Tunnel information modelling to support interactions in mechanized tunnelling

Christian Koch, christian.koch@nottingham.ac.uk
University of Nottingham, United Kingdom

Felix Hegemann, felix.hegemann@rub.de
Ruhr-University Bochum, Germany

Markus König, koenig@inf.bi.rub.de
Ruhr-University Bochum, Germany

Abstract
A transparent, holistic and detailed design of individual systems and processes in mechanized tunnelling are essential for a robust and low-risk construction of tunnels. In this context, the complex interactions between the ground, the boring machine, the tunnel lining, the built environment and the flow of production materials play a significant role. Traditionally, the entire tunnel design information is available in the form of independent, dispersed and heterogeneous data files. Since these data sources are barely linked in practice, this leads to unilateral decisions that do not consider all relevant aspects. Existing research has either focused on very general multi-model container approaches that have not been adapted to tunnelling projects, or on semantic tunnel models that solely cover small parts of the entire projects. In this paper a tunnel information modelling framework, basically providing four interlinked sub-domain models and linked project performance data is presented. Due to their distinctive impact on the tunnel design and construction process a ground model, a boring machine model, a tunnel lining model, and a built environment model are first individually created, and then linked within an open IFC environment using the Model View Definition concept. Based on the proposed framework selected case studies are presented to verify its potential and advantages when (1) interactively visualising real time-dependent settlement monitoring data in an environment-aware context and (2) generating advanced numerical simulation models to predict settlements. These case studies are conducted using real project data of the metro tunnelling project Wehrhahn-Linie in Duesseldorf, Germany.

Keywords: Information Modelling, Mechanised Tunnelling, Visualisation, Numerical Simulation

1 Introduction

Due to the ongoing expansion of urban areas worldwide, sustainable solutions must be found to face the challenge of increasing mobility in an efficient and environment-friendly manner. One option is the extension of underground transportation systems using tunnels. The stable, economical and sustainable design and construction of tunnels requires reliable knowledge regarding the expected impacts of the construction method on the built environment. In this context, insights into the dynamic interactions between the geological conditions, the existing infrastructure and the tunnelling advancement process. Mechanized tunnelling is an established flexible and economical construction method for underground structures that is characterized by its trend towards larger shield machine diameters, meanwhile up to 19.25 m, and its constantly growing range of application areas (Guglielmetti et al. 2008).

The construction process using Tunnel boring machines (TBM) involves risks that are related to various factors like surface settlements, gap grouting, face stability etc. Since risk is a combination of the aforementioned factors, their interactions have to be studied and simulated by separate and specialized project teams while designing and constructing the tunnel. Consequently, coordinated interactions of machine operations, surveying, logistics and preliminary investigation processes are very important, especially in case of difficult situations such as the removal of obstructions or tunnelling under sensitive structures. In particular, interactions between the soil, the TBM, the tunnel support system, the above-ground buildings and the material flow play an important role in achieving successful project completions. Therefore, the team members need to collaborate intensively. As a result, large amounts of data are generated, including data gathered during previous site investigations, data from the design stage, and data obtained from measurements made during the advance.

The project data that is shared among the team members varies in terms of type, scale, format and life cycle phase. While some data is used to describe the structural behaviour of the machine, the tunnel lining and the soil, other data is related the site logistics of the entire tunnelling process (type). Difference in model scale refers to the resolution of data items, both in terms of space and time. On the one hand, for example, multi-scale infiltration models require data items in a spatial and temporal resolution of micrometres and seconds, respectively, whereas, on the other hand, site logistics models deal with data items of centimetre/metre and hours/days resolution, respectively. In addition, the project-related data might be available in different formats and from dispersed resources such as texts, drawings, spreadsheets, diagrams or to complex three-dimensional partial models (format). Finally, it is important to recognize the life cycle phase in which the data is being created or used in order to make assumption about the reliability or uncertainty of this data. For example, during the design phase engineers usually work with uncertain soil parameters, whereas during the construction phase they rely on real-time measurements that produce much more confident parameters.

In order to use and analyse this diverse data in an efficient and practical manner, a consistent and holistic information model needs to be provided. Consequently, diverse software applications need to able to obtain required data automatically, efficiently, and in correct type, scale, and format from the underlying information model. Also, results from numerical driving simulations using structural models can be provided by the integrated information model. A further advantage of such a model is the ability to provide a 4-dimensional visualization of the relationships between stored data through mapping in space and time.

