Highlights

- Integration of information and numerical modelling for mechanised tunnelling
- The BIM-to-FEM concept links an IFC Tunnel Information Model and the simulation model ekate
- The SATBIM framework integrates multi-level information and numerical modelling
- Both concepts allow for an uninterrupted design-through-analysis workflow
- High efficiency in modelling and analysis of tunnelling process is achieved

From digital models to numerical analysis for mechanised tunnelling: a fully automated design-through-analysis workflow

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Abstract

Large infrastructure projects involving the construction of tunnels in urban areas constitute complex, integrated and multi-disciplinary systems, which require building and construction information modelling as well as computational design assessment tools for decision making during all project phases and during their complete life cycle. Even if the underlying information needed for computational analysis is stored in an information model, the translation to computational models is still cumbersome and requires significant manual work for model generation and set-up as well as excessive computing resources and time. To address these shortcomings, this paper presents a systematic summary of concepts for integrated information modelling, numerical analysis and visualisation for urban mechanized tunnelling. Our first approach "BIM-to-FEM" is characterised by a fully automated link for error-free data exchange between a standalone Tunnelling Information Model and the process-oriented simulation model for mechanized tunnelling "ekate". In the second approach "SATBIM", a fully automated data exchange workflow is established between a parametric multi-level information model for tunnelling and multi-level numerical models based on both Finite Element and Isogeometric Analysis, where meta models are employed for real-time design assessment. We discuss the different applications of these

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concepts, such as scenario-based exploration of design alternatives, real-time design assessment within a TIM based on meta-models, and the potentials of using these models for the process control during construction. Furthermore, we present two case studies where real project data has been used for the integration of information and numerical modelling. The examples in this paper indicate clear advantages of this approach compared to traditional approaches in terms of efficiency of modelling achieved by reduced user interactions and error-free information exchange, and show the benefits of multi-level model representation and real-time analysis tasks.

Keywords: Building Information Modelling, Industry Foundation Classes, mechanised tunnelling, numerical simulation, multi-level modelling, visualisation

1. Introduction

Growing urbanisation and the need for environmentally friendly urban transportation as well as national and transnational high-speed mobility have increased the necessity for underground infrastructure and tunnels in particular. The design of such complex infrastructural projects involves both information modelling to facilitate design and analysis tasks as well as design assessment to ensure safety and robustness of the proposed solutions. In current engineering practice, information and computational modelling processes constitute separated tasks, which can be cumbersome and involve significant manual, time-consuming efforts for preparation and analysis, as well as excessive computing resources. Furthermore, even if the information required for the design assessment of underground works is stored, managed and processed in an adequate digital form and environment, we still lack a direct link for the generation of computational models and a feedback loop to visualise and process the analysis results, and eventually update the design.

For the generation of tunnel designs and the assessment of design alternatives in different phases of a typical design procedure, a number of boundary conditions, such as the tunnel location and existing buildings and infrastructure above and below ground, the construction method and related construction details (i.e. driving parameters), geometrical properties (e.g. depth, diameter, lining thickness), the ground behaviour and possible critical geological conditions [1] needs to be considered. Then, tunnel design is assessed based on analytical, empirical, or numerical models. In the framework of the "Observational Method" [2], ground settlements due to tunnelling are characterised by the ground (or volume) loss parameter. This is an empirical parameter that depends on soil conditions, tunnel configurations and the tunnelling method [1]. The volume loss parameter can be described in terms of the "gap" parameter [3] or, in case of Earth Pressure Balance (EPB) shield tunnelling, in terms of volume loss at the tunnel face (V_f), around the shield (V_s) and the tail (V_t) [4]. It is then used to derive analytical expressions of surface settlements [1]. However, this methodology involves the determination of a number of empirical parameters that are project-specific, and hence cannot be generalised. Likewise, commonly employed analytical and simplified numerical solutions for the tunnel design adopt a number of assumptions (e.g. plane strain assumption, tunnel lining as elastic material, perfect circular tunnel geometry, etc.), linear springs to consider soil-structure interaction effects [5; 6; 7; 8]. Therefore, Finite Element (FE) simulations are generally used in order to achieve a higher level of confidence for the safety predictions and the quality of the design of tunnelling projects [9]. In recent years, sophisticated 3D numerical models have been developed to investigate different phenomena resulting from the tunnel-soil-structure interactions such as, influence of the TBM operational parameters on the induced settlements and pressure distribution around the tunnel [10; 11], the influence of segmented tunnel linings [12; 13], the interaction of TBM with the surrounding soil in difficult ground conditions [14; 15; 16], the stability of the tunnel face [17; 18], the interaction of the tunnel construction process with existing buildings [19; 20; 21] and foundations [22; 23]. Furthermore, multi-disciplinary research has been carried out to promote the development and implementation of more sophisticated digital and computational tools in underground construction [24]. In this collaborative research, a special focus is on the development of information and computational models and design concepts to deal with the manifold complex interactions of the components and processes in mechanised tunnelling in urban areas.

A different, until now mostly independent aspect of the project development is the adoption of Building Information Modelling (BIM) for the design, construction and management of buildings or industrial facilities over their entire lifecycle [25]. In the last decade, BIM has been increasingly used also for complex infrastructural projects such as mechanised tunnelling to facilitate design and analysis tasks and therefore increase the productivity in design, construction and operation [26; 27]. Moreover, recent developments in software platforms for tunnel information modelling allow for a multi-scale information representation of the built environment with adequate Levels of Detail (LoD) [28] and simultaneous collaborative design among multiple experts from different domains [29]. Tunnelling information models have a strongly interdisciplinary character, and require an intensive interlink and exchange of data between the individual stakeholders during the different stages of the project. Data interoperability in tunnelling projects is facilitated by the use of Industry Foundation Classes (IFC), which allow for data exchange between several BIM software tools [30]. Finally, in recent years, BIM has been also increasingly used for facility management, i.e. operation and maintenance of tunnels, however, so far only as a source of geometric-semantic information for the facility management data base, and not as an integral model for tunnel lifecycle management [31; 32]. Yet, although a BIM model appears to carry all information necessary to create numerical models, directly generating numerical simulations from BIM data still involves manual and time-consuming preparation, linking and conversion of the various utilised data formats.

Nowadays, each large infrastructure project requires both information management and design assessment in the form of numerical analysis, often on different LoDs, and commonly for the whole lifecycle. Therefore, there is an evident need for a robust link between both information modelling and computational modelling. This link is an important step towards BIM level 3 maturity in terms of integration of the design and assessment for underground infrastructure. In recent years, the link between information and numerical models has been established for structures, where BIM-to-FEM workflows have been developed by several authors to enable fully automated structural analysis of different architectural forms, historical masonry, and timber structures [33; 34; 35; 36]. Moreover, the concept of Analysis in Computer Aided Design (AiCAD) employs Isogeometric Analysis (IGA) for an integrated design-through-analysis workflow also for structural engineering applications such as the analysis of structural membranes, shells, and lightweight structures [37; 38; 39; 40; 41; 42]. The integration of information and numerical modelling in tunnelling, characterized by an automated link between digital ("informational") and numerical models, is associated with additional challenges compared to the previously mentioned applications in structural engineering, due to i) the complexity of the system involving different components (ground, lining structure, TBM, overlaying structures) with diverse information sources and formats; ii) modelling of the tunnel construction process rather than static analysis; and iii) the scale of the models, which could span from the meter to the kilometre scale. To address these challenges, in this paper we present a systematic summary of two different approaches for establishing such a robust and fully automated link between the information and numerical models in the context of tunnelling. Technical details of the methodology and implementation of these approaches can be found in [43; 44; 45; 46; 47].

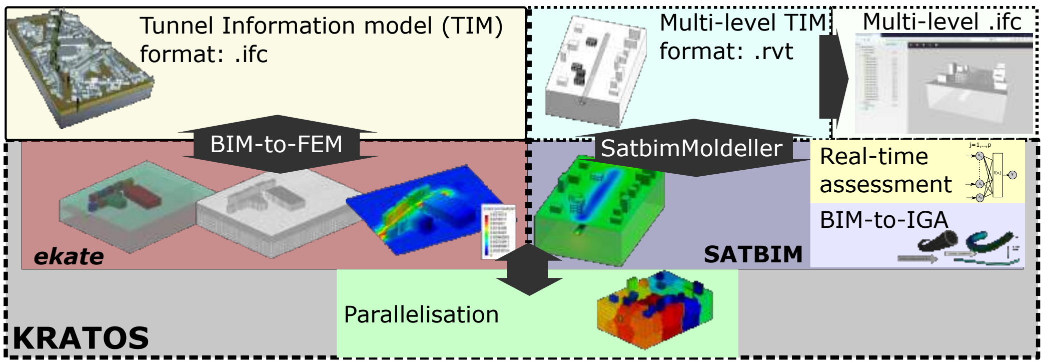

Figure 1: BIM-to-FEM and SATBIM: Integration of information and computational modelling for mechanised tunnelling.

