain reliable results from such a simulation study a number of requirements must be fulfilled. The simulation model must reflect processes relevant to performance and include the corresponding boundary conditions. The performance relevant processes can be grouped into four areas, namely the TBM processes, the backup system logistics, the tunnel logistics and the surface logistics. Main influences onto the system lie within the geology, occurring disturbances and their consequences as well as resource supply. Figure 1 gives an overview of these factors which will be discussed in detail below. The theoretical drilling performance is highly dependent on soil conditions and machine properties. Therefore the advance duration depends on advance rate and segment length. Beyond this further influences on performance may arise from the need to protect critical surface infrastructure. The duration of ringbuild is determined by the number of segments per ring and the duration to install each segment. Both core processes are influenced by the capabilities of the logistic systems within backup, in the tunnel and on the surface. Therefore their capacities and layout have a large impact on the performance which can be expected. Since the most important items to be transported are segments and grout, their production, storage and delivery have to be matched in timing with the demand of the TBM. The influences arising from disturbances of all these process chains need to be quantified. Furthermore, additional performance reductions can be result from the chosen technology. An example of such a constraint is the extension of the belt conveyor of an EPB machine. After a certain length (i.e. 200m) of tunneling, the progress must be stopped and the belt is extended by another 200 meters. Furthermore a regular maintenance schedule is usually followed which again influences the probability of technical problems. Maintenance is usually performed at a regular cycle that entails a period of unproductiveness. For this reason maintenance works can be considered as planned downtimes.

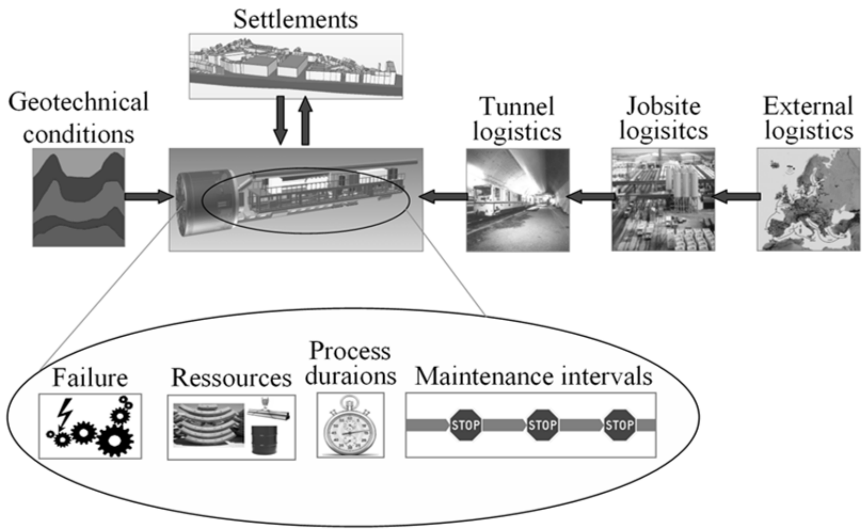

Figure 1: Schematic representation of performance related influences on TBM projects

5 OBJECTIVE

In Rahm et al. (2012) we introduced the multi-method simulation model of an EPB machine. The model is based on distinct simulation modules that correspond with the assembly groups of the real machine. The processes of each component were analyzed and modeled accordingly by application of discrete-event statecharts. For the simulation of technical disturbances, an approach based on the combination of System Dynamics and discrete-event simulation was introduced. The durations of ringbuilding and disturbances are calculated by evaluation of probability functions. In order to determine the duration of excavation a particular advance rate is calculated for each segment. The duration is the result of the advancement rate multiplied with the length of a segment. Shaheen, Fayek, and AbouRizk (2009) introduced a detailed expert system based on Fuzzy Logic to calculate the advance rate of TBMs. The resulting advance rate is the highest possible one according to the prevailing soil conditions and TBM related parameters. Unfortunately, this approach did not include performance reductions resulting from logistic bottlenecks, technical disturbances or wear. For this reason, the estimated maximum speed might not be maintained. This publication presents the evolution of the multi-method simulation model of an EPB machine first introduced in 2012 (Rahm et al. 2012). The enhanced model considers two additional aspects. Firstly, performance losses resulting from weak spots in the supply chain are integrated. The simulation of the supply chain comprises the delivery and consumption of lining segments (related to *ringbuild*) and backfilling grout (related to *advance*). And secondly, the performance reduction caused by worn cutting tools is considered. Thus, results gathered from simulation experiments will be enhanced. Contrary to Shaheen, Fayek, and AbouRizk (2009) the discussed model simulates each distinct advance step. For this reason, the excavation speed might vary from segment to segment. Therefore, the influence of worn tools on each advance step can be considered. However, a formula to express the relation between geological conditions, wear of the tools and the excavation speed with a crisp value is not available. The correlation of these parameters is somewhat fuzzy and uncertain. Taking this uncertainty into account, the authors propose an approach to reduce the advance rate due to the current signs of wear based on Fuzzy Logic. Thus, the presented approach addresses one of the uncertainties related to mechanized tunneling in an innovative manner. The accuracy of the advance rate as an important parameter of the simulation model can be improved. Additionally, the categorization of the wear according to the described fuzzy sets allows the determination of a suitable moment for the change of the cutting tools. This maintenance operation requires several hours. In case, technological constraints or a technical disturbance require a very long standstill, the change of cutting tools might be sensible in order to reduce the total amount of downtime.