This paper presents the development of an integrated tunnel information modelling framework. The holistic tunnel information model consists of several sub-models, which represent the various data sources of a tunnelling project. Based on the proposed framework selected case studies are presented to verify its potential and advantages when (1) interactively visualising real time-dependent settlement monitoring data in an environment-aware context and (2) generating advanced numerical simulation models to predict settlements. These case studies are conducted using real project data of the metro tunnelling project Wehrhahn-Linie in Duesseldorf, Germany.

2 Background

2.1 Current practices in tunnel project data management

Tunnelling project documents are usually available in many different formats and from loosely coupled and dispersed resources (Figure 1). The type and format of data differs widely (e.g. CAD drawings, text reports, spreadsheets and diagrams). This complicates their integration in simulation and visualization models, because required data has to be organized from multiple resources, and documents have to be searched for appropriate parameters. Additionally, these parameters usually have to be manually integrated and updated in case of design changes. Thus, in tunnelling practice, numerical simulation, for example, is still not used to the extent that the possibilities of current simulation models would suggest. This is mainly due to the enormous efforts in the modelling and, in particular, in the collection and integration of all available information on the project in a form that provides automatic model generation for settlement prediction simulations (Guglielmetti et al. 2008, Meschke et al. 2011).

In practice, data exchanges between numerical calculations and simulations during the planning phase of tunnel projects are often performed manually and, therefore, very rarely. However, various data management systems exist that are used by construction companies, engineering firms and equipment manufacturers to manage data for large construction projects, usually with the goal of controlling project costs. The focus of these systems is mainly to efficiently structure the large amount of raw data generated during a tunnelling process (Guglielmetti et al. 2008). In general, (Scherer & Schapke 2013) conclude that the prevailing heterogeneity of application models and the lack of

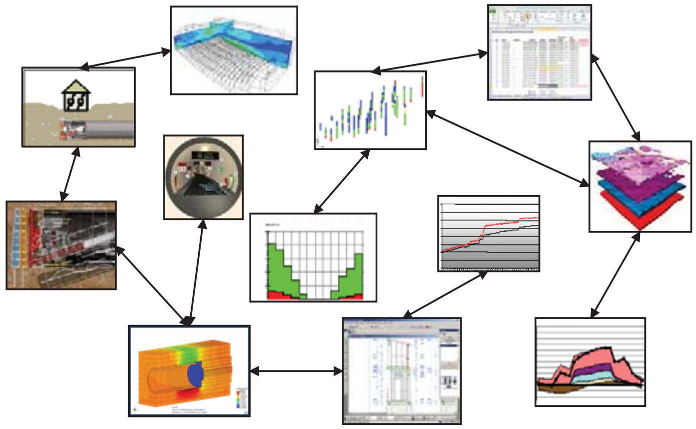


Figure 1 Loosely coupled, unformatted and dispersed tunnel project information in practice

explicitly defined collaboration processes still hinder the efficient collaboration between owners and contractors, because there is little ability to efficiently reuse information from design and ongoing construction execution to analyse the risk and consequences of current planning decisions.

2.2 Research on infrastructure information modelling

Building Information Modelling (BIM) is an up-to-date modelling concept involving the generation and the management of a three-dimensional (3D) digital representation of physical and functional characteristics of a building or construction facility during its entire life-cycle (Eastman et al. 2008). Building information models are commonly used as shared data and knowledge resources to support planning, construction, management, utilization, revitalization, and demolition activities. Although the BIM concept is currently predominantly applied to building construction projects, in many other construction domains it has been considered suitable to provide a methodology for defining information models and supporting a semantically coherent exchange of these models using standardized exchange format, such as the Industry Foundation Classes (buildingSMART 2015).

