APPLICATION OF BUILDING INFORMATION MODELLING IN A TUNNELLING PROJECT AND THE DATA EXCHANGE WITH A PROCESS CONTROLLING SOFTWARE

F. Hegemann, J. Stascheit & U. Maidl

Maidl Tunnelconsultants GmbH & Co.KG, Duisburg, Germany

J. Ninić

University of Nottingham, Faculty of Engineering, Dept of Civil Engineering, Nottingham, United Kingdom

ABSTRACT: Building Information Modelling (BIM) is already well known and accepted in the construction of buildings. There are initiatives and pilot projects to also apply BIM for infrastructure projects such as tunnels. However, due the different conditions in tunnelling, where a linear structure is created, the BIM process of building construction cannot be directly adopted. Thus, new BIM processes are required that are tailored to the specific needs of tunnelling projects and that capture the tunnel digitally through all project phases from design to maintenance.

In this paper the generation of the essential BIM models for capturing a tunnel construction process in mechanised tunnelling is introduced. More precisely, a tunnel model with one pipe is modelled where each ring consists of several ring segments. The rings are located along the tunnel alignment to represent the tunnel. Additionally, a 3D ground model is constructed consisting of multiple ground layers. These BIM models are imported into the Desite MD software, which can be used to view and manipulate the BIM models. With the integrated JavaScript functionality of Desite MD, methods are developed to exchange data with the process controlling software PROCON, which stores the measured sensor and construction data of the tunnel advance. In one example of the data exchange, measured data from the tunnelling process is integrated into the tunnel BIM model by linking the data to the corresponding segments of the tunnel. Thus, a holistic BIM model is generated during the tunnel advance containing increasing knowledge, which can be applied for the maintenance of the tunnel after the construction is finished.

1. INTRODUCTION

BIM - Building Information Modelling - is currently receiving great attention in industry and research. At least in building construction, BIM has long since taken on an indispensable role in the design and management of buildings. However, when applying BIM in infrastructure projects such as tunnels, there are still some challenges with respect to curved and line-like structures, or different plan management and contracting. Nevertheless, there are already some uses of the BIM method, which generates added value in all phases of a tunnelling project - planning, construction and operation. This article focuses on the construction phase.

The basis for a Building Information Model is usually a three-dimensional geometric description in different levels of detail. This initially represents the externally visible part of the BIM and, in addition to the visualisation, also allows an easy-to-understand navigation through the project information. Even if the 3D representation can be meaningfully used for a better understanding of complex components, the actual added value of a BIM results from the combination of geometry and information, which extends over all phases of the work. By enabling the assignment of each occurring piece of information and each measured value to the corresponding geometric descriptions of the 3D model in a time-based and location-based manner, intelligent database queries and Big Data analysis methods (Toll et al. 2014) can be applied to generate at any time a very accurate picture of the target and the actual state of the project. Broken down in its temporal evolution, one now obtains a transparent, holistic digital model of the tunnelling process and the tunnel, with which the most varied tasks can be carried out efficiently.

In the construction phase, machine data and further additional information is added as data sources. All necessary data can be integrated spatially and temporally into the BIM. This allows a constant target-actual comparison, which allows adjustments in both directions. If the construction deviates from the plans, this can be quickly recognized and corrected accordingly. If the assumed conditions deviate from the conditions encountered, then the modelling basis can be adapted just as quickly and a corresponding prognosis can be made about the now-expected system behaviour. However, it is important to include only data in the BIM model that is required for evaluations to avoid overloading it and, thus, lose the clarity that makes a BIM model so valuable.

In order to optimally use the aforementioned possibilities and, thus, benefit from the actual added value of BIM in the planning and construction phase of shield tunnels, a clear and simple data integration is required between all participating software modules and service providers. Data integration should possibly be carried out at any time by authorised project participants by pushing a button to prevent complex, error-prone processes. In addition, to ensure time and location independent data integration, it must be automated using secure and compatible interfaces.

