Abstract: This paper presents a simulation model, which focuses on the material flow during the excavation process of an Earth Pressure Balanced Shield Machine (EPB-Shield). The dependencies between system elements are being analyzed and rebuilt. The excavation-related machine elements cutting wheel, excavation chamber, conditioning unit and screw conveyor are implemented as reusable and configurable components to create a flexible simulation model. Time-variant soil parameters along the tunnel lining are considered. A simulation experiment demonstrates the dependency of the advancement rate and therewith the overall performance to under-designed downstream elements.

1 Introduction

Nowadays the machine-based tunnelling in soft rock is dominated by Earth Pressure Balanced Shield Machines (HERRENKNECHT et al. 2011). The ability to establish a counterforce that withstands the forces of an unstable tunnel face as well as the wide spectrum of soils where the EPB-Shield can operate efficiently are considered to be the main reasons of its success.

As usual in the construction industry, each tunnel project can be regarded as a unique structure. Nevertheless, the driving processes are always very similar and variations are often limited to the tunnel dimensions and the time-dependant soil parameters. Although very useful, the computer based simulation is still used only sporadically as a planning tool. Until now the few simulation-models that have been developed are mainly focused on the prognosis of the advance rate in different soil conditions (CHUNG et al. 2006 and OURDEV et al. 2007). The material flow of the segment erection, as a part of the advancement cycle, was never analyzed in detail. The duration of the process was only considered as a mean value to the duration of the soil excavation to estimate the total project time (LEITNER et al. 2005).

The EPB-Shield must be understood as a system whose performance is not only determined by the efficiency of the cutting wheel in a certain soil formation. The segment erection is an important part of the whole driving process. Due to the linear arrangement of the machine components and processes, the performance and downtimes of single elements have significant influences to their predecessors. The isolated concentration on the performance of the cutting wheel still leads to misconceptions of downstream elements that must be corrected by enormously time-consuming reconstruction of machine elements during the operational phase. Only in combination reliable knowledge about the material flow processes can be gathered, to reveal optimisation potential in tunnelling with EPB-Shields. The transparent analysis
of different scenarios will reduce faults during the planning phase and result in a more continuous course of project.

Within this paper a flexible simulation model is presented to analyse the interactions and dependencies between excavation processes, supply-chain and support processes. Thereby constraints and input parameters are considered, for example, constraints of the time-variant soil formations.

The aforementioned system elements for the excavation process are modelled as reusable simulation components in the software *AnyLogic* by *XJ Technologies*. The time-dependent parameters of the current soil-formation are considered in the model. The whole concept and the implemented simulation components are verified by a simulation experiment that reveals the dependency of the advancement speed to downstream elements.

### 2 Concept

To model the behaviour of the machine, the system has been analysed in terms of its elements, processes and material flow as well as their interactions. The first step of this analysis is the formulation of a *literal interpretation* of the system to identify the relevant elements and generate a general understanding of the system. The *causal-loop-diagram* derived from this interpretation is afterwards used to display the effective relationships in a mere qualitative way. The method of *System Dynamics* is capable of quantifying these relationships. Following this, the behaviour of the system can be simulated.

#### 2.1 Informal description of the system

Tunnelling with an EPB-Shield machine is characterized by a cyclic advance process. When a certain length is excavated, the erection of the segments begins. After the completion of the ring of segments, the excavation starts over again. Figure 1 shows a cross-section of the machine, where the system can be described as follows (MAIDL et al. 2010 and GIRMSCHEID 2008):

![Figure 1: Cross-section of an EPB-Shield (HERRENKNECHT AG 2011)](image)
The tool-tipped cutting wheel (1) is pushed into the residual soil by the thrust jacks (4), where it loosens the soil in the area of the tunnel face. Through openings in the wheel, the muck spoil can enter the excavation chamber (2). The bulkhead (3) separates the pressurized excavation area from the rest of the machine. The spoil inside the excavation chamber is mingled into a homogeneous mass that could be modified to more processable material by the addition of a conditioning agent. This enables the EPB-Shields to access the operational field of Slurry Shields. The conditioning agent can be added either directly into the tunnel face via the cutting wheel or into the excavation chamber to compensate sudden pressure losses. A pressure tight screw conveyor (5) discharges the muck spoil from the excavation chamber and passes it on to a secondary transporting system that carries it out of the tunnel to the ground surface. The instable geological formation which is often found in soft rock requires security measurements that prevent the arch from collapsing. After a certain length of excavation, the advance must be stopped to erect a ring of segments (7), which prevents the collapse of the tunnel arch during its life-cycle. The segments usually consist of reinforced concrete and are set into place by the segment erector (6). After the erection of the ring, the thrust jacks use the new segments as a new abutment to force the cutting wheel into soil and therewith initiate the next cycle of advancement. The special feature of this machine type is the ability to establish a counterforce medium to withstand instable conditions of the tunnel face. This enables a regulation of the excavation flow which leads to a minimization of the settlements. In order to establish the supporting medium, the soil in the excavation chamber is pressurized until it cannot be compressed any further by the acting forces of water and/or earth. All forces are then in the state of equilibrium.