In this paper, we give an overview of our joint efforts in the last five years to address the challenges and to demonstrate the opportunities of integrated design and analysis for urban tunnelling. To this end, we present two different information modelling approaches for mechanised tunnelling and the related workflows for an error-free data exchange with a computational analysis framework, including the feedback for effective visualisation of the analysis results within the information model (see Figure 1). New features of this concept presented in this paper include the incorporation of buildings on different level of details in conjunction with a respective an application case study presented in Section 4.3.

Firstly, in Section 2, we present an approach, called “BIM-to-FEM”, for linking a standalone application for a Tunnelling Information Model (TIM) with FE analysis (using the ekate framework). Our second approach for information and numerical modelling on different LoDs within a unified environment, called “SATBIM”, is presented in Section 3. The main difference between these two approaches is the information model that is used as a source of the geometric-semantic information for the generation of numerical models and as a visualisation platform. The BIM-to-FEM approach is based on a holistic, object-oriented TIM that is organised as a multi-model container and where the individual components are interlinked within an open IFC environment (Section 2.1). In contrast, within SATBIM we developed a fully parametric multi-level information model in a state-of-the-art design tool that can be exported and visualised in an open IFC environment considering different representation context for LoDs (Section 3.5). A common feature of both approaches is the use of the open-source finite-element framework `KRATOS` [48; 49] as a simulation engine with implemented parallelisation strategies (Section 2.2.3). Using this computational platform with support for parallel computing (Sections 2.2.4 and 2.2.3), the BIM-to-FEM approach employs a simulation model called "ekate" (Section 2.2), whereas in SATBIM we developed a multi-level simulation modelling approach (Section 3.1) for the assessment of complex 3D soil-structure interactions in tunnelling (see Figure 1,bottom). Moreover, advanced features that extend this integrated information and numerical platform, such as the application of isogeometric analysis for a high-accuracy assessment of segmented tunnel linings (Section 3.3) and a real-time design assessment in TIM (Section 3.4) are presented as well. In the last Section 4, a number of examples demonstrates the advantages of our approach compared to traditional workflows in terms of modelling and computational efficiency, the benefits of multi-level model representation, the error-free information exchange, real-time analysis and visualisation.

2. BIM-to-FEM: Integration of design and numerical models for tunnelling

The first approach, called "BIM-to-FEM", proposes a fully automated link between the TIM framework and ekate, a process-oriented FE simulation for mechanized tunnelling [50].

2.1. Tunnelling information model

The authors have previously presented a tunnel information modelling framework that supports four interlinked subdomain models and linked project performance data [30]. With respect to their distinctive impact on the overall tunnel design and production process, a ground or soil model, a TBM model, a tunnel lining model and a model of the built environment have been separately devised, and then interlinked within an open IFC environment using the IFC concepts of Proxies, Property Sets and Model View Definitions (Fig. 2a).

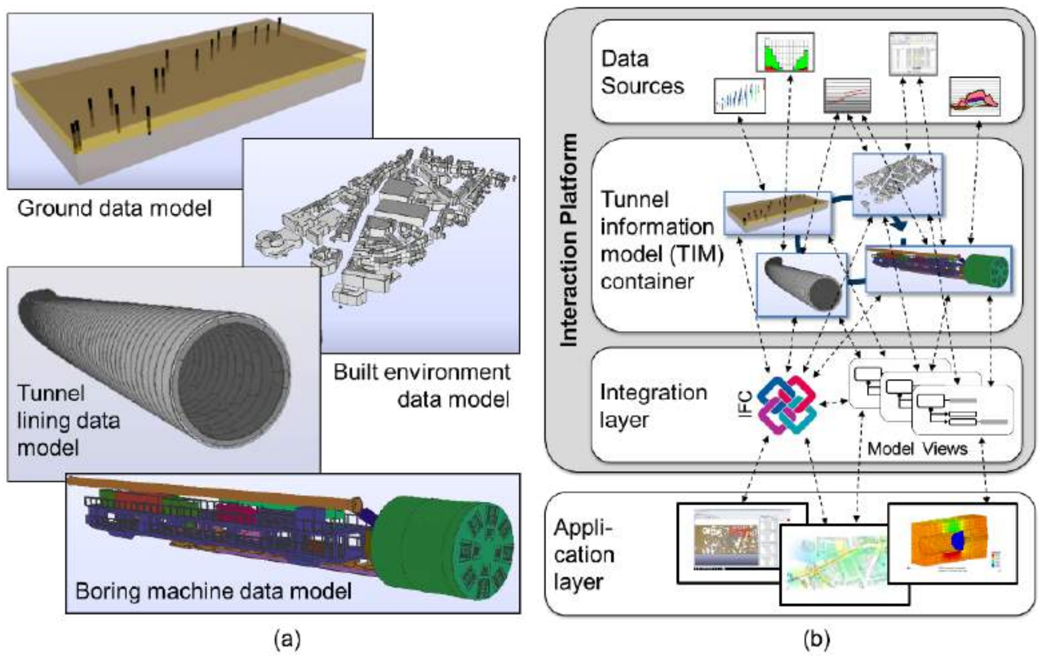

Figure 2: (a) Four main subdomains of the tunnel information model; (b) Tunnel information modelling framework based on a unified interaction platform and an application layer.

To provide uniform access to all relevant project data, existing project documents have been collected, classified, structured and linked into a holistic, object-oriented TIM (see Fig. 2b). The organisation of all data sources is established in an interlinked container adopting the ontology of a multi-model container approach [51]. This enables the models to be semantically outlined as well as individual objects to be linked, such as linking ring built data to specific entries of settlements or the corresponding machine performance data. Accordingly, this fundamental information model forms the basis for all possible interactions of the project teams and software applications.

For the purpose of providing uniform access to all relevant data, stored in the four sub-domain models, an IFC-based integration layer is proposed (Fig. 2b). This procedure has the advantage of being able to re-use existing IFC-based model viewing and querying tools as well as providing an Open-

BIM and long-term data-exchange for the individual models, for example providing the integration for maintenance tasks.

In addition, the integration layer provides different model views to support management tasks, numerical analyses or context-aware settlement visualisations. The incorporation of model views primarily allows to filter the involved models due to the context of the subsequent task, for example, that a settlement visualisation does not necessarily require a detailed model of the boring machine, but rather a an approximate shape (i.e. a model at low level of detail) to indicate the shield position. Secondary, these model views also enable some kind of model checking, to make sure that specific parameters are available, for example that each ring assigns a ring number. Based on all these modelling concepts from the interaction platform, specific application scenarios, which are then part of the application layer (Fig. 2b), can be built, executed and integrated into subsequent decision making processes.

2.2. Simulation model for mechanised tunnelling

2.2.1. "ekate": FE simulation with support for high performance computing

The process oriented finite element model has been developed within the framework of the object-oriented finite element code `KRATOS` [48; 49]. It is denoted as "ekate" (Enhanced Kratos for Advanced Tunnelling Engineering). "ekate" facilitates parallelization and execution on distributed-memory computing clusters via MPI and considers all relevant components involved in mechanized tunnelling, i.e. the shield machine, the hydraulic jacks, the segmental linings, the soil and the ground water, the annular gap grouting and face support pressure and their relatively complex interactions. Here, a brief illustration of the model is presented; a detailed description can be found in [11; 52]. Fig. 3 shows the main components involved in mechanized tunnelling (left) and their representation in the finite element model (right). Shield skin tapering and its weight are considered. The conical shield skin interacts with the excavated soil by means of the surface to surface contact condition. The shield is supported on the lining and moved forward by means of hydraulic jacks. The jacks are modelled by truss elements. In order to realistically simulate shield advancement, particularly along curved tunnel routes, an automatic steering algorithm is employed in order to control jack movements [16]. Then the jacks are retrieved to assemble a new ring. The sequential excavations are repeated by pushing the jacks onto the newly installed rings, eliminating the excavated soil elements. After segments erection and shield advancement, the resulting annular gap is usually filled with pressurized grouting mortar, modelled by a two-phase finite element formulation.