2. BACKGROUND

2.1 BIM IN TUNNELLING

Establishing Building Information Modeling for tunnelling projects has already been tackled on several occasions (Vilgertshofer et al. 2016), (Hegemann et al. 2012), (Schindler et al. 2016). Most of these approaches aim at developing a data model based on the IFC (Industry Foundation Classes) (BuildingSMART 2017) format to store and exchange tunnel-relevant data. IFC is a STEP-based standard that was originally developed for building construction, but was extended for the infrastructure sector. In IFC5, many of these extensions, such as IfcTunnel, IfcBridge, IfcRoad or IfcRail, are to be taken into account in order to make the IFC standard usable for infrastructure as well (Amann and Borrmann 2015). Currently, however, these classes are unknown to standard BIM software like Autodesk Revit (Autodesk 2017), Allplan (Nemetschek 2017), Bentley (Bentley 2018), (Bentley 2019) or Desite MD (Ceapoint 2019). Thus, general classes like proxy classes or common building classes have to be applied when capturing tunnelling structures.

2.2 PROCESS CONTROLLING SOFTWARE

In order to ensure an efficient and safe tunnel advance, monitoring of the tunnelling process is imperative. Tunnel boring machines are equipped with a large number of sensors whose measured values are recorded continuously or in short intervals of a few seconds. The accumulated flood of data can only be used for the monitoring and optimisation of the advance, if its semantics as well as the local and temporal position are taken into account and being processed clearly and comprehensibly by an evaluation software (Fig. 3a) (Maidl and Stascheit 2014). The data analysis can be done in many ways: Data from past construction phases can be evaluated to analyse problems, or the tunnel boring machine can be monitored in real time, with corresponding real-time analyses running in parallel. Such a process is denoted as process controlling.

Ultimately, such a process controlling system already represents a BIM in a broader sense, since semantic information is linked to a geometric model of the tunnel which is reduced to the excavation process.

To implement such a central, globally accessible process controlling system, a web application is required that can be accessed from any location via internet. Flexible access to the data is important in order to make data available for analysis and computation to both, different software and different users, at any time and from anywhere. Another advantage of a web application is the variety of interfaces that can be provided for the different types of users like human users or software applications. Human users access the data via the web browser without installing new software and retrieve data from different devices from everywhere. Software applications that require data for calculations or evaluations usually cannot download data on their own. These rely on so-called REST

(Representational State Transfer) interfaces of integrated web services of the web application. REST describes a standard for implementing web services, whereby the focus lies on the machine to machine communication. By means of a REST request, data can be read, edited, generated and deleted. External software applications can therefore use the implemented REST structure to extract TBM data, perform their analyses and calculations, and then write back their results. Fig. 6a shows the architecture of the web application.

3. HOLISTIC TUNNELLING BIM MODEL

For a consistent and holistic modeling of the tunneling process certain information have to be captured. Of course, the tunnel structure itself has to be modeled to store all relevant tunnel data during the construction process. Additionally, the tunnel model can be applied for maintenance purposes when operating the structure. As the tunnel construction mainly depends on its surrounding ground, a ground model is required which stores all required ground information. Thus, to create a holistic tunneling model, at least a tunnel model and a ground model must be generated (Fig. 1).