6 SOLUTION APPROACH

6.1 Logistical Weak Spots

The simulation model presented in Rahm et al. (2012) did not consider performance loses related to the supply chain. This aspect is remedied in the simulation model discussed in this publication. The operation of a TBM is stringently bound to the disposability of certain resources throughout the operation. The most obvious ones are the lining segments that form the actual tunnel. If the segments are not delivered on time by the MSV or the delivery train the ringbuild cannot be executed. This consequently leads to an unplanned downtime resulting from lack of materials. This logistical disturbance is related to the *ringbuild.* Another essential material is the grouting mortar. The grouting mortar fills the annular gap between segment and soil that is formed when the shield advances. The storage of grouting mortar on the TBM usually just slightly exceeds the amounts consumed during an excavation cycle. Nevertheless, the TBM must not *advance* without grouting. One reason, why the amount of mortar might not be sufficient is again a delay of the MSV or the train. Another reason might arise from the soil conditions encountered. If the infiltration depth of the soil is much higher than anticipated, the demand of mortar to correctly fill the annular gap increases. No matter what the reason is, the advance must be slowed down if not stopped totally if the material is running low. The simulation model implements three threshold values to consider this issue. The first threshold value (20% left of total storage) triggers a reduction of the current advance speed by 20%. In case the remaining grout drops to 10% of the total storage the (already reduced) advance speed is cut in half. Finally, the excavation will stop completely if there are only five percent left. This induces the requirement of not running the grout pumps dry.

6.2 Fuzzy Logic

The theory of Fuzzy Logic was introduced by Zadeh (1965). Zadeh was seeking a way to express statements that are not 100% true or false but rather a bit of both. Fuzzy Logic provides a formal description to express imprecision and uncertainty in a mathematical context. The basic idea is the definition of sets based on multi-valued logic. Each fuzzy set $\tilde{X}$ is represented by a pair$\left(x, \mu_{\tilde{X}}(x)\right), x \in \mathbb{R}$. While, x describes the statement, $\mu_{\tilde{X}}(x)$ defines to which grade the statement is a member of the set $\tilde{X}$. For this reason, $\mu_{\tilde{X}}(x)$ is called membership function and ranges from zero to one ($\mu_{\tilde{X}}(x) \in [0,1]$). Following this, $\mu_{\tilde{X}}(x) = 0.25$ means that x is part of the set $\tilde{X}$ to a grade of 25%. In case Fuzzy Logic is used to regulate a control it is called Fuzzy Control. This multi-value control theorem allows for a calculation of output values according to a set of inputs that is no longer restricted to crisp values like true or false. Furthermore, Fuzzy Control enables the emulation of human behavior, e.g. the stepwise adjustment of a control value (IEC 61131-7 2000).

6.3 Influence Of Worn Cutting Tools

The desired output is the determination of an advance rate in relation to the wear of the cutting tools and the advance rate of the previous excavation step. Following this, wear and previous advance rate represent the linguistic input variables of the fuzzy inference system (see Figure 2). The linguistic variable *previous advance rate* offers the categorization of five fuzzy sets. An advance with up to 15 millimeter per minute (mm/min) is assumed to be *very slow*. The range from 15 to 35 mm/min is considered to be *slow*. A *mod-*

erate advance rate ranges from 25 up to 60 mm/min. A *fast* progress is expressed by an advance rate from 50 up to 90 mm/min. If the advance rate exceeds 90 mm/min the progress is *very fast.* The linguistic variable *wear* is also divided into five distinct fuzzy sets. The presented approach assumes that wear from zero to 20% is considered to be *very low*. Wear from 30% up to 70% is still *moderate*. In case the wear exceeds 90% it is *very high*.