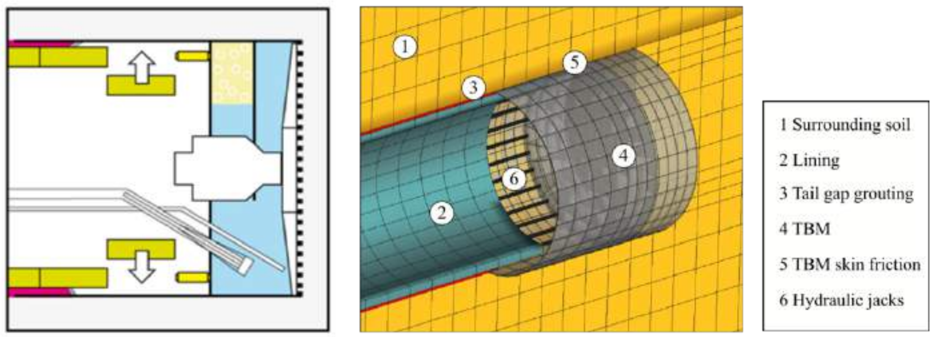

Figure 3: Computational simulation of mechanized tunneling advancement process: Components involved in mechanized tunnelling (left) and finite element simulation model "ekate" (right).

2.2.2. Incorporation of buildings

Tunnelling in urban areas requires to put particular attention on the mutual interaction between the ground and existing surface structures, as ground deformations are influenced by the building stiffness as well as its position relative to the tunnel path and, vice versa, the risk of building damage is influenced by tunneling induced settlements. Therefore, buildings are integrated into the numerical tunnel advance model, in which buildings are designated from a 3D city model and simulated with volume elements with a substitute stiffness or with a detailed spatial discretisation of the main structural components as shown in Fig. 3 right. However, the use of detailed discretisation of surface structures, in particular for large models with several surface structures, requires high computational costs. For this reason, the level of detail of the building discretisation is usually reduced, and buildings are represented by substitute structures with an equivalent stiffness. Vulnerable buildings that require a particular attention can be further discretised with a higher level of detail (Fig. 4). A node to volume Lagrange tying algorithm is used to impose deformation constraints at the locations of the building foundations independently of the discretisation of the soil. A procedure to couple tunnel advancement simulations and detailed building models using surrogate models is presented in [53].

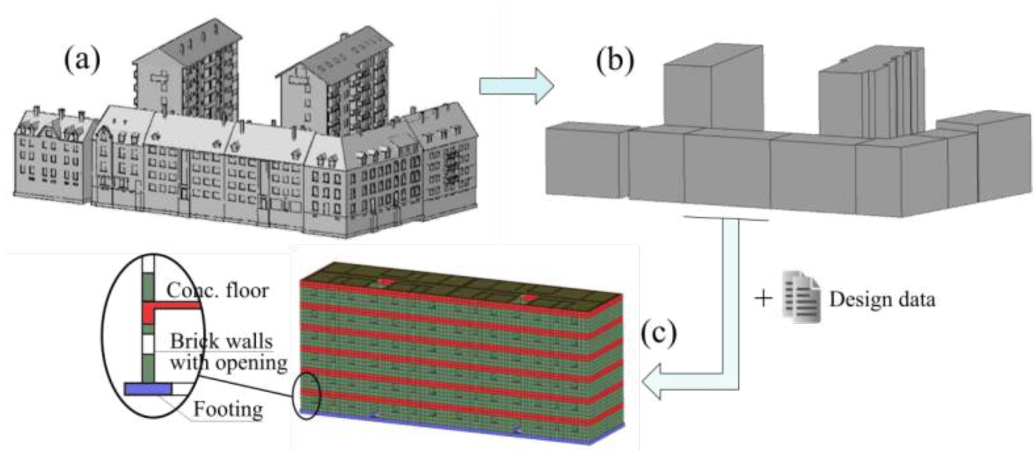

Figure 4: Integration of buildings in numerical tunnel advancement simulations: (a) 3D city model, (b) volume geometries with substitute stiffness and (c) detailed discretization of the main structural components.

Considerable effort is required to generate such a sophisticated computational model for the individual building considering the required LOD. An automatic modeller that is integrated within the so-called TIM, which is a BIM-based model, has been developed as a numerical simulation tool to simplify the modelling process and to reduce errors due to inexperience. All relevant information, needed for a FE-simulation is automatically extracted from the BIM sub-models and subsequently employed to perform an FE-analysis of the tunnel drive [54].

2.2.3. Parallelised Computing

In 3D high fidelity computational models of large project sections with a high spatial as well as temporal resolution of the domain and the advancement process, respectively, computability may become a critical issue due to the size of the model. Therefore, parallelization strategies with domain decomposition (see e.g. Fig. 5) are inevitable. However, in tunnel problems, challenges arise from the presence of the ground water and the large stiffness contrast between the TBM, the tunnel shell and the soft ground, which have to be considered in designing an appropriate simulation strategy [55; 56].

The computational model for mechanized tunneling "ekate" is equipped with essential components for parallel computing on distributed-memory systems using MPI, such as domain decomposition, parallel assembly and par-

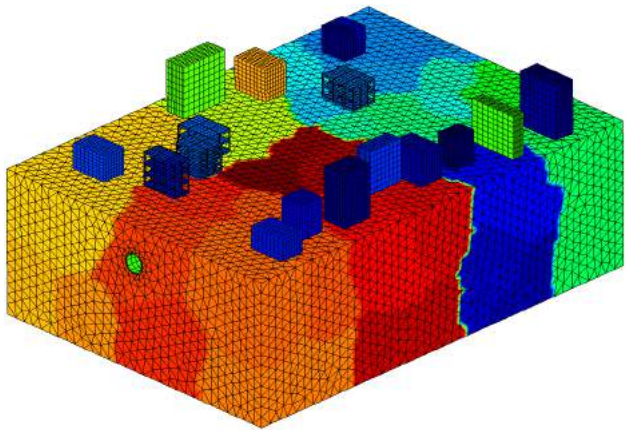

Figure 5: Example of domain decomposition for parallellised tunnel simulations using 64 partitions.

allel solver. In a recent study [57] it was found that the application of a multigrid preconditioner as sub-preconditioner enhances the robustness of the iterative solution process. In a tunnel benchmark problem characterized by three different discretisations with $\sim 230k$, $\sim 250k$ and $\sim 880k$ degrees of freedom running on $8 \sim 64$ processors a speed-up in the range of $2 \sim 5$ was found (the speed-up was measured against a simulation with 8 processes). The overall parallelisation strategy achieves a good scalability and is up to 10x times faster as compared to a parallel direct solver. For details, we refer to [57].

2.2.4. Simulation Engine

To effectively solve the computational model in parallel, including the contact conditions between the TBM and the surrounding ground, a set of extension packages has been developed in companion with the open-source software `KRATOS` [48; 49]. In Fig. 6, the left column shows the existing software components and the additional extensions are described on the right column. The additional extensions are implemented considering the interoperability with the `KRATOS` kernel and existing software components, while maintaining the extensibility and performance of the code.

The central part of the parallelized software package specifically designed for numerical simulations in mechanised tunneling is the

`PetscSolversApplication`, which provides the interface to the linear algebra backend PETSc and the block preconditioner construction. To support

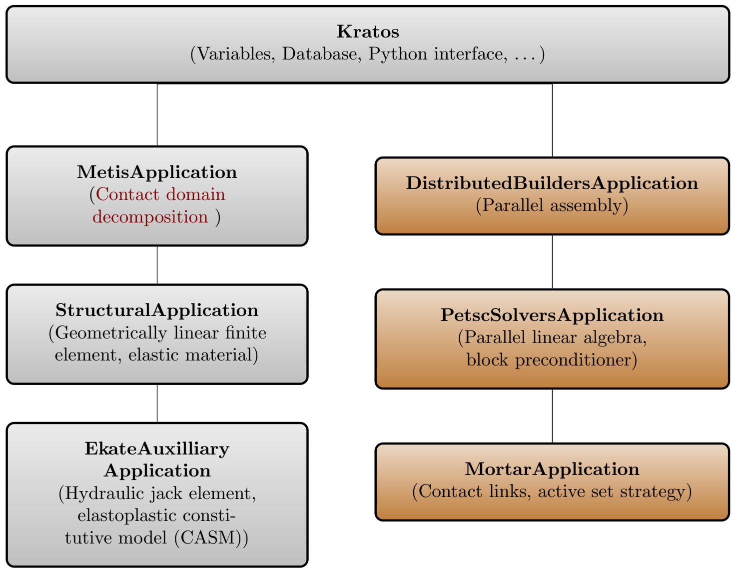

Figure 6: Structure of the simulation software: existing `KRATOS` components, extended components for parallel simulation.

for `PetscSolversApplication`, the

`DistributedBuildersApplication` is implemented to assemble the linear system in parallel. It is noted that the domain decomposition is created a priori by the existing `MetisApplication`, and the `DistributedBuildersApplication` computes the local linear system in each domain and assembles the submatrices to a PETSc-compatible parallel matrix. The contact algorithm accounting for the interaction between the TBM and the soil is implemented in the `MortarApplication`.