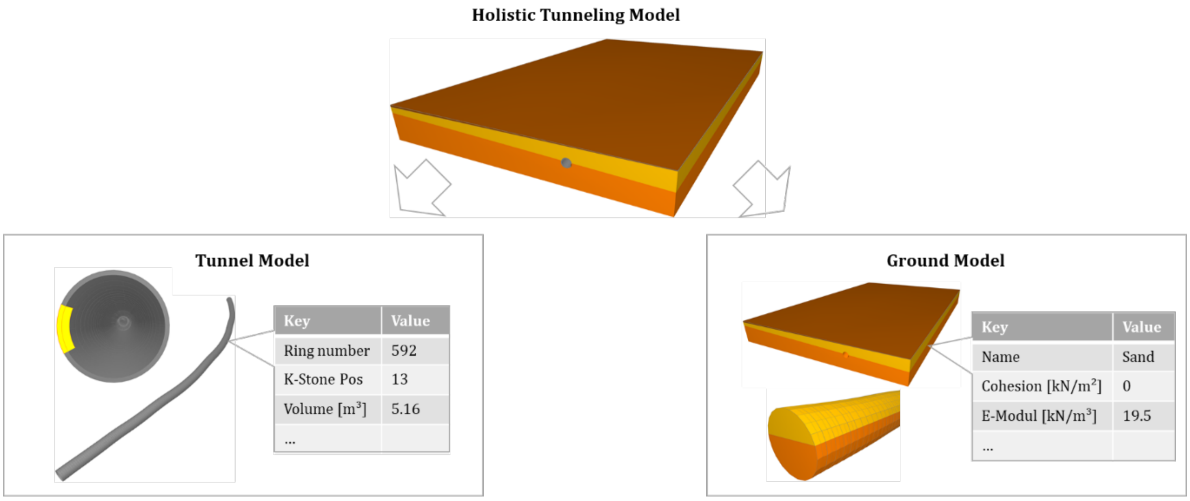

Figure 1: A holistic tunnelling model consisting of a tunnel model and a ground model where the individual objects have assigned semantic information.

3.1 TUNNEL MODEL

The tunnel model represents the tunnel's structure, which can consist of one or multiple tunnel tubes. Along a given alignment, the individual lining rings are placed that form the corresponding tunnel tube. Each of these rings consists of a number of segments depending on the ring system of the project. As each ring is constructed with a specific taper, the rotation of the ring around the alignment axis determines in which direction the tunnel is proceeding. As this process follows certain rules, an algorithm is employed that arranges the individual segments in such a manner that the tunnel structure follows the given alignment. Of course, this arrangement does not define how the tunnel is built at the end, as it is well known that the tunnel follows the TBM. However, it is accurate enough to be applied in the planning phase and small rotations and translation can shift the modelled rings into their final positions when the respective data is provided by the TBM navigation after construction has finished.

The algorithm for generating the tunnel structure can be implemented by any suitable software. Autodesk Revit is one of them and provides an efficient and interactive way for the implementation. The Revit add-on Dynamo enables the user to graphically program certain functionalities. More complex algorithms can be coded directly in Python (Jackson 2011). Thus, Dynamo is an efficient tool to implement the tunnel construction algorithm. The input for this algorithm is the tunnel alignment, which is imported as a DWG AutoCAD file, where the alignment is usually designed. Additionally, Revit families are required for the individual segments of the tunnel. In these families the standard ring information like the outer and inner diameter, width, etc. are applied. By exchanging the Revit families, the same algorithm can be used for any tunnelling project. During the tunnel generation, specific project parameters are added to the individual elements like the ring number or the ring rotation around the alignment axis. This information is required for the final BIM model and will be exported along with the geometry.

3.2 GROUND MODEL

The ground model captures the surrounding ground of the tunnel as well as the expected excavation volume. Each ground layer of the model consists of a number of closed volumetric shells. Thereby, the shape of the tunnel is cut from the ground layers leaving a hole in the layers. Each ground layer has assigned geological parameters giving information about the structure of the ground. The generation of the layers of the ground model should be performed by a geological expert who can create a sufficiently accurate model as the ground represents one of the biggest uncertainties during a tunneling project. The modelling of the layer volumes is usually performed in a design software like AutoCAD that is capable of creating the complex ground shapes. At the end, the ground model is saved in the native file format of the design software. Thus, the ground parameters cannot be added yet. This will happen after the model junction (see chapter 3.3.).

For detailed evaluations of the excavated ground including target-actual comparisons, the excavated ground is modelled, too. Here, for each ring one slice of the ground is generated. The slice has the diameter of the excavation diameter of the machine and the length of the ring. For each slice, one or multiple volumetric shells are generated for each ground layer that intersects with the corresponding ring, respectively. This can be achieved by using the Boolean operation "Intersection" on the ground layers and the corresponding ring volume. Typical design software offers a programming interface, such that these slices can be generated automatically by providing the tunnel alignment and the modelled ground.

3.3 MODEL JUNCTION

Since the tunnel model and ground model are generated by different software, the individual models have to be joined into one holistic model while considering their individual export formats. Therefore, a software is required that is capable of reading many different formats for exchanging three-dimensional models and their properties. Desite MD can handle the required formats and, thus, can be applied to perform the model junction. The tunnel model is imported into Desite MD via a direct Revit interface, which transfers the three dimensional model of the tunnel as well as the individual object properties. The ground model is imported via a DWG AutoCAD file where only the three dimensional model is imported. After the import of the ground model, the individual layers have to be selected and the corresponding ground parameters are added to the layers. To perform this efficiently, the parameters are read from a file (e.g. CSV), where the data can be easily entered.