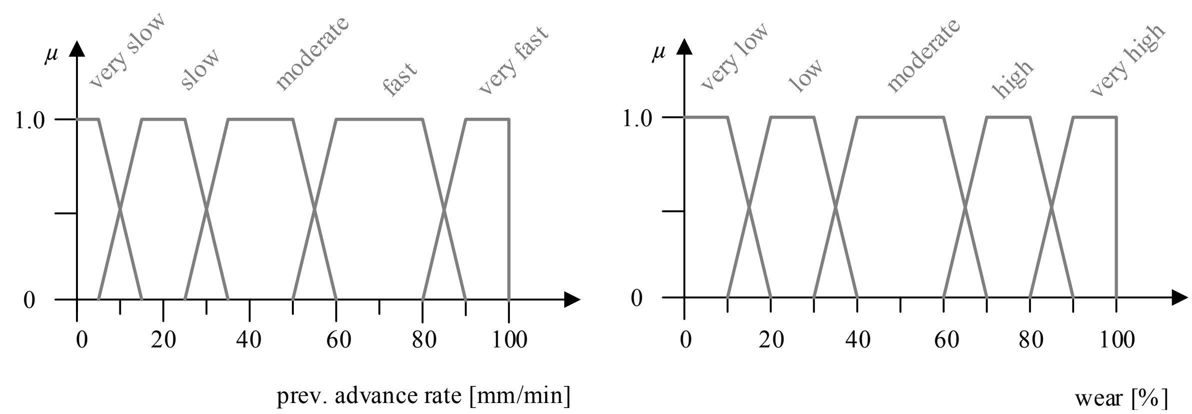

Figure 2: Graphic representation of linguistic input variables previous advance rate and wear

Since the output of the fuzzy interference system is again an advance rate, the classification for the input *previous advance rate* is reused to express the output *advance rate*.

In order to calculate a specific value, subjected to the input variables, a set of deductive rules must be provided. These rules determine how any possible combination of the input parameters must be handled. The set of rules applied for the interference system at hand is given in Table 1. According to these rules, a **very fast** *advance rate* is possible if the *previous advance* rate was **very fast**, **fast** or **moderate** as long as *wear* is **very low**.

Table 1: Set of inference rules applied to define the output a*dvance rate*

		previous advance rate				
		very slow	*slow*	*moderate*	*fast*	*very fast*
wear	*very low*	***fast***	***fast***	***very fast***	***very fast***	***very fast***
	Low	***fast***	***moderate***	***fast***	***fast***	***very fast***
	Moderate	***very slow***	***slow***	***moderate***	***fast***	***fast***
	High	***very slow***	***slow***	***slow***	***moderate***	***moderate***
	very high	***very slow***	***very slow***	***slow***	***slow***	***slow***

7 IMPLEMENTATION

The graphical representation of the linguistic variables depictured in Figure 2 are easy to understand for human eyes. However, a different representation must be applied to consider them in simulation model. For this reason, the Fuzzy Control Language (FCL 2013) is applied. The FCL provides a standard for the Fuzzy Control Programming (IEC 61131-7 2000). The structure of the language is kept clear and simple. The following section briefly explains the transformation from the graphical to a machine-readable representation. At first, the name and corresponding data type of the input and output variables must be specified. The following code statement shows the definition for the presented approach.

```
VAR_INPUT
```

```
    prevAdvanceRate  :    REAL;
    wear:                 REAL;
END_VAR
VAR_OUTPUT
    advanceRate  :        REAL;
END_VAR
```

As a second step, the fuzzy sets (membership functions) of the linguistic variables must be transcribed. The following programming code exemplarily shows the fuzzification of the linguistic variable *wear* (see Figure 2). The wear is divided into five fuzzy sets. All of these sets have a trapezoid shape. For this reason, the coordinates of all four corners are specified. Each pair of numbers in brackets represents a corner. The first number gives the x-coordinate, while the second represents the y-coordinate.

```
FUZZIFY wear
    TERM very low    :=  (0 , 0)  (0 , 1)   (10 , 1)   (20 , 0) ;
    TERM low         :=  (10 , 0) (20 , 1)  (30 , 1)   (40 , 0);
    TERM moderate    :=  (30 , 0) (40 , 1)  (60 , 1)   (70 , 0);
    TERM high        :=  (60 , 0) (70 , 1)  (80 , 1)   (90 , 0);
    TERM very high   :=  (80 , 0) (90 , 1)  (100 , 1)  (100 , 0);
END_FUZZIFY
```