2.3. BIM-to-FEM workflow

Generating a realistic three-dimensional tunnel simulation model capable of representing the main components involved in a bored tunnel construction process requires considerable effort. In addition to the experience required to generate an accurate numerical model, data from many different sources is required for the generation of a holistic simulation model. This data is most often not centrally stored and therefore not easily accessible. Additionally, the format, in which project data are stored, is typically not compatible with the formats required by FE programs. This is especially true in the case of geometrical data, such as CAD drawings. Although existing design drawings are most often used as the basis for an FE model, a direct import into an FE program is most often not successful as the imported data generates a geometry that often does not fulfill the requirements of the FEM model, such as model connectivity. Even if the geometry is successfully imported, other necessary aspects of a FE model, such as boundary conditions and material properties, must still be applied manually. These incompatibilities inevitably result in additional efforts for the generation of a simulation model, which, especially in the case of complex 3D FE models, is a time consuming process.

To this end, an automatic modeller, which is integrated within the TIM, has been developed as a numerical simulation tool to automatise and simplify the modelling process, and to reduce errors due to a lack of experience of the user. This modeller is part of a "BIM-to-FEM" interaction platform, that automatically extracts the relevant information (geology, alignment, lining, material and process parameters), needed for a FE-simulation from TIM sub-models and subsequently performs a FE-analysis of the tunnel drive. All process data and material parameters are stored and can be exported as text files. Moreover, for the geometrical representation, each individual component is defined as volumetric data contained in proprietary ACIS (.sat) format. The necessary boundary conditions and construction sequences are automatically incorporated based upon the design data. This simplifies the information flow and limits errors that jeopardize the structural analysis. The modularity of the developed TIM-based modeller has been accomplished by connecting various scripts and software, which perform specific tasks during the model generation.

After the simulation has been performed, the results are transmitted back to the TIM platform for visualisation purposes. Then, results are presented in time-dependence and in interaction with the domain models, which allows to draw context-aware conclusions based on the interaction .Fig. 7 outlines the workflow of the proposed automatic modeller.

3. SATBIM: Multi-level information and numerical modelling for urban mechanized tunnelling

The second approach, called SATBIM, is a framework for integrated multi-level information and computational modelling of soil-structure interactions in tunnelling. This framework consists of multiple components: parametric multi-level Tunnel Information Model (ml-TIM), multi-level computational model, and SatbimModeller which is a link between first two com-

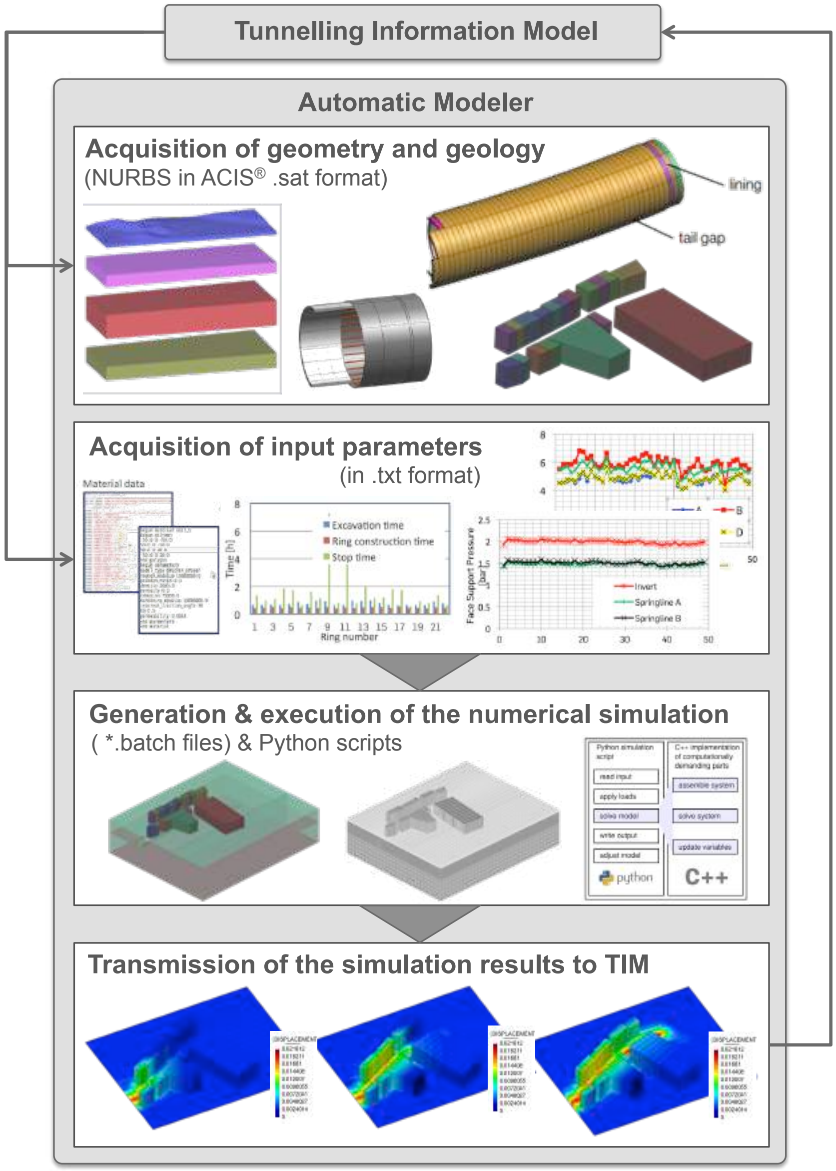

Figure 7: Schematic illustration of the workflow of a TIM-based automatic model generation.

ponents. It is available as an open-source user-friendly toolbox for design, structural analysis, visualization and optimization of the tunnel design.

In this framework we have also considered all important components of the tunnelling process relevant for the predictions of the response of the surrounding soil during excavation (see Fig. 8). The SATBIM framework also accounts for ground modelling on the geometric and material level (Fig. 8 (1)); the segmental lining with support measures applied at the tunnel face and at the tail void (Fig. 8 (2) and (5)); the TBM and the hydraulic jacks (Fig. 8 (3)); existing infrastructure, and implicitely, the soil-structure interaction effects between the individual components (Fig. 8 (6)).

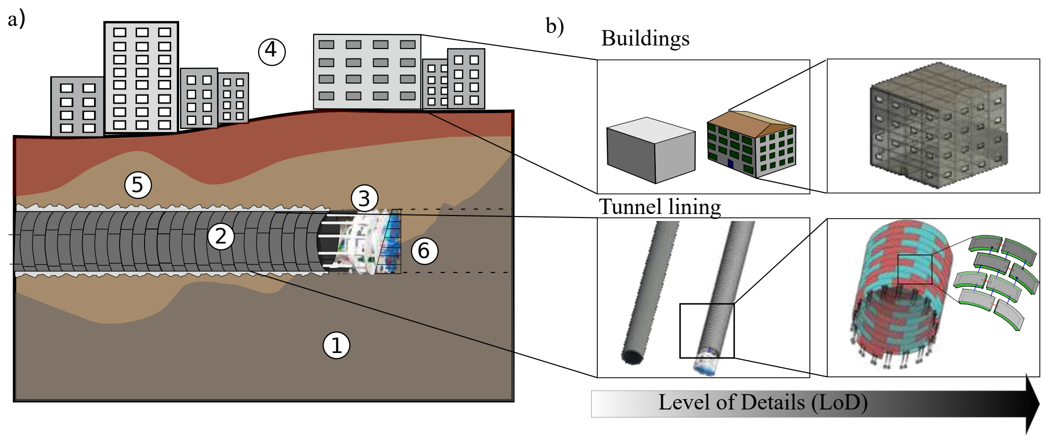

Figure 8: (a) Main components of urban tunnelling process: (1) Surrounding soil; (2) Segmented tunnel lining (3) Tunnel Boring Machine (TBM); (4) Existing Infrastructure; (5) Tail gap grouting. (b) Modelling of tunnelling components on different LoDs.