The use of standardized exchange formats is particularly helpful during the design phase, when many project participants must work simultaneously on different aspects of the tunnelling project. Information can then be exchanged quickly and uniformly. The visualization capabilities using BIM also enable complex relationships to be easily identified. IFC is based on an object-oriented data model and is therefore adaptable and easily extensible. Using IFC, objects to be modelled are first organized into spatial regions, such as building floors, before other physical elements are created and linked to the spatial objects. An element basically consists of a visualization component and a set of semantic information attached to the element. IFC was originally developed for the modelling of buildings, but has now been extended to other fields of application in civil engineering, including bridges (Lebegue et al. 2012, Ji et al. 2011) and roads (Rebolj 2008, Lee & Kim 2011). The modelling of tunnels in shield tunnelling has been presented in (Yabuki et al. 2013, Amann et al. 2013, Borrmann et al. 2014, Borrmann et al. 2015) with an IFC-based multi-scale product model. These product models provide a minimum number of new IFC classes required to represent tunnels and their alignment, and also makes it possible to model various geometric spaces, such as work spaces, to define the complete interior of a tunnel in a hierarchical manner. However, the management of measured data, such as settlements or machine data, or the modelling of the tunnelling machine itself is not provided.

To model large-scale infrastructure, Geographic Information Systems (GIS) have recently been used. However, GIS is predominantly aimed at the management of spatial and geographical data, rather than at the modelling of individual structural details as with BIM. GIS uses the Open Geospatial Consortium (OGC) standard GML as a data model. Several modelling approaches based on GML are GeoSciML (Sen & Duffy 2005), GroundXML based on LandXML (Obergriesser et al. 2009) and CityGML (Kolbe 2009). Since 2012, the CityGML (Groeger et al. 2012) has been accepted as an international standard by the OGC. CityGML was developed for the storage and interoperable access of 3-dimensional models of cities and includes geometrical, semantic and topological aspects (Kolbe 2009). Although CityGML is designed to represent cities, Tegtmeier et al. (2009) have proposed an extension of CityGML which provides further classes for surface-based modelling of geological conditions. Techniques to combine IFC and CityGML are presented in (Isikdag & Zlatanova 2009) and (Hijazi et al. 2011). The approaches described mainly deal with the modelling of building structures and the land-use planning of building construction. A methodology for modelling soil and underground structures is presented in (Zobl & Marschallinger 2008). There, a distinction is made between geological features, such as layers of soil or groundwater, and underground structures, such as sewers or tunnels. The model, however, is designed exclusively for the final product and does not deal with construction related equipment (e.g. TBM) and measurements (e.g. settlements).

2.3 Research on multi-model data management and Linked Data

Based on the heterogeneous nature of construction projects, Scherer & Schapke (2011) have presented a process-centric, multi-model based and distributed Management Information System with the aim of better utilising planning and control models and supporting decision making on all different management levels. They use multi-models as they seem to be a promising approach to support information analysis and collaborative work over multiple application domains. According to (Scherer & Schapke 2011], the fundamental idea of a multi-model is to combine distributed application models, or selected views of them, in a single exchangeable information resource, a so-called multi-model container (Hilbert et al. 2011). Within this container, the application models, e.g. building model, cost model, project schedule model, are bound together by a link model that explicitly specifies the interdependencies among the different application models referencing the respective model elements by their unique identifiers.

In order to improve the information exchange with various sources outside traditional BIM environments Linked Data and Semantic Web technologies have been applied to Architecture, Engineering and Construction (AEC). Curry et al. (2013), for example, have proposed cross-domain AEC data sharing and integration by means of Linked Data as a technology for cloud-based building data services. They have demonstrated their approach in an owner-occupied office building within the context of building energy performance. Corry et al. (2014) have used Semantic Web technologies to access soft AEC data across various stakeholders for the purpose of optimising building performance. They conclude that much more research is needed to arrive at a robust building management framework that drives operational efficiency.

2.4 Problem statement and objectives

With regard to tunnel information modelling, existing research has either focused on (1) semantic tunnel models that solely cover small parts of the entire project, e.g. only focus on the tunnel lining structure neglecting essential parts such as the ground and/or the boring machine, or on (2) very general multi-model container approaches that have not been adapted to tunnelling projects. In order to overcome these limitations the objective of this research is to create and verify a tunnel information modelling framework that basically contains and interlinks all relevant tunnelling project data. Due to their distinctive impact on the tunnel design and construction process the ground, the boring machine, the tunnel lining structure and the built environment need to be integrated.

3 Methodology

3.1 Tunnel interaction platform

In order to uniformly access tunnel project data, an interaction platform is proposed (Figure 2a). This platform contains the actual data sources, a multi-model tunnel information container and an integration layer. The integration layer provides a unified interface to various tunnelling software applications, ranging from data processing and visualisation software to numerical simulations.