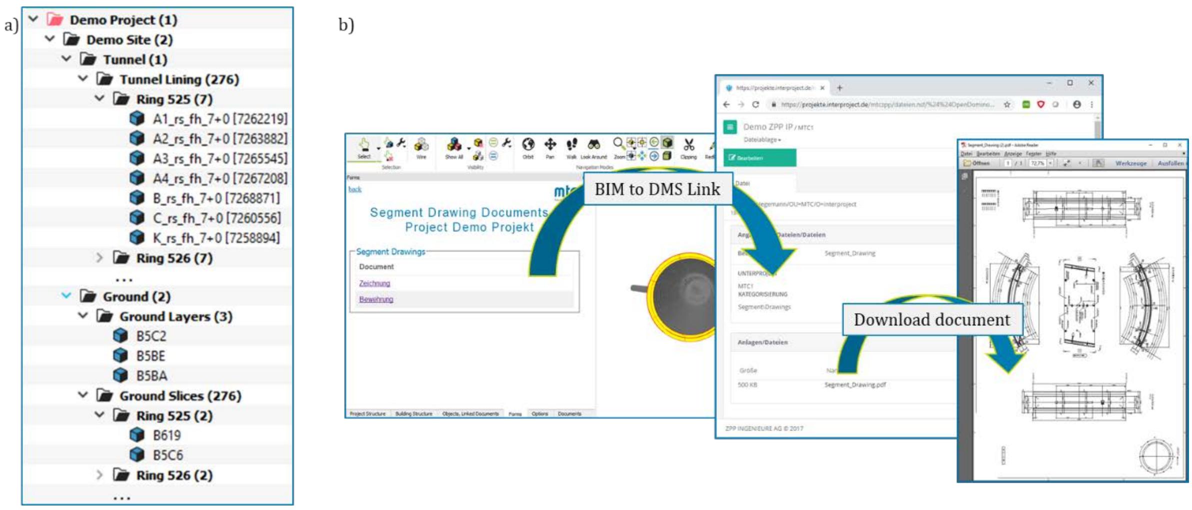

Figure 2: a) Building structure of the holistic tunnelling model; b) Linkage of different document types to objects of the model and opening them in a DMS.

The imported models still represent distinct models in the junction software. Thus, a building structure has to be generated that defines the individual sub-models and their elements (Fig. 2a). Generating an adequate structure is important to easily navigate through the model when targeting specific model information. When generating the building structure, the tunnel and the ground model are represented by a building element (IFC: IfcBuilding) due to the fact that an individual IFC class for the sub-models is still missing in the IFC framework. The tunnel sub-model is further divided by the individual tunnel tubes represented by building storey elements (IFC: IfcBuildingStorey). Each tunnel tube contains one space element (IFC: IfcSpace) for each ring which gets its corresponding segment objects assigned. This assignment is performed automatically based on the ring number property of each segment. This structure is in accordance to the structure proposed in (Vilgertshofer et al. 2016).

The ground sub-model is divided into the two categories “Ground Layers” and “Ground Slices”, each represented by a building storey element. The “Ground Layers” category contains the individual layer objects. One sub-section, in form of volumetric objects, should be added to the model for each ground layer to encapsulate the individual layer volumes belonging to the same layer. The “Ground Slices” category contains the ground slices for each ring. It is structured according to the tunnel tubes of the tunnel model where each ring is captured by a space object which is assigned its corresponding elements. To perform the assignment of the volumetric objects to their corresponding volumetric object automatically, the slice objects require a “ring number” property. While this property is not a priori provided by the design software, for large projects with thousands of rings this assignment can only be performed by an algorithm. Thus, some kind of identifier of the ring is required that can be used by the algorithm. A possible way to identify the rings is an appropriate naming scheme of the AutoCAD layers that are imported into Desite MD. Otherwise, the ring number has to be added manually, which is a tedious and time-consuming task yet needs to be performed only once per project.