The investigation and evaluation of different design alternatives is essential for ensuring optimal design solutions. In the conceptual phase, a designer often only needs approximate estimations for many different scenarios, e.g. tunnel track alternatives. To ensure a seamless workflow, the computation time should be minimised. Firstly, a preliminary analysis is conducted for large tunnel sections to access the overall fitness of the selected design alternative. Secondly, if the global analysis indicates the potential for hazards at certain tunnel sections, a more detailed evaluation of the model is conducted. Therefore, in SATBIM we adopt the so-called multi-level approach to enable a representation with a seamless level of detail (LoD) at the larger scales with acceptable computing costs (e.g. kilometre), and, at the same time, allowing a consistent shift to a higher LoD for scenarios where the potential hazards are identified and further analyses are required (e.g. 10-100 m scale). SATBIM enables that transition by dynamically generating the simulation models from fully-parametric BIM models at the required LoD for the specific problem to be solved.

3.1. Multi-level information and numerical modelling of urban mechanised tunnelling

In the SATBIM framework, a fully parametric multi-level Tunnel Information Model (ml-TIM) has been developed within the industry-standard design tool Revit and its scripting plug-in Dynamo [58], considering all important components of the urban tunnelling process. The concept of different LoDs refers to different levels of abstraction for an infrastructure facility, i.e. LoD specifies the reliability and maturity of information in the model along the design process. In our implementation each component of the information model supports all the different LoDs at once, allowing an automatic switch between different LoDs in order to perform different required tasks. In the SATBIM framework, we defined three different LoDs for each component: low (LoD 1), medium (LoD 2) and high (LoD 3). In general, the information models are described as follows: LoD 1 is a non-volumetric geometric representation; LoD 2 is a simplified volumetric representation of the component including material properties; and LoD 3 is described with a detailed volumetric and semantic representation of the component. All individual components on different LoDs in the ml-TIM are illustrated in Fig. 9 (a). The consistency between different LoDs is preserved by adopting a parametric dependency between classes (so-called Revit "families") representing different LoDs of the same component. For each tunnel component and on each LoD, a Revit family for the corresponding component was created, preserving the geometric consistency between the LoDs. At the same time, different components can share common parameters, preserving the consistency of the full model obtained by combining different components.

A number of Dynamo script-based rules for parametric classes of individual tunnelling components and their dependencies was implemented, which allow to parametrically generate the design model for the tunnel project in Revit. In this parametric model, the user selects model parameters for each component based on project data including the LoD. By combining all the individual components (lining with its alignment and grouting, soil with excavation, TBM, and buildings), the complete ml-TIM is generated as illustrated in Fig. 9 (b).

Based on geometric and semantic descriptions of the ml-TIM, computational models for each tunnel component, each at its respective LoDs (low,

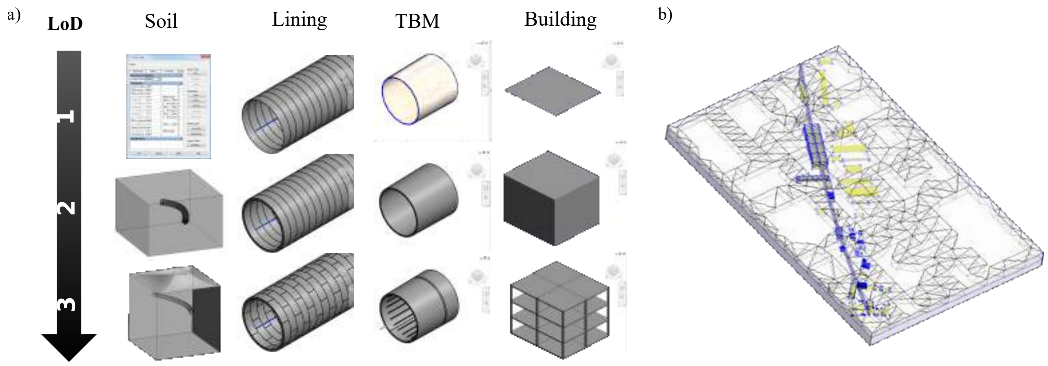

Figure 9: (a) Tunnel information model components on different LoDs: soil, lining, TBM and buildings; (b) ml-TIM for 1 km long tunnel section generating combining parametrised components on different LoDs (LoD 3 soil, LoD 2 lining, LoD 2 TBM and LoD 2/3 builidngs.)

medium and high), have been developed and implemented. Each component (lining, soil, TBM and buildings) is modelled considering adequate geometric and material representations, interfaces between individual components, as well as the representation of the construction process in the tunnelling simulation (see Fig. 10 (a)).

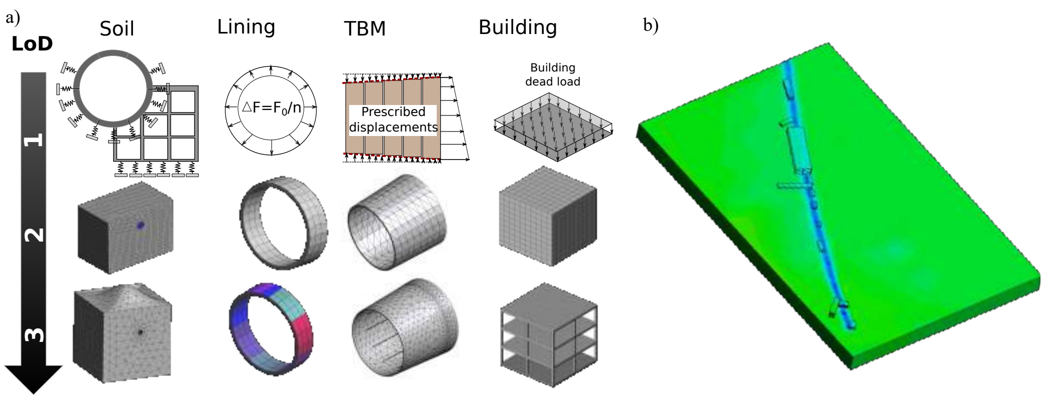

Figure 10: (a) Computational model components on different LoDs for: soil, lining, TBM and buildings; (b) Simulation results for ml-TIM model from Fig. 9.

In general, LoD 1, represented with non-volumetric models in the ml-TIM, is described with analytical/empirical models; LoD 2 represented with simplified volumetric models in the ml-TIM is described with adequate 3D FE numerical models; and LoD 3 with a detailed volumetric representation in the ml-TIM is described with sophisticated 3D FE models on the geometric and material level. The details of these models can be found in the SATBIM technical report and references [44; 45; 46].

3.2. SATBIM modeller

The SATBIM framework provides an integrated platform for structural analysis, visualization and optimization of urban mechanized tunnelling. Those steps were developed using different tools: i) ml-TIM: the Autodesk tools Revit and Dynamo [58]; ii) FE mesh and boundary conditions: pre/post-processor GiD [59] and iii) computational model in the open-source Finite Element (FE) platform `KRATOS` [48; 49]. An interface SatbimModeller has been developed to integrate all these tools into a user-friendly platform with a high level of automation (see Fig. 11). The SatbimModeller enables modelling, analysis and visualization in a unified way. This interface is mainly written in Python, using a modular architecture that allows for easy extension and adaption of the platform.

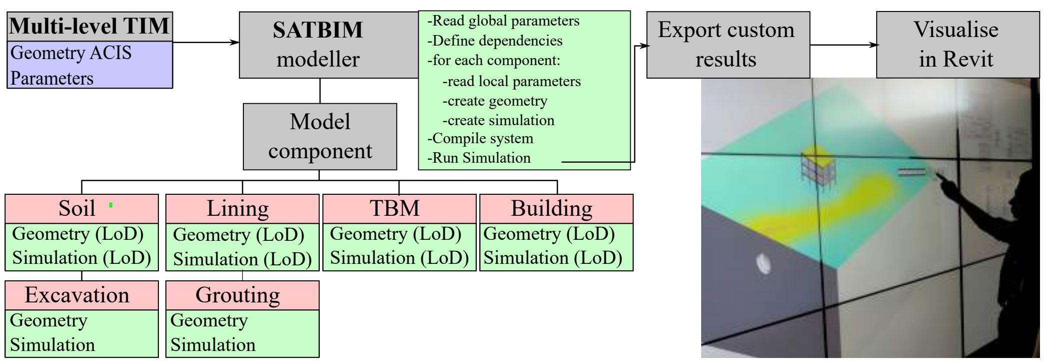

Figure 11: Structure of SatbimModeller: A Python interface for generation of computational models, simulation setup and visualisation of numerical results back in design model..