3.2 Tunnel information model container

All relevant data needed for the planning, construction and maintenance of tunnels is collected, classified, structured and linked into a holistic, object-oriented Tunnel Information Model (Figure 2a) using the concept of a multi-model container (Scherer & Schapke 2011). This fundamental information model forms the basis for all possible interactions of the project teams. In particular, four main sub-models were specified and linked: a ground data model, a TBM model, a tunnel lining model and a built environment model (Figure 2b). These models were chosen to represent the tunnelling process

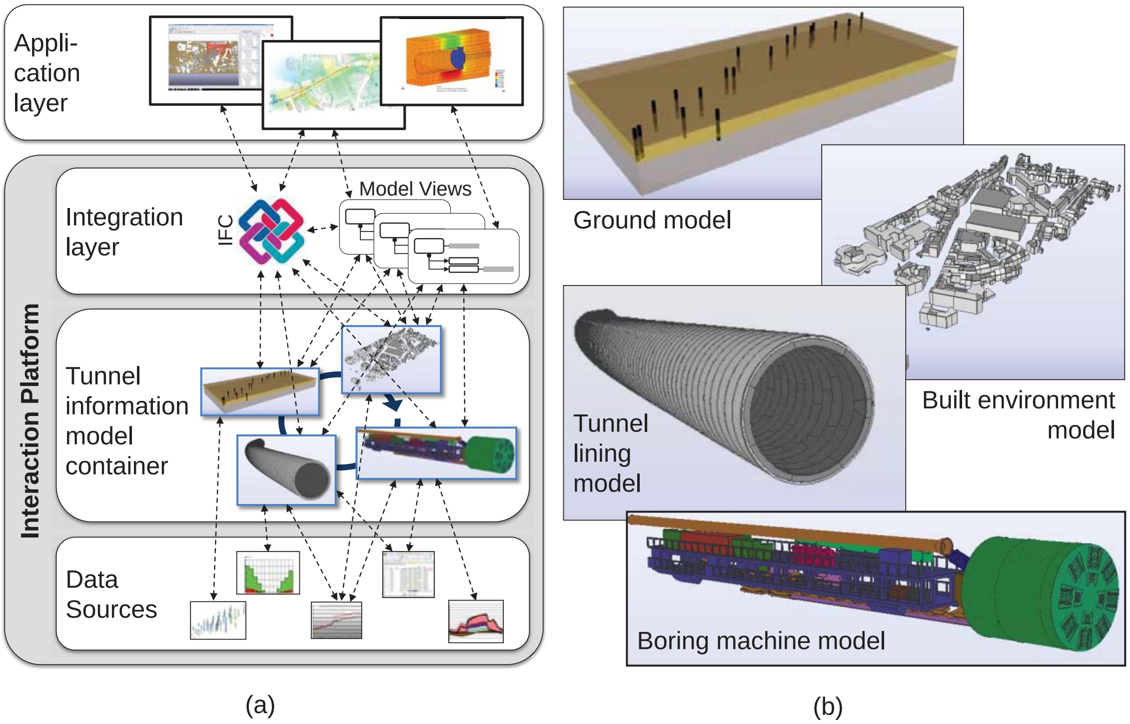


Figure 2 Tunnel interaction platform providing a unified access to project data sources using a tunnel information model and an integration layer (a). The tunnel information model contains of four main sub-models (b)

due to their significance. The built environment model influences, for example, the speed of advancement, the possible settlements or the state of the annular gap grouting.

3.2.1 Ground data model

The ground data model provides the fundamental basis for the detailed analysis of the entire excavation process. On the basis of borehole results, set at strategic places along the proposed alignment, profiles are created which can then be analysed and evaluated to determine individual soil layers and parameters to obtain a geologist's view of the underground for the proposed tunnel alignment. The profiles are stored in the form of so-called surface models (B-Reps) attached with relevant attributes in the hybrid ground data model. During tunnelling, advance exploration in the near field of the TBM is usually carried out continuously and results are carefully evaluated. The exploration information is usually available in great resolution, either as a tensor field or as an attributed point cloud and it is stored as voxel data within the ground data model. Consequently, the ground data model must support both coarse resolution surface data as well as high-resolution underground geology data. Thus, methods for integration, consistency checking, transfer and versioning of surface as well as point data have been developed (Hegemann et al. 2013) to properly manage the ground data model.