After the structuring process of the project is finished, further information can be added to the now holistic BIM model. For example, documents can be linked to specific objects in the model. This can either be physical documents, which are located on the hard drive, or links to documents stored in a web-based document management system (DMS). The connection between the BIM model and a web-based DMS is shown in Fig. 2b.

4. DATA EXCHANGE WITH A PROCESS CONTROLLING SOFTWARE

During the construction phase, data between the BIM model and external applications is only exchanged to monitor the advance, coordinate processes or in accounting. With respect to the BIM software, no design tools are required in this phase. Thus, it is more efficient to use simpler, clearer and more cost-efficient BIM applications without modeling tools. An example is the already mentioned Desite MD, which has an efficient viewer for displaying BIM models and also includes a JavaScript interface to create project-specific evaluation forms.

The JavaScript interface enables the automatic integration of data from external data sources into the model via specific forms. The forms are designed and implemented specifically for this purpose. Thus, a bidirectional communication between a BIM application and an external web application like process controlling or simulation software can be realised via such JavaScript interfaces, frequently using JSON as a data exchange format.

In such a JavaScript-based form, specific REST requests are defined that are adapted to the corresponding interface of the web application. This enables the transmission as well as the request of information from the web application. Thus, the BIM application can request, for example, the actual excavation and ring location from the web application and thereby present the actual state in the model. On the other hand, after a data update, the BIM application can write target data to the web application in order to immediately perform target-actual comparisons of sensor measurements.

Fig. 3b shows the general structure of the communication between a BIM application and a web application for process controlling. The exchange of data takes place via REST interfaces, whereby information is transmitted by means of JSON. The JavaScript form can interpret this format and derive further steps, such as the manipulation of the BIM model. The manipulations are done using the

JavaScript-based programming interface (API) of the BIM application. This allows both changes to the geometry (e.g., coloring of objects) and adaptation of the semantic information of model objects.

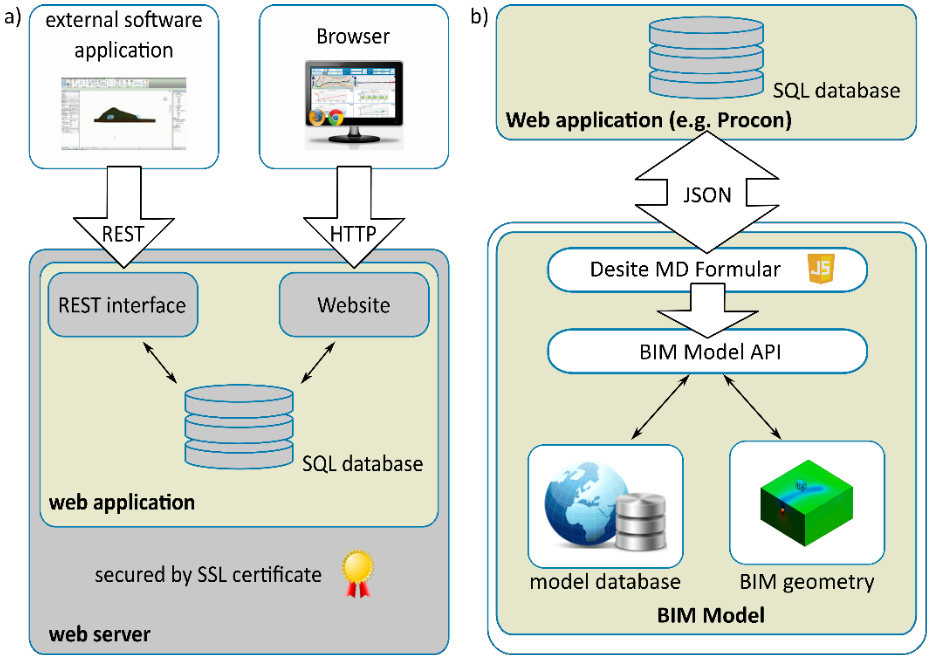

Figure 3: a) Structure of a process controlling software; b) Concept of linking the BIM model with external data sources.