2.2 Qualitative description of dependencies

The composition and dependencies of the system will be described in a mere qualitative way with the causal-loop-diagram. The graphical representation of the causal relationships is simplified, while still displaying the required information. The causal relationships for the regarded elements are as follows:

1. If the geotechnical parameters of the soil are favorably for the excavation process, the speed of advancement increases. The amounts of muck spoil increases.
2. If the geotechnical parameters of the soil are not favorably for the excavation process, the amount of required conditioning agent increases.
3. The flow into the excavation chamber is increased by muck spoil and conditioning agent.
4. The flow into the excavation chamber increases its content.
5. If the discharge flow is increased, the material flow out of the excavation chamber is increased as well.
6. The flow out of the excavation chamber decreases its content.
7. If the excavation chamber is filled, then further excavation is limited.
8. In case of the restriction (see Nr. 7), the amount of excavated soil is additionally reduced by the amount of needed conditioning agent.

Figure 2 shows the causal-loop-diagram for the above mentioned causal relationships. Relationships are indicated as arrows between two values. A positive polarity between cause and effect is displayed by a plus sign (+) and implies an enhancement/ increase of the dependant value if the origin value is enhanced/ increased. If an increase of the origin value causes a decrease of the dependant value a minus sign (-) is used to indicate the negative polarity (BOSSEL 2004).

Figure 2: Causal-loop-diagram of material flows while heading

The dependencies illustrate the linear arrangement of the process during the excavation works. The one feedback loop leads from the content of the excavation chamber to the excavation volume. If the screw conveyor is not dimensioned in accordance to the performance of the cutting wheel, it may provoke a reduction in the excavatable volume of soil and therewith a reduction of the performance. This feedback loop occurs only if the excavation chamber is filled to capacity.

2.3 Quantification of the material flows

The established causal-loop-diagram reveals the dependencies that lead to dynamic variations of the system, but it is incapable of quantifying them. To overcome this limitation, the stock-and-flow-diagram is used to analyse the quantities of the material flows in the system. The notation distinguishes between stocks, flows and system parameters (BOSSEL 2004 and STERMAN 2000). For each element of the EPB-Shield a stock-and-flow diagram was created to model the system. In this paper however, only the diagram for the cutting wheel is presented.

Figure 3: Stock-and-flow-diagram of the cutting wheel
In Figure 3 the diagram displays the propagation of the volume flow coming from the element *earth* and then being passed on to the *excavation chamber*. The amount of soil that can propagate at each time step is mainly determined by the diameter and the ratio of spacing of the cutting wheel. The length of the *cutting wheel* is needed to calculate the three dimensional stock *Content CW*. The *InputRate* increases the content only during the heading process, whereas the outflow is depending on the external information *Content of EC* and *Discharge Flow*.

3 Simulation model

The Java-based simulation software *AnyLogic* by *XJ Technologies* was used to implement the model. *AnyLogic* enables the simultaneous combination of discrete-event, system dynamic and agent-based simulations. This is important since further work with this model aims to combine the event-driven processes with the system dynamics of the material flow (*XJ TECHNOLOGIES 2011*).

The EPB-Shield is a highly complex system that can be separated in several elements and processes. So far only four elements of the machine and the soil itself have been implemented in a self-contained *Active Object Class (AOC)*, where the information of the *stock-and-flow-diagram* and the formulas for the calculation of the material flows are considered. All necessary attributes, variables and methods for the reproduction of effective structures were integrated in these modules. This modular hierarchy simplifies the creation of new simulation models on the basis of concrete project specifications. Figure 4 shows the composition of the simulation elements and the flow of materials between them.

![Figure 4: Simulation model including propagation of material flow](image)

4 Integration of time-variant soil parameters

Variations in the soil are the main reason for the dynamic behaviour of an EPB-Shield. The geotechnical parameters along the tunnel lining influence the speed of advancement, the performance of the screw conveyor, compressibility and many other system values.

The established simulation model considers changes of the soil as homogeneous sections of a certain length. An Excel-Sheet is used to define the starting and ending point, where all parameters are of a constant value. So far only the parameters of the
density are used to calculate the volume of the excavated soil. A constant rate of conditioning agent is added and the stability of the soil formation is set.