The transcription of the set of rules is showed hereafter. The FCL allows the definition of several rule blocks. However, this is not needed for the presented approach. The first line inside of the rule block defines the Boolean operator and the algorithm to define the membership function of the output variable. Following this, the particular rules are listed as shown in Table 1. The set of inference rules comprises nine rules. However, the example shows only the first since the other rules follow the same principle.

```
RULEBLOCK No1
    AND:        MIN;
    RULE 1:     IF prevAdvanceRate IS slow AND wear IS low THEN advanceRate IS moderate;
END_RULEBLOCK
```

In order to calculate a specific value for the advance rate a defuzzification of the linguistic variable *advanceRate* must be executed. The definition of the fuzzy sets is performed similar to the input variable *wear*. However, the specification of an output value requires the declaration of a defuzzification method. The authors chose the commonly used method *Center-of-Gravity* (COG).

```
DEFUZZIFY advanceRate
    TERM very slow   :=  (0 , 0)  (0 , 1)   (5 , 1)    (15 , 0) ;
    TERM slow        :=  (5 , 0)  (15 , 1)  (25 , 1)   (35 , 0);
    TERM moderate    :=  (25 , 0) (35 , 1)  (50 , 1)   (60 , 0);
    TERM fast        :=  (50 , 0) (60 , 1)  (80 , 1)   (90 , 0);
    TERM very fast   :=  (80 , 0) (90 , 1)  (100 , 1)  (100 , 0);
    METHOD : COG;
 END_DEFUZZIFY
```

8 EXAMPLE

The presented approach is illustrated by an artificial example comprising four experiments. The parameters of this example were assumed by the authors and are not related to any real-world project.

8.1 Project Details

The tunnel simulated in this example has a total length of 8000 meters and a diameter of 10 meters. The tunnel alignment passes three different soil conditions. The first layer is encountered twice throughout the project. The following Figure 3 depictures the soil formations encountered throughout project progress.

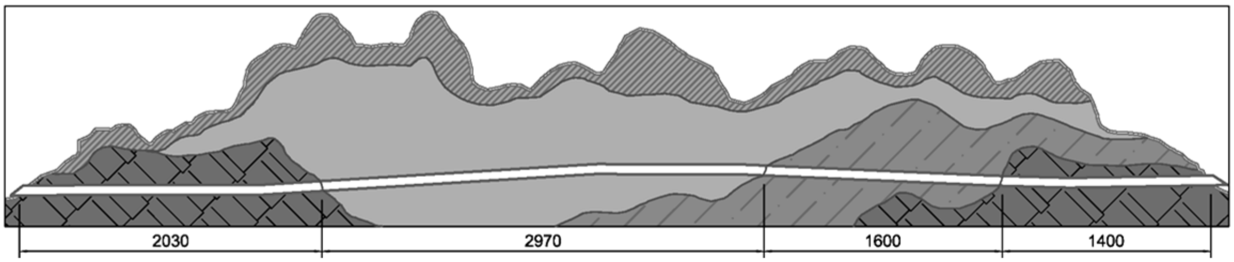

Figure 3: Different soil conditions of the example

The tunnel is constructed by assembling a ring of eight segments (7+1 structure). Each ring has a length of two meters. The transportation of all materials to the backup system is managed by a single Multi-Service-Vehicle (MSV). This MSV drives from the shaft (starting position) to the backup trailer of the TBM. The durations for loading and unloading are considered in the simulation setup. The annular gap (space between segment and soil originating from the shield) is assumed to be ten centimeters. Furthermore, the surrounding soil will consume some of the mortar by infiltration. This simulation model applies a simplification that increases the annular gap and thereby the amount of mortar needed. This simplified infiltration is also calculated by a probabilistic function and ranges from 0 to 10 cm. Thus, the amount of grout required for one ring including infiltration ranges from 2.4 to 4.8 m³. Since the space on a TBM is highly restricted, there is only little storage for the materials. As a result, the MSV delivers grout and segments for only one ring on each trip. The muck is transported out of the tunnel by a belt conveyor. The duration of the ringbuild is the product of the time required to install one segment and the number of segments per ring. The duration for a single segment installation is determined by a triangular probability function. The entire list of input parameter applied in the simulation model, including their value or range, is presented in Table 2.