5. CASE STUDY

The presented approach was applied in a case study. In this case study, the tunnel model consists of one tunnel tube with 276 rings. The rings have an outer diameter of 12.0 m, a length of 2.0 m and are arranged from seven segments with a "7+0" system. The ground model consists of three ground layers, where the tunnel is intersecting the bottom and middle layer. The model junction was performed in Desite MD including the assignment of the ground parameters to the corresponding ground layer objects which were read from a CSV file.

The generation of the holistic model was performed as described in chapter 3.3 except the ground layers were directly attached to the "Ground Layers" section as each ground layer consists only of one volumetric shell. The assignment of the ring numbers to the ground slices was done manually as the tunnel consists of only 276 rings. After the structuring process was finished, the complete project was exported into an IFC4 file and reimported into a new project which now has the desired structure with only one model.

Earth pressure data and measurements of thrust force were downloaded from the process controlling software PROCON and assigned to the corresponding segments. For the earth pressure, the minimal and maximal values per ring were extracted as well as the corresponding limits. With respect to the thrust forces, only the maximum values were queried from PROCON as well as their limits. By considering the orientation of the tunnel rings, which is stored in the tunnel model, and therefore knowing the position of each segment, the forces of the individual thrust groups are assigned directly to those segments they actually acted on. This data assignment was performed using a JavaScript-based form, implemented in Desite MD, which was specifically developed for this purpose and can be applied to extract each required sensor data from PROCON. In addition, several documents like the segment drawings, ring building reports, segment production reports, face reports, or borehole reports were assigned to individual objects of the model. These documents are not stored in the BIM model itself but the model contains mere links to the documents stored in a web-based document management system. In this case the document management system Interproject (ZPP Ingenieure 2019) is applied. The links are deposited in the properties of their corresponding object and can either be directly accessed or by using specific forms which filter for specific documents.

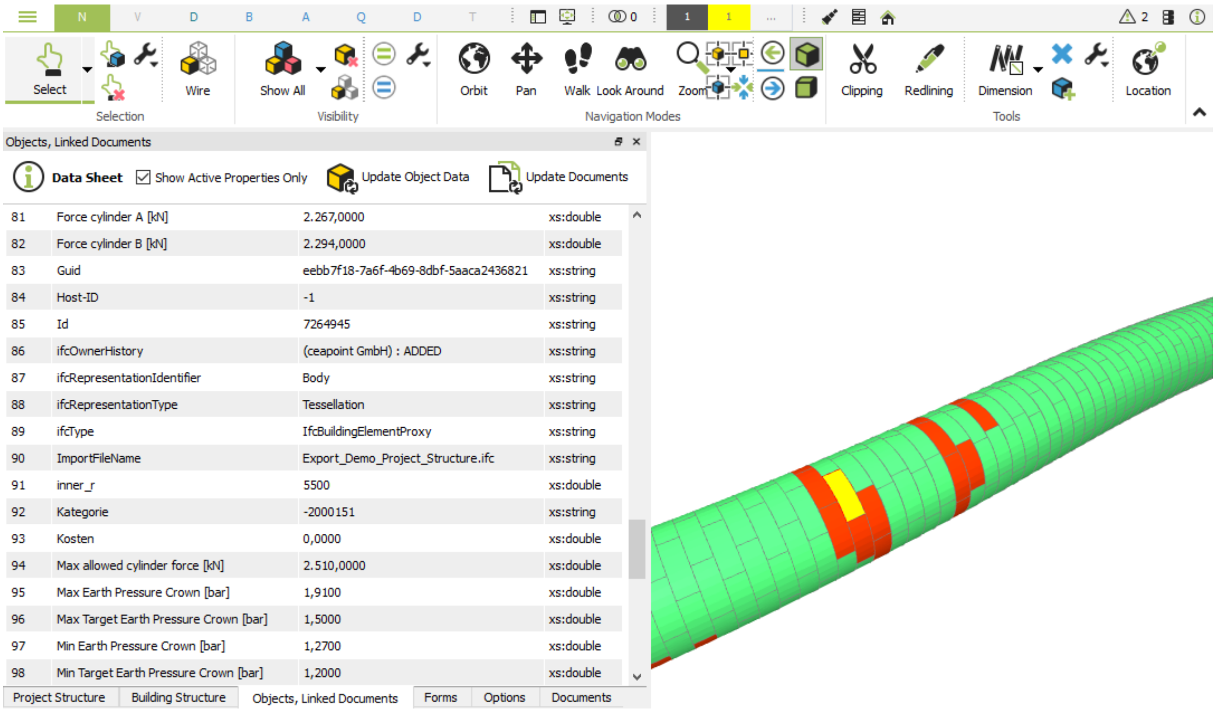

Figure 4: Highlighting of the tunnel model with respect to the force analysis and evaluating the properties of a critical segment.