SatbimModeller enables an uninterrupted workflow for generation, setup and execution of the simulation model, connecting the ml-TIM with the simulation software `KRATOS` and the GiD pre/post-processor. All information about the geometry, process parameters and material parameters obtained from the ml-TIM is used for the generation of numerical simulations of soil-structure interaction during mechanised tunnelling. The FE mesh and boundary conditions of the numerical model are generated based on geometric (stored as ACIS files) and semantic (stored as text files) data exported directly from the ml-TIM as illustrated in Fig. 11. Furthermore, SatbimModeller automatically generates the simulation scripts to model the construction process and soil-structure interactions, executes the numerical models in the simulation software `KRATOS`, and creates custom outputs for visualisation of the simulation results in BIM, as illustrated in Fig. 11 (left).

3.3. BIM-to-IGA for design of segmented tunnel linings

SATBIM platform has been further extended to allow for the direct use of high-order geometry definitions of the lining structure in design software to generate higher-continuity finite element models, maximizing the computational and modelling efficiency [60]. A fully automatized design-through-

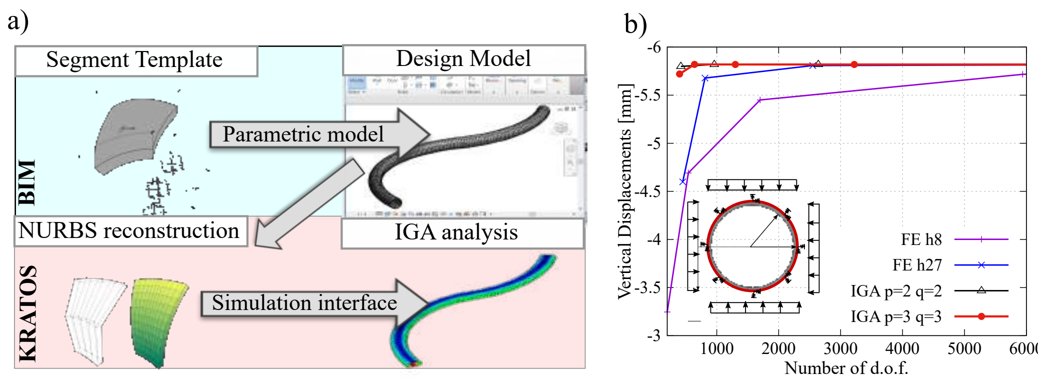

Figure 12: (a) Design-through-analysis workflow for BIM-IGA assessment of the tunnel lining. (b) Comparison of performance of IGA and standard FE models in terms of convergence of vertical displacement with mesh size

analysis workflow solution for segmented tunnel lining is developed based on a fully parametric design model realized as a Revit plugin (as shown in Fig. 9 (a)) and an isogeometric B-Rep analysis software (IBRA), connected through an interface implemented within the Revit plugin Dynamo (see Fig. 12 (a).). Firstly, we developed a fully parametric design model for 3D segmented tunnel linings on different LoDs for arbitrary tunnel alignments based on the so-called universal ring approach. Secondly, we integrated and employed a higher-order finite element method based on isogeometric analysis (IGA) [61] in order to analyse the forces and the bending moments in the lining segment with high resolution. Finally, a robust interface from the design model to the analysis tool is developed for i) the reconstruction of NURBS with trivariate representation suitable for IGA analysis from the original boundary representation using the trimmed NURBS model of the lining segment, and ii) generation of the simulation script based on semantic data extracted from the BIM model (e.g. tunnel depth, material parameters, water level. etc.) and automatic execution of the analysis. Fig. 12 (b) shows that, using this computational approach, an accurate prediction of the tunnel displacement is achieved with a significantly lower number of degrees of freedom as compared to the standard FE approach. This allows to analyse large tunnel sections on the kilometre scale without compromising the accuracy of the geometrical representation and the achieved numerical solution.

3.3.1. Isogeometric analysis

Isogeometric analysis (IGA) is a finite element method employing Non-uniform rational B-Spline (NURBS) basis functions [62]. IGA offers higher degree of continuity within a patch. On the patch interface, C^0 continuity is retained and C^1 continuity can be achieved by introducing additional bending patch [63]. With the help of Bézier decomposition concept, a NURBS patch can be decomposed to independent Bézier elements, where the shape function values and gradients can be computed a priori to improve the computational efficiency [64]. IGA typically obtains a better accuracy than standard FEM employing Lagrange shape functions of the same order, and with p-refinement it outperforms the FEM counterpart of first and second order (see Fig. 12(b)). It is noted that, the p-version of the standard FEM requires re-meshing and sophisticated data structures to deal with internal shape functions on edges, faces and volumes. Using the IGA technology, refinement simply involves a linear transformation of all terms defined at the control points, including the control coordinates and weights.

3.3.2. Variational hyperstatic approach for soil-structure interaction

Hyperstatic reaction method (HRM) emerges as a versatile tool to represent the interaction between soil and support structures (e.g. lining). This interaction is modeled by means of nodal Winkler-type springs and results in passive loads due to the reaction of the soil with respect to displacement of support structure [65]. HRM has been used extensively to study the behavior of twin tunnel [66], segmental lining [67; 68; 69], reliability of tunnel lining design [70], to name a few.

The HRM approach is extended to support surface-type springs, namely Variational Hyperstatic Reaction method (VHRM). In the new approach, the soil-structure interaction is incorporated in the weak form, leading to a consistent linearization and improved computational efficiency. It also extends the applicability of HRM to FEM from only using beam elements for analysis to use volumetric element and mesh refinement.

3.4. Real-time design assessment

In situations where rapid decisions are required or a large number of design alternatives has to be explored, design assessment has to be performed in near real-time. As already mentioned, for complex engineering problems like mechanised tunnelling characterised with various time-dependent tunnel-soil-structure interactions, the adoption of analytical or empirical solutions for the prediction of tunnelling-induced effects on the environment is often inadequate due to the number of associated assumptions and oversimplifications. On the other hand, the use of sophisticated numerical simulations is inefficient, even when employing fully automated model generation of numerical models and parallel computing (see Section 2.2.3), because the evaluation of a single design alternative might still take hours.

To overcome this problem, in the SATBIM framework, we propose a novel concept for on-demand design assessment for mechanised tunnelling using simulation-based meta models. It includes: i) generation of the data set using our unified numerical and information modelling platform; ii) training of the data set with a hybrid machine learning approach to create simulation-based meta models; iii) real-time meta model-based assessment in the design tool. The workflow of the proposed concept is illustrated in Figure 13. The advantage of employing simulation-based meta models compared to analytical and empirical solutions is that meta models, as "surrogates" of 3D simulation models, are able to account for complex interactions between tunnelling components, and therefore predict the physical response more accurately. Furthermore, meta models can be trained to predict different phenomena at the same time (surface settlements, risk on buildings, stresses in tunnel structure). For the trained data set generated for given ranges of geometric and semantic parameters that describe the tunnel design, meta models are able to interpolate and, to a certain extent, extrapolate the prediction from the given parameter ranges. Hence, one can test a nearly infinite number of parameter combinations within the chosen range based on a discrete number of simulations used for meta model training. Meta models with their capabilities of real-time predictions can be used for further analysis such as sensitivity analysis [71; 45], model update and optimisation of the tunnel

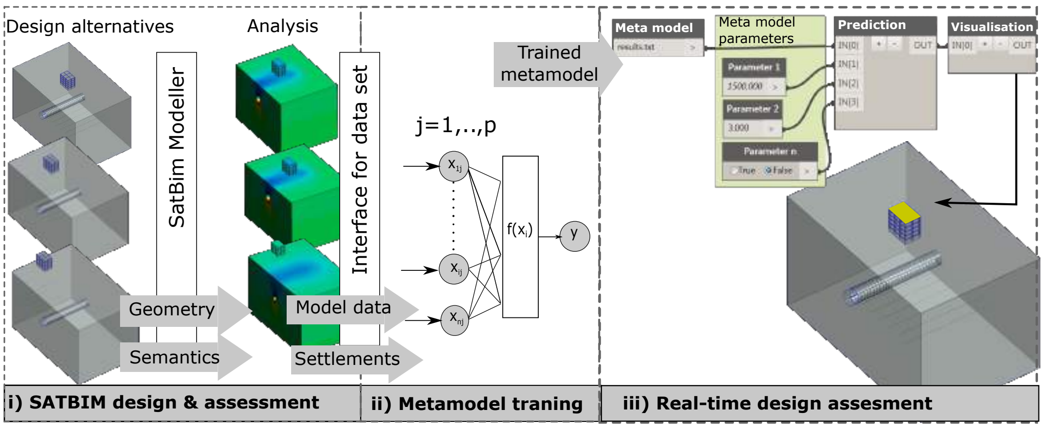

Figure 13: Workflow of real-time predictions for design optimisation within the Tunnelling Information Model.

design and construction process [72; 73; 74], or for stochastic, polymorphic and interval analysis [75]. Moreover, the concept that employees simulation-based meta models has been recently developed for real-time steering control of tunnel boring machines during construction [76; 77].