Tab**le** 2: List of project parameter applied in the example

Name	**Value / Range**	**Unit**
Length of tunnel	8000	m
Diameter of tunnel	10	m
Segments per ring	8	Pcs
Width of ring	2	m
Volume of mortar storage on TBM	5	m³
Annular gap	0.1	m
Infiltration (increasing annular gap)	min = 0 ; mode = 0.05 ; max = 0.1	m
Technical design advanced rate of TBM	100	mm/min
Duration segment installation	min = 3 ; mode = 4.5 ; max = 8	min
Number of MSV	1	Pcs

The duration for the process *advance* is a result of the advance rate and the segment length (i.e. 2 m). The highest possible advance rate is assumed to be the same in the different soil conditions. This assumption is made in order to clarify the performance reducing influences of wear, logistical deficiencies and technical failure. The occurrence of technical disturbances and the corresponding duration of fault remedy are computed by evaluation of probabilistic functions. As discussed in Rahm et al. (2012) every machine element of the TBM can exhibit a technical failure after a particular, but random, period of time. This is expressed in a mean time between failures (MTBF). In case a technical disturbance occurs, the fault remedy depends on the machine element and the type of failure. This time is expressed as the mean time to repair (MTTR). A triangular function is applied to define a value for MTBF and MTTR of a particular component. Table 3 shows the upper and lower bound as well as the mean value of the specific triangular function. Unfortunately, the data accessed by the authors does not contain information about technical disturbances. For this reason, these values are assumptions made by the authors.

Table 3: List of values for the calculation of MTBF and MTTR

Machine element	**MTBF**			**MTTR**			**Unit**
	min	mode	max	min	mode	max	
Belt conveyor	20	100	200	0.1	2	10	h
Cutting Wheel	200	300	1000	1	7	8	h
Erector	300	500	500	3	10	20	h
Grouting Unit	50	250	500	1	2	5	h
Main Drive	400	1000	2000	10	20	80	h
Screw Conveyor	20	150	200	0.1	2	10	h

The influence of wear on the other hand is calculated by the Fuzzy-Logic approach presented in section 6 and 7. This approach requires specific values for the input variable *wear*. In the presented simulation model wear of the cutting tools is expressed by a percentage. Every excavation step this value is increased by a certain amount. This amount is related to the encountered soil condition and determined by sampling a uniform distribution. The ranges of wear per segment according to the three distinct soil layers of this example are presented in Table 4.

Table 4: Ranges of wear in percent per segment for the encountered soil layer

	Min	**Max**
Soil layer 1	0.5	0.8
Soil layer 2	0.2	0.5
Soil layer 3	1.0	1.5

In case the wear of the cutting tools exceeds a specific threshold, the change of tools is mandatory in order to prevent the damage of the mounting of the tools. Therefore, an additional threshold value (95%) is implemented to consider this circumstance.

8.2 Simulation Experiments

The example illustrates the influence of the discussed aspects on the TBM performance. For this reason, four simulation experiments are executed. For each experimental setup only one simulation run is executed in order to provide the comparability of the distinct simulation experiments. Furthermore, the seed value is fixed to regenerate the same sequences of random numbers. The following Figure 4 compares the project makespan according to all four simulation experiments. The first experiment demonstrates the starting point since no restriction to the performance is considered. The TBM executes the excavation with the highest possible speed of 100 mm/min. The undisturbed project execution has a make span of 239 days. The second experiment highlights the influence of technical disturbances and logistical bottlenecks to a TBM project. The project is delayed eight days in total only due to lack of resources or technical disturbances. Following this, the third experiment exemplifies the Fuzzy Logic based approach to consider constraints resulting from wear. The artificial parameters of the example show a major influence on the project duration. The make span increases to 359 days. The last experiment combines all the performance influencing aspects in one simulation setup. The project has a total duration of 385 days. It is clearly visible how the performances of the different experiments decrease constantly. This originates, of course, from the consideration of additional influences on the advance rate. The slower the advance rate is the longer is the duration to excavate one ring. As a consequence, the make span increases.