Based on the integrated model, data evaluations can be performed. To analyse the quality of the constructed tunnel, the extracted PROCON data are evaluated. By highlighting all segments where the thrust force or the earth pressure exceed their limits, the user is quickly informed about critical segments that have to be investigated (Fig. 4). The critical segments can be selected in the model and additional information can be extracted for the investigation. For once, documents relating to the critical segments are easily identified. For example, the segment drawings or segment reinforcement documents can be used to gain information about the resistance of the segments (Fig. 2b). Production documents provide information about the segment production from the segment tracking including the production date, tests, etc. By clicking on the document link stored in the properties of the object, the web page of the document in the DMS is opened in the standard browser of the operating system. This page captures the meta information of the document (e.g. workflow details, uploaded by, etc.) and provides a direct download link of the document (Fig. 2b). In case a more detailed investigation of the critical segment is required, the excavation and ring construction processes can be evaluated by opening PROCON charts out of Desite MD. Custom-designed Desite MD forms provide links to specific PROCON charts containing sensor data like forces, earth pressures, etc. for the selected ring. Thus, the user is able to apply data from multiple data sources at a time to assess the critical segment and the required actions.

Another evaluation investigates the excavated ground volume and ratio. By extracting the excavated volume for each layer and ring from the “Ground Slices” objects, a target value is computed. This target value is exported into a CSV file which can be imported by the process controlling software PROCON. In PROCON, target-actual comparisons can be performed considering actual data from the separation plant and the target values from the BIM model. The described evaluation is presented in Fig. 5.

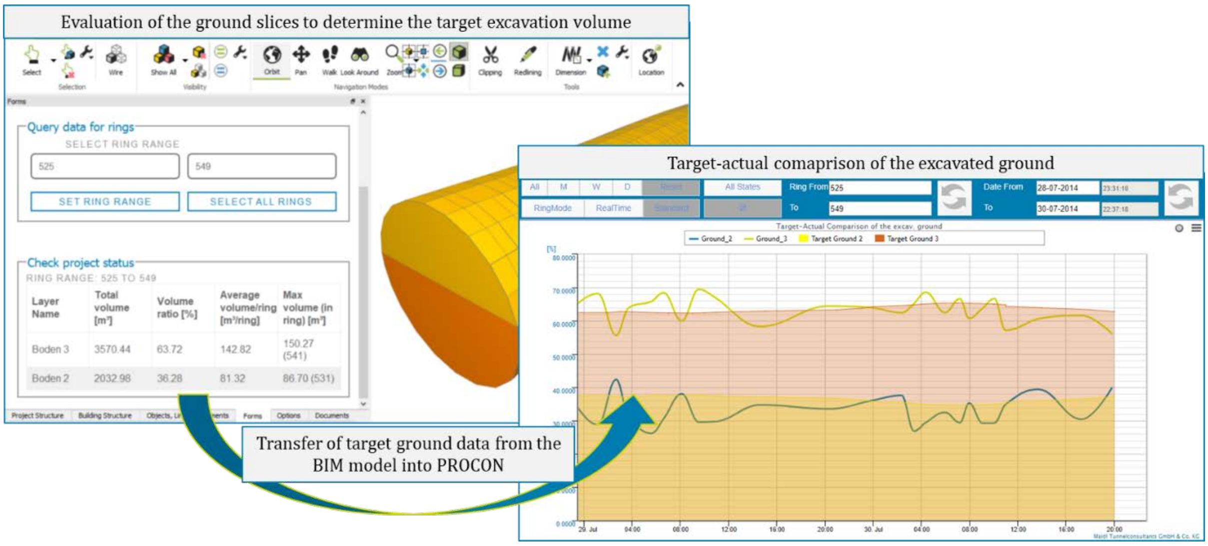

Figure 5: Target-actual analysis of the excavated ground in PROCON while applying the target values from the BIM model.