3.5. Multi-level IFC representation

To express the different levels of detail of the models in IFC exchange scenarios, the modelling concept of Geometric Representation Sub Contexts is used. An example configuration for the buildings is outlined in Figure 14. Therefore, a main instance of *IfcGeometricRepresentationContext* exists by default, defining the usual configuration of a 3D model in IFC. Based on this parent context, three sub contexts are created, and their targetView is named after the corresponding level of detail. The geometries of the different LoDs are altogether modelled under the same product representation of the building, which are then linked individually to the corresponding sub-context. For LoD 1, buildings are just represented by a footprint using the *IfcFaceBasedSurfaceModel* entity, while LoD 2 represents an extrusion body using the *IfcExtrudedAreaSoild* entity, and finally LoD 3 represents the most detailed version using a multitude of instances of the *IfcSolid* model to represent the individual components. The tunnel model also has been modelled in the same manner and is described in [46].

Based on this modelling concept, individual configurations of models including the selection of different levels of detail can be performed. Figure 15

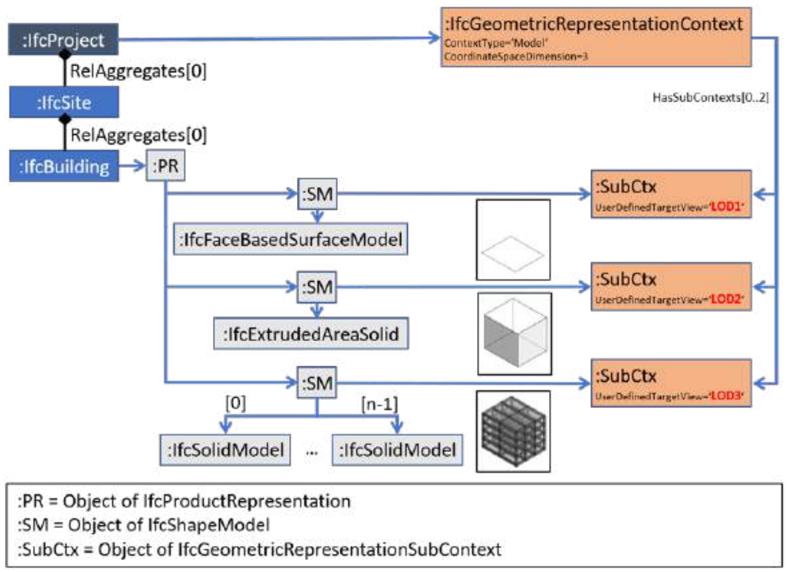

Figure 14: Instance diagram for multi-level representation of buildings in IFC

shows an example IFC-based web application, which allows to select these LoDs by means of representation sub contexts. It can be well observed, that buildings near the lining are represented in a higher detail than the ones which are at a longer distance.

4. Case studies and discussion

4.1. Case study: Wehrhahn-Metroline in Düsseldorf

In this case study, a section of the eastern branch of the Wehrhahn-Metroline project (Düsseldorf), for which reference monitoring data is available, is simulated using the "BIM-to-FEM" approach. The "BIM-to-FEM" interface automatically extracts the relevant information (geology, alignment, lining, material and process parameters) needed for a FE simulation from the TIM sub-models to subsequently performan FE analysis of the tunnel drive (Fig. 16). The model is characterised by multiple soil layers according to the geological survey and real-time process data is employed to further enhance the reliability of the analysis [73]. Finally, an effective visualisation of the results of the computational analysis is provided within the TIM.

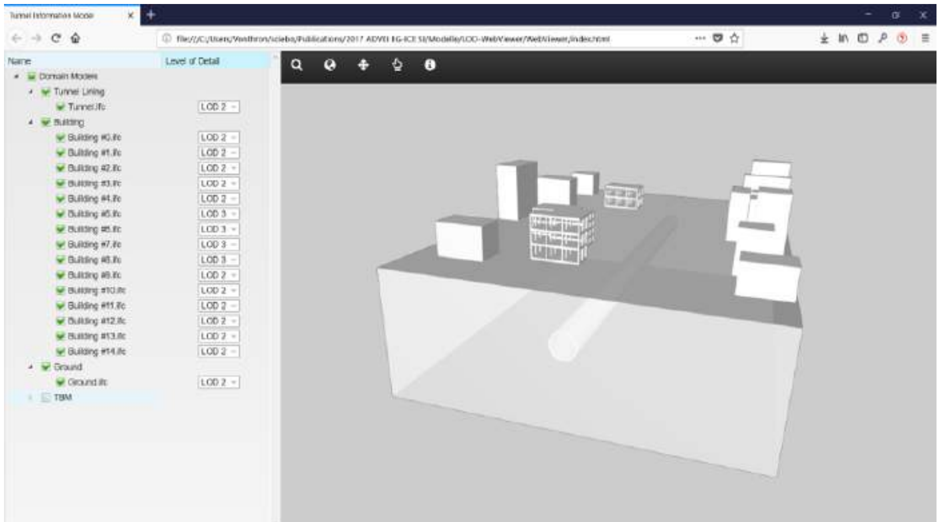

Figure 15: Web-based IFC application, which allows to select LoDs by means of representation sub contexts.

4.2. Visualisation of simulation results in TIM

Using the integrated TIM container of the Wehrhahn Metroline, the time-dependent development of tunnelling induced settlements can be visualised both in the context of the built environment (static) and the dynamic position and performance of the TBM. This is needed to easily identify potentially endangered buildings in the above-ground built environment that are exposed to large settlements. Moreover, the TBM's operational performance data can be visualised and analysed over time in combination with the time-dependent settlements.

For example, in case a settlement value is unexpectedly high, the corresponding thrust force and grouting pressure values can be analysed to investigate the cause. Fig. 17 depicts a specific project situation, where the high thrust force value (Fig. 17, bottom left zoom box, peak in curve) is correlated with a heaving above the TBM (Fig. 17, bottom 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 verifies the high potential of an integrated information model and the visualization of different interacting aspects of a tunnelling project in order to communicate potential problems and identify correlations. More details on the aspect of visualisation for settlement monitoring purposes can be found

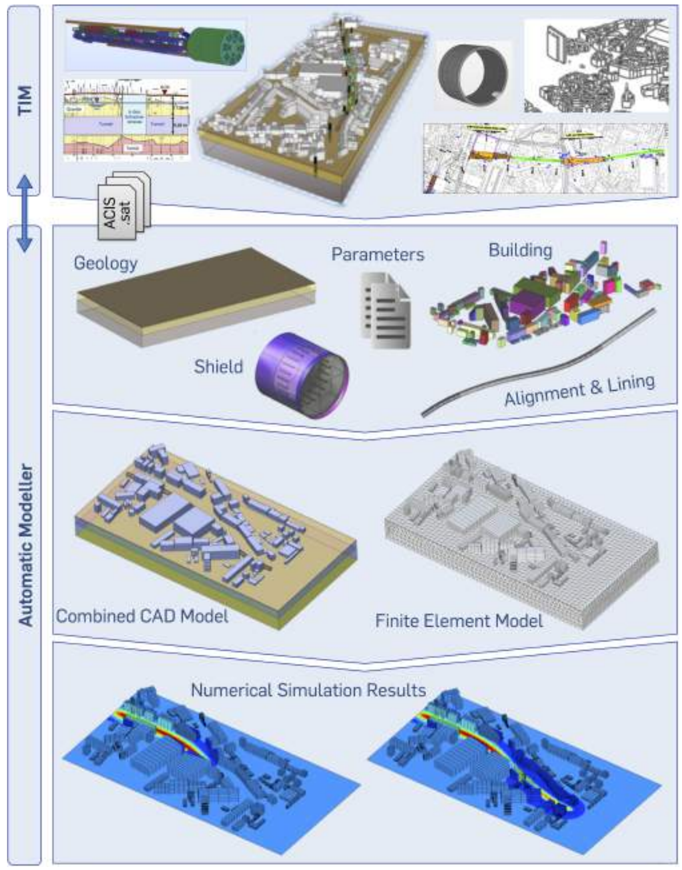

Figure 16: "BIM-to-FEM" approach applied to the numerical simulation of a section of the Wehrhahn-Metroline in Düsseldorf: Digital city model (top), FE model (middle) and snapshot of a simulation result for the settlements (bottom).

in [78].