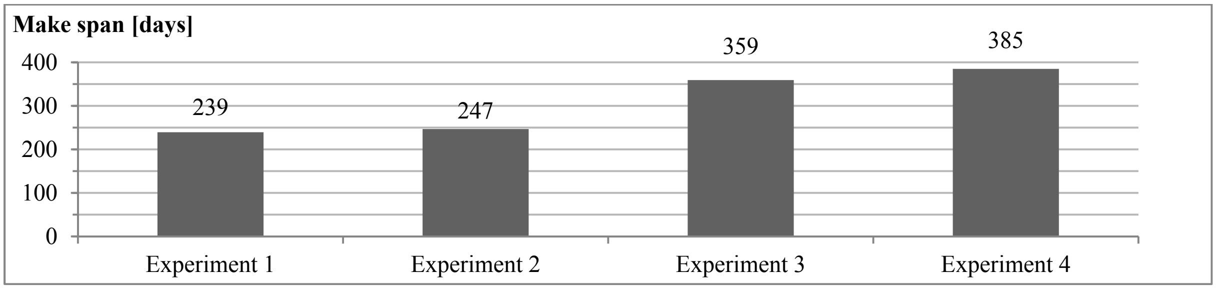

Figure 4: Comparison of the make span of four simulation experiments

Figure 5 illustrates the advance rate simulated in the fourth simulation experiment. It is clearly visible how progressing wear decreases the advance rate. The change of worn tools enables again a faster progress. Furthermore, different compressions of the maintenance cycles can be seen. This indicates the distinct soil layers where various wear per segment is assumed. Another aspect strikes the eye. The highest possible advance rate of 100 mm/min is never reached. This circumstance results from the applied method of defuzzification (i.e. COG) and the shape of the fuzzy set *very fast*. The center of this set only slightly exceeds the 90 mm/min.

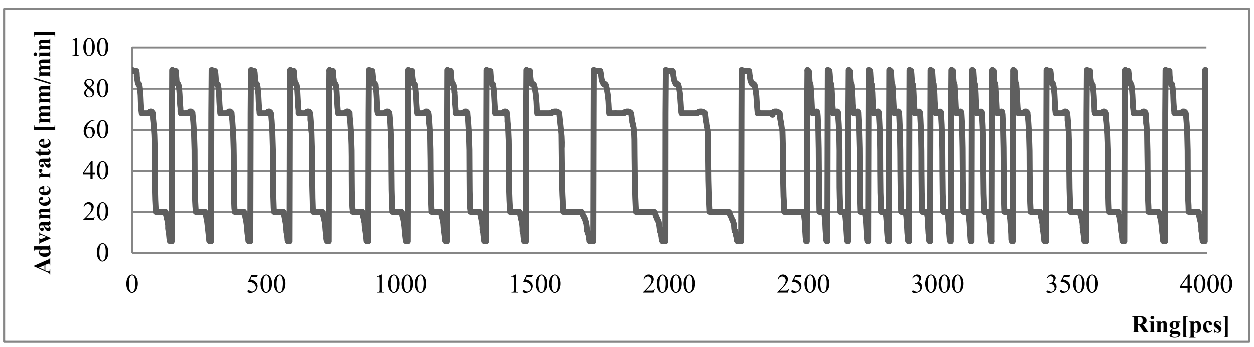

Figure 5: Advance rate for each ring of simulation experiment 4

9 CONCLUSION

This publication presents an approach to consider the effect of geological conditions in a simulation model of a TBM project. The advance rate for a particular ring is calculated by a Fuzzy Logic inference concept. The wear of the cutting tools and the advance rate of the previous ring are evaluated. Corresponding to the extent of these values, the advance rate for the current ring is calculated. Thus, the presented approach provides an innovative possibility to consider the influence of wear on the performance of a TBM project. The authors provided detailed information about concept and implementation. A virtual example visualizes the concept. The correlation of advance rate and wear of the cutting tools is clearly visible. Additional simulation experiments highlight the influence of wear on the overall performance in context with disruptions resulting from logistical deficiencies or technical failure. Future research must address the sensitivity of the Fuzzy Logic approach concerning the definition of the fuzzy sets, the defuzzification method and applied rules. However, the realistic assessment of input and output variables requires a thorough investigations and the evaluation expert knowledge. A more detailed decomposition of the fuzzy sets will improve the smooth operation of the concept. Nonetheless, the authors showed that the approach is applicable to the problem at hand. Finally, the simulation model must be validated with real data in order to progress from the prototype approach presented in this publication. Thus, the consideration of uncertainty in the developed simulation model will strongly enhance the simulation model and gather much more valuable results.

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