6. CONCLUSION

The application of BIM in shield tunneling projects presented in this paper shows that there is a multitude of applications for BIM in tunneling that go far beyond pure 3D visualisation and that also offer meaningful application possibilities in the construction phase. Through open interfaces and increasingly compatible data exchange formats, a wide variety of applications can be combined and cooperate with each other on the same database. This not only simplifies data management and consistency, but also opens up the possibility of dealing with complex issues in a short time with sophisticated software tools.

REFERENCES

[1] AMANN, J.; BORRMANN, A. Open BIM for Infrastructure – mit OKSTRA und IFC Alignment zur internationalen Standardisierung des Datenaustausches. In Tagungsband zum 6. OKSTRA-Symposium, Köln, Deutschland (2015).

[2] AUTODESK, Autodesk Revit, http://www.autodesk.co.uk/products/revitfamily/ (2017).

[3] BENTLEY, Bentley GenerativeComponents, https://www.bentley.com/en/products/productline/modeling-and-visualization-software/generativecomponents (2018).

[4] BENTLEY, Bentley MicroStation, https://www.bentley.com/en/products/productline/modeling-and-visualization-software/microstation (2019).

[5] BUILDINGSMART: IFC Introduction. https://www.buildingsmart.org/about/what-is-openbim/ifc-introduction/ (2017).

[6] CEAPOINT, Desite MD / MD Pro – CEAPOINT GmbH, https://www.ceapoint.com/desite-md-md-pro/ (2019).

[7] HEGEMANN, F.; LEHNER, K.-H.; KÖNIG, M. IFC-based product modeling for tunnel boring machines. Proceedings of the 9th European Conference on Product and Process Modeling, Reykjavík (2012).

[8] JACKSON, C. Learning to Program Using Python. CreateSpace Independent Publishing Platform (2011), ISBN: 978-1461182054.

[9] MAIDL, U.; STASCHEIT, J. Real time process controlling for EPB shields/Echtzeit-Prozesscontrolling bei Erddruckschilden. Geomechanik und Tunnelbau 2014, 7, 64-71.

[10] NEMETSCHEK, Nemetschek Allplan, http://www.allplan.com/ (2017).

[11] SCHINDLER, S.; HEGEMANN, F.; KOCH, C.; KÖNIG, M.; MARK, P. Radar interferometry based settlement monitoring in tunnelling: Visualisation and accuracy analyses. Visualization in Engineering (2016).

[12] TOLL, D.G.; ZHU, H.; OSMAN, A.; COOMBS, W.; LI, X.; ROUAINIA, M. (eds.) 2nd International Conference on Information Technology in Geo-Engineering (2014), ISBN: 978-1-61499-417-6.

[13] VILGERTSHOFER, S.; JUBIERRE, J.R.; BORRMANN, A. IfcTunnel - A proposal for a multi-scale extension of the IFC data model for shield tunnels under consideration of downward compatibility aspects In 11th European Conference on Product and Process Modelling, Limassol, Cyprus, 2016.

[14] ZPP INGENIEURE, ZPP INTERPROJECT, https://www.zpp.de/publikation/zpp_produktblatt/zpp_interproject/html5.html#/1 (2019).

Dr.-Ing. Felix Hegemann
Place of work: Maidl Tunnelconsultants GmbH & Co.KG, Duisburg, Germany
E-mail address: f.hegemann@maidl-tc.de

Dr.-Ing. Janosch Stascheit
Place of work: Maidl Tunnelconsultants GmbH & Co.KG, Duisburg, Germany
E-mail address: j.stascheit@maidl-tc.de

Dr.-Ing. Ulrich Maidl
Place of work: Maidl Tunnelconsultants GmbH & Co.KG, Duisburg, Germany
E-mail address: u.maidl@maidl-tc.de

Dr.-Ing. Jelena Ninić
Place of work: University of Nottingham, Faculty of Engineering, Dept of Civil Engineering, Nottingham, United Kingdom
E-mail address: jelena.ninic@nottingham.ac.uk