Table 1: Example for homogenous sections of soil

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Section from</th>
<th>Section to</th>
<th>Density moist</th>
<th>Density float.</th>
<th>Cond_Rate</th>
<th>EPB -Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,00</td>
<td>1,50</td>
<td>21,00</td>
<td>11,00</td>
<td>0,20</td>
<td>no</td>
</tr>
<tr>
<td>2</td>
<td>1,50</td>
<td>3,00</td>
<td>20,00</td>
<td>9,50</td>
<td>0,35</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>3,00</td>
<td>4,50</td>
<td>19,50</td>
<td>10,00</td>
<td>0,15</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>4,50</td>
<td>5,00</td>
<td>18,00</td>
<td>9,50</td>
<td>0,25</td>
<td>no</td>
</tr>
</tbody>
</table>

5 Case Study

The following simulation experiment displays the correlation between excavatable soil and discharge flow. The parameters of the elements are shown in Table 2:

Table 2: Parameters of the simulation experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of cutting wheel</td>
<td>10</td>
<td>[m]</td>
</tr>
<tr>
<td>Ratio of spacings in cutting wheel</td>
<td>0,5</td>
<td>[-]</td>
</tr>
<tr>
<td>Penetration rate</td>
<td>2,0</td>
<td>[m/h]</td>
</tr>
<tr>
<td>Length of cutting wheel</td>
<td>0,1</td>
<td>[m]</td>
</tr>
<tr>
<td>Length of excavation chamber</td>
<td>2,0</td>
<td>[m]</td>
</tr>
<tr>
<td>Diameter of screw conveyor</td>
<td>0,4</td>
<td>[m]</td>
</tr>
<tr>
<td>Revolution speed of screw conveyor</td>
<td>1,6</td>
<td>[1/min]</td>
</tr>
<tr>
<td>Filling degree of screw conveyor</td>
<td>0,3</td>
<td>[-]</td>
</tr>
<tr>
<td>Pitch of screw conveyor</td>
<td>0,36</td>
<td>[m]</td>
</tr>
<tr>
<td>Number of screw conveyor</td>
<td>1</td>
<td>[-]</td>
</tr>
<tr>
<td>Duration of heading</td>
<td>90</td>
<td>[min]</td>
</tr>
<tr>
<td>Duration of ringbuild</td>
<td>60</td>
<td>[min]</td>
</tr>
</tbody>
</table>

Figure 5 highlights some results of the experiment. The decrease of inflow at about 35 minutes in the upper plot visualises the change of soil (at 1.5 meters, see Table 1). The second formation of soil is obviously characterised by geotechnical parameters that reduce the volume of excavated soil under the current parameter specification of the machine.
After approx. 55 minutes the filling degree reaches 100% - the excavation chamber is filled completely. At this state the limitation of the inflow down to the performance of the discharge flow occurs. This restriction leads to a reduction of the advancement rate from formally 2.0 m/h to currently 0.72 m/h.

After 90 minutes the heading stops and the ringbuild begins, which has a constant duration of 60 minutes. Since the present soil formation does not require a counterforce medium to withstand the acting forces at the tunnel face, the discharge flow can continue and therewith reduce the content of the excavation chamber. When the heading starts over again (at 150 minutes), the excavation chamber is not totally filled and therefore the advancement rate is not reduced until the full state occurs again at about 185 minutes.

The diagrams display that an inadequate dimensioning or performance of the screw conveyor can result in a drastically reduction of the advancement speed. The enlargement of the excavation chamber is not purposeful in this context, since the necessity of a supporting medium will result in a permanently filled excavation chamber.

6 Conclusion and Outlook

This paper presents a computer-based simulation model of the heading with an EPB-Shield. The machine elements related to the excavation process and the discharge of the muck spoil have been modelled as reusable simulation components, which can be configured flexibly and easily. Time-variant ground profiles can also be considered. This simulation model can simplify and support the planning of machine elements, so that there is no loss of performance of the excavation works due to insufficiently dimensioned downstream elements. Even simple simulation experiments demonstrate
the fact that the overall performance of a TBM does not exclusively depend on the cutting wheel’s performance, but must consider the efficiency of the supply chain elements. The presented model is another step to establish the simulation as planning tool in the construction industry. To complement the simulation of the EPB-Shield, the second core process ringbuild will be modelled. Bearing the cyclic process sequence of the EPB-Shield in mind the total process sequence should be simulated to analyse the interactions, dependencies and impacts between the core processes themselves and the supply-chain or support processes in general. Comparing the simulated data with real project data is the final step to upgrade the simulation model for the use in the field. This comparison will reveal the need for potential corrections of the model due to differences to the real system. The complete and validated simulation model will be a powerful planning tool for the decision-makers in mechanized tunnelling. The planning of a project could become more transparent in regards to construction management and logistics. The unsteady characteristic of the learning curve could be smoothed and therefore enable a constant project progress resulting in a higher overall performance.

7 References