3.2.2 Tunnel boring machine model

The TBM is another important element in the context of analysis, planning and execution of mechanized tunnelling projects. The current focus is the use of so-called earth pressure balance (EPB) shield machines, although other types will be considered in future research tasks. A formal description of EPB machines was carried out for the first time using an extension of the Industry Foundation Classes (IFC, see Hegemann et al., 2012). These additional IFC classes represent, in accordance with the existing IFC class structure, spatial areas (IfcSpatialElement) and physical machine elements (IfcElement). Significant geometric and semantic information is thus available for use in interaction modelling. In particular, classes for storing machine and operational data that are dependent on the advancement rate have been implemented, which can set in relation to the physical elements of the TBM. This was necessary in order to provide capabilities to query performance characteristics of the TBM. In Figure 3 the IFC classes for modelling TBM heads are highlighted.

3.2.3 Tunnel lining model

The shield tunnel lining model is based on the Industry Foundation Classes and has been developed in cooperation with the Technical University of Munich (Amann et al. 2013). Analogous to the machine model, classes were specified to model both spatial regions (IfcSpatialElement) and tunnel elements (IfcElement). While the spatial elements represent such regions as the tunnel support system (IfcLiningSpace), the concrete building elements describe physical components such as the ring segments (IfcRingSegment). However, the tunnel model was designed parametrically, in contrast to the machine model. The explicit geometry of the individual tunnel elements will be generated only at program runtime based on the defined alignment. Furthermore, IFC classes have been assigned additional characteristics in order to take into account the temporal aspect of the TBM advancement. This, in turn, supports time-based queries for the developing tunnel structure.

3.2.4 Built environment model

The built environment model includes all above-ground and underground structures in the area influenced by the tunnel. These buildings, especially their stiffness and mass, have a great influence on the size and shape of the settlement trough. Special attention was paid to how the various levels of detail (LoDs) can be modelled. Therefore, the well-established standard CityGML have been applied and extended by specific attributes. The building structures are represented by coarse surface geometries and reduced characteristics (CityGML models with a LoD2 and LoD3) as well as by detailed building models consisting of individual components with detailed properties for each component (IFC models). In this context, urban models in the CityGML format and building models in the IFC format were integrated. In Figure 2b a built environment model using CityGML (LoD2) is highlighted.

3.2.5 Integration layer

Within the frame of an integrated visualisation, the four sub-models are linked on the basis of the Industry Foundation Classes. Sub-models that are not specified using the IFC, e.g. the ground data model, can be exported to IFC files. This provides a unified access to all relevant tunnel project data. Moreover, this procedure offers the advantage of re-using IFC-based viewing and querying tools.

In addition, different Model Views can be specified to define the subset of information in the multi-model container required to perform a specific analysis, for example a context-aware settlement visualisation or an advanced numerical simulation.

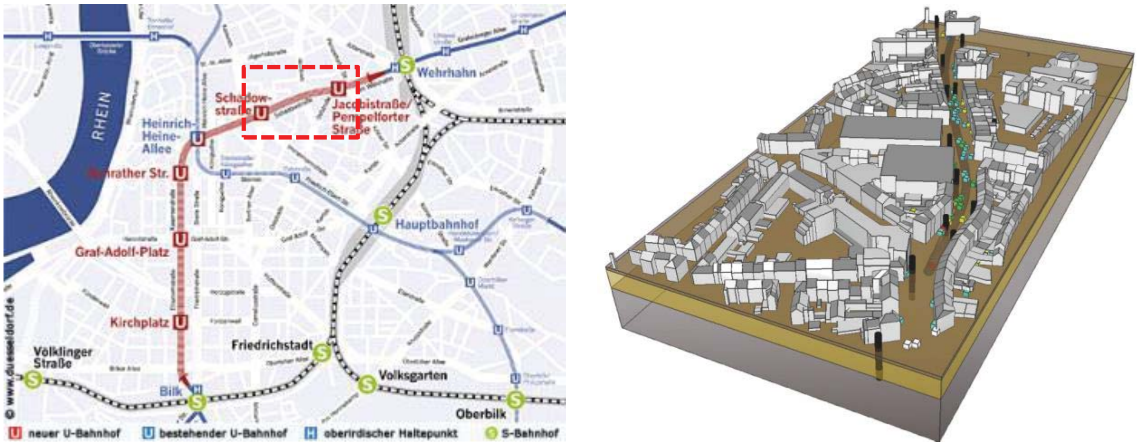
3.3 Application layer

Based on the unified IFC-based access, different applications ranging from data management software, visualisation clients up to numerical simulations can now read the corresponding data from the tunnel information model and provide analysis results in a compact form to the user. By defining a unified interface, various applications can access the web service in a general manner to retrieve data.

4 Case studies

4.1 Wehrhahn-Linie tunneling project

The "Wehrhahn-Linie" (WHL) is a subway tunnel construction project in the city of Düsseldorf, Germany, and will connect the southern district "Bilk" with the district "City Centre". In total a 3.4 km long track will be built by a shield machine (hydro-shield). The outer diameter *Do* of the tunnel is 9.49 m; the average overburden is 1 to 1.5 x *Do*. The tunnel section is constructed with a 45 cm thick reinforced concrete segmental lining. During the approximately 1 km long advance of the east branch ("Ostast") of the project, comprehensive settlement measurements were carried out. For the two case studies described below, a tunnel section between the subway stations "Schadowstraße" and "Jacobistraße" with a footprint area of 730 m x 340 m is examined (Figure 3a). The project period considered contains the shield drive from June to December 2011.



(a) (b)

Figure 3 Wehrhahn-Linie subway tunneling project: (a) Map of the city of Duesseldorf with focus highlighted, (b) Integrated IFC-based visualization of the entire Tunnel Information Model for the extract depicted in (a)

Using the reports on geotechnical investigations, data of 18 boreholes, laboratory test and groundwater measurements along the tunnel route three main soil layers and the groundwater level are identified, each both in terms of geometry and mechanical properties, and implemented in the WHL ground model. The boring machine model consists of a total of 86 elements, of which 54 elements belong the backup equipment part and 32 elements are part of the machine itself. The cutting wheel geometry (Do = 9.49 m) and the total weight of the implemented machine correspond to the TBM actually used in Duesseldorf. For each machine element, both relevant geometric and semantic information is stored. In this case, about 200 to 300 values from about 250 data sources are collected for each ring. This means that about 50,000 to 75,000 values need to be recorded for a single ring. Therefore, only average values from measurements and operating conditions (driving, stopping, ring building, etc.) are stored in the WHL machine model. The WHL tunnel lining model consists of a total number of 534 rings with a mean ring width of 1.5 m. The rings are composed of 7+1 segments and the annular gap grout. The outer diameter of a ring is 9.2 m with a thickness of 0.45 m per segment. Each ring is additionally assigned information about the date of installation and the installation time, including the TBM driving time, length of ring construction and any downtime. The built environment model is generated on the basis of a 3D CAD model of the Capital City of Düsseldorf as laser scan data. In this model, individual buildings are initially separated from each other and buildings outside the model range are removed, resulting in a model consisting of approx. 200 buildings. To account for the buildings above the tunnel axis, for example in numerical simulations, equivalent replacement (surrogate) models of buildings are provided. These equivalent models contain semantic information such as the effective stiffness of the structures or the masses of the buildings. The relevant information is collected, for example, from an extensive analysis of original records of house construction plans. Here, a total of approximately 6,000 settlement data points is available, gained from both terrestrial measurements using classical methods such as tube water levels (550 points) and from satellite measurements (5,500 points). The combined tunnel information model of the Wehrhahn-Linie is depicted in Figure 3b.

4.2 Case study on visualising settlements

Based on the integrated tunnel information model of the Wehrhahn-Linie a dedicated Model View for settlement visualisation is developed. This is done to visualise the advance-driven surface settlements in the context of both the built environment (static) and the dynamic position and performance of the TBM. This allows, on the one hand, to easily identify potentially endangered buildings in the above-ground built environment that are exposed to large settlements. On the other hand, the TBM's operational performance data can be visualized and analysed over time together with the time-dependent settlement values. For example, in case a settlement value is unexpectedly

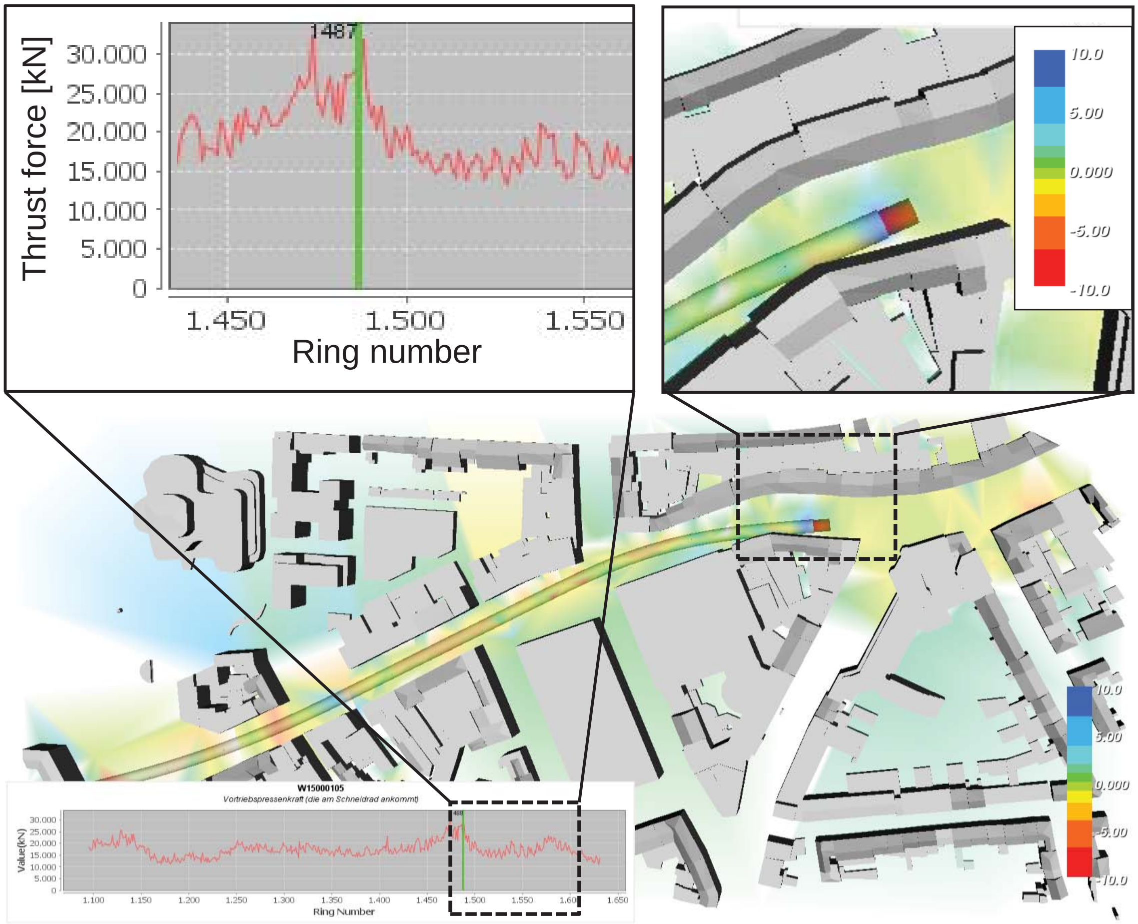


Figure 4 Time-dependent visualization of settlements in the context of the (static) built environment and the (dynamic) TBM performance. Note the high thrust force that is correlated to the heaving above the TBM (best viewed in color)

high, the corresponding thrust force and grouting pressure values can be checked in order to determine the cause.

Figure 4 illustrates a specific real project situation, in which the high thrust force value (Figure 4, top left zoom box, peak in curve) is correlated with a heaving above the TBM (Figure 3Figure 4, top right zoom box, blue colour). According to internal project information, the TBM had to drive through a bearing slurry wall that caused heaving on the surface. This exemplifies and verifies the high potential of an integrated information model when visualizing different interacting aspects of a tunnelling project in order to communicate potential problems and identify correlations.

4.3 Case study on generating numerical simulations

The integrated tunnel information model of the Wehrhahn-Linie was also used to generate Finite Element (FE) simulation models. For this purpose a second dedicated Model View is defined to particularly specify required information about the topology of the ground, the geotechnical parameters of the soil layers, the dimensions and parameters of the surrogate building models, the advance rates of the boring machine as well as measured support pressures and grouting pressures (more details in Schindler et al. 2014).

The procedure of generating FE simulations within the advanced FE framework *ekate* (Meschke et al. 2011) is depicted in Figure 5. In the first step, the relevant simulation are is defined within the context of the tunnel information model in order to specify model dimensions, number of rings and boundary conditions. Based on this, all relevant FE input parameter for the soil, the existing buildings, the TBM and the tunnel lining are automatically extracted. Next, this information is used to prepare an enhanced CAD model that includes both geometry and material information as well as time-dependent operational process data. Following that, the advanced FE framework *ekate* is used to

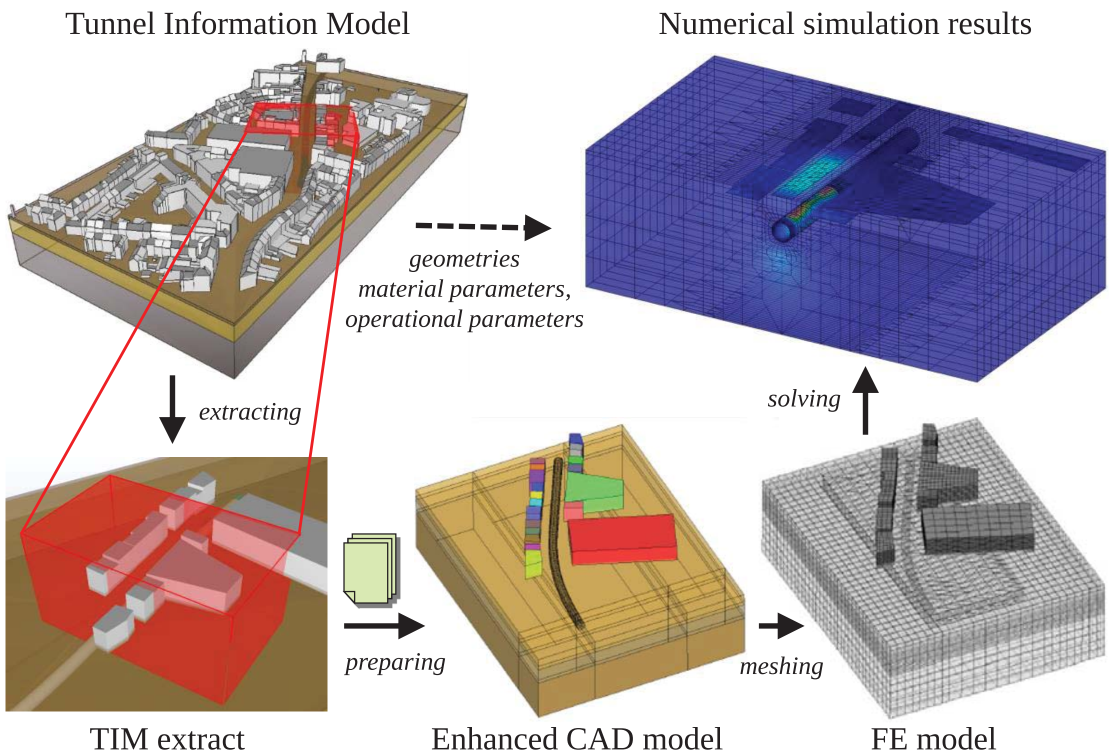


Figure 5 Generating Advanced Finite Element Simulations to predict settlements using the tunnel information model of the Wehrhahn-Linie project

discretise the domain, solve the system and visualise the simulation results (Meschke et al. 2011, Schindler et al. 2014).

5 Conclusions

The complex relationships that arise during the construction of tunnels using TBMs can be merged in corresponding models. Of course, such models require a variety of data, including ground data, tunnel data, data on the tunnel boring machine, but also information about the tunnel logistics and data of the above-ground building structures. Structural models, process descriptions and interaction relationships link the data in an integrated tunnel information model. Investigations can now be performed and evaluated for quantities such as subsidence, fault conditions, or alignment properties. This is useful not only for a holistic anticipatory design process and controlled tunnelling operations, but also for visualization and presentation purposes. The proposed integrated tunnel information modelling framework shows the benefits of such coupled techniques. It helps to better understand the construction process, the evaluation of alignments or construction measures, and also to better access possible risk scenarios and provide options for risk reduction.

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