4.3. Case study: Reference project in urbanized area

The proposed TIM concept is also demonstrated by means of a numerical simulation of a twin-tube tunnel passing beneath an urban area. The outer diameter of the tunnel is 10.97 m. It is driven by two hydroshield machines through a soft homogeneous ground with an overburden varying between 4 m and 20 m. Both tunnel tubes are supported by a 50 cm thick segmental concrete lining shell. A model of a selected region of the project, considering the construction of the first tunnel tube only, is presented here. The topology data of the subsoil, the geotechnical properties of the soil layers, and existing

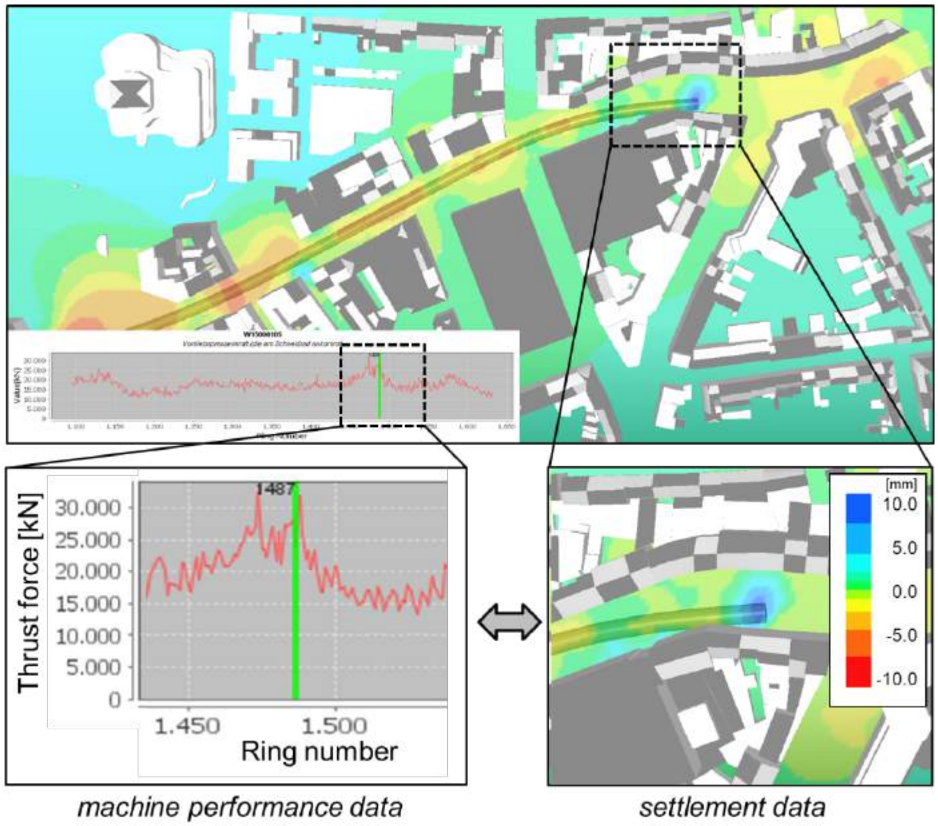

Figure 17: Time-dependent visualisation of settlements in the context of the (static) built environment and the (dynamic) TBM performance. Note the high thrust force that is correlated to the heaving above the TBM (best viewed in colour).

structures, represented by means of substitute models for buildings (as a simplified approximation), have been directly included, through the BIM, into the presented numerical simulation. As shown in Figure. 18, the tunnel passes under a steel frame warehouse. The presented case study at this section reveals the merits of the BIM-FEM coupling and shows that it is feasible to conveniently perform an automatic numerical simulation for a tunneling project with minimum user intervention. This section is equipped with a sensor field to monitor the settlements during the construction phase of the tunnel. A comparison between the measured settlements perpendicular to the tunnel axis, and the predicted ones, is also presented in Figure 18. Relatively small settlements were recorded in this example, which renders an assessment of the prediction quality difficult. However, we would like to highlight that we focus on advantages in terms of modelling efficiency, error-free information exchange etc, and that the prediction quality of the model depends on various factors including availability and quality of data and choice of the constitutive model for the ground and the calibration of the prediction model.

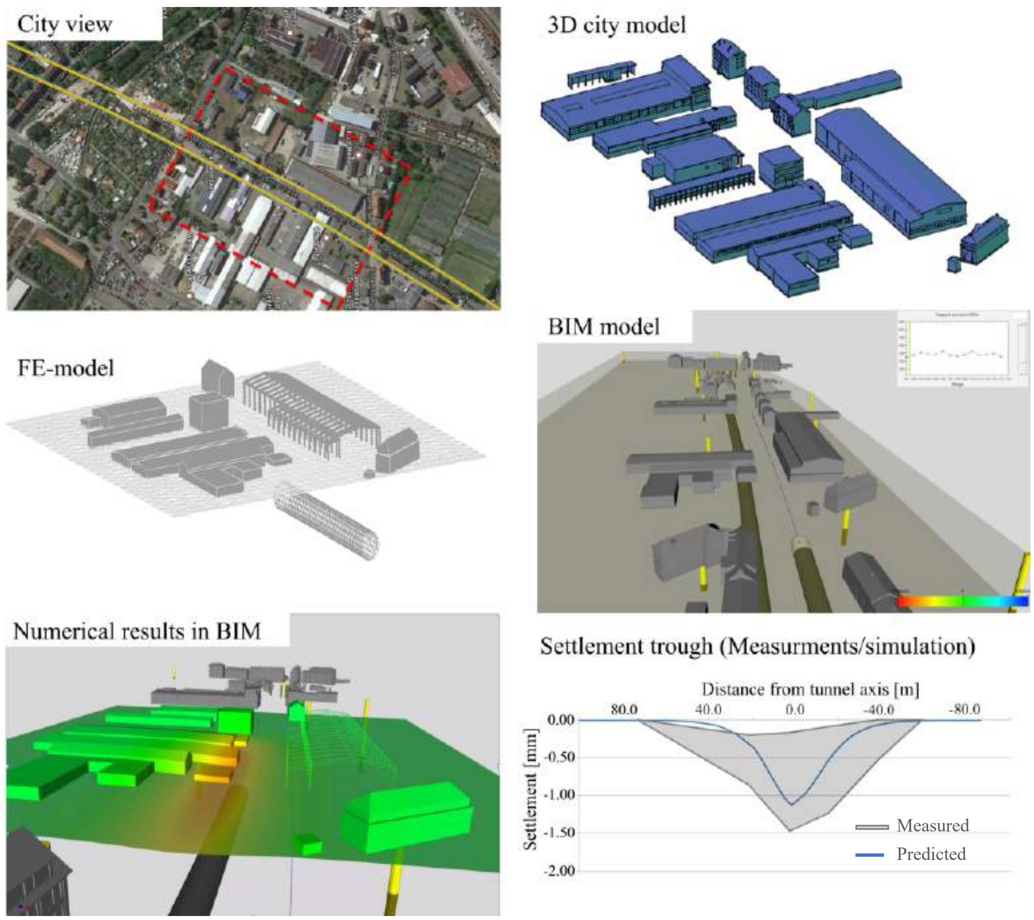

Figure 18: Schematic representation for the "BIM-to-FEM" approach for the provided reference project.

Following the same methodology as presented in Section 4.2, Figure 19 shows the feedback from a FEM-based settlement analysis corresponding to Figure 18, where the tunnel boring machine directly advances alongside a facade of a large building. Here, an IFC-based model viewing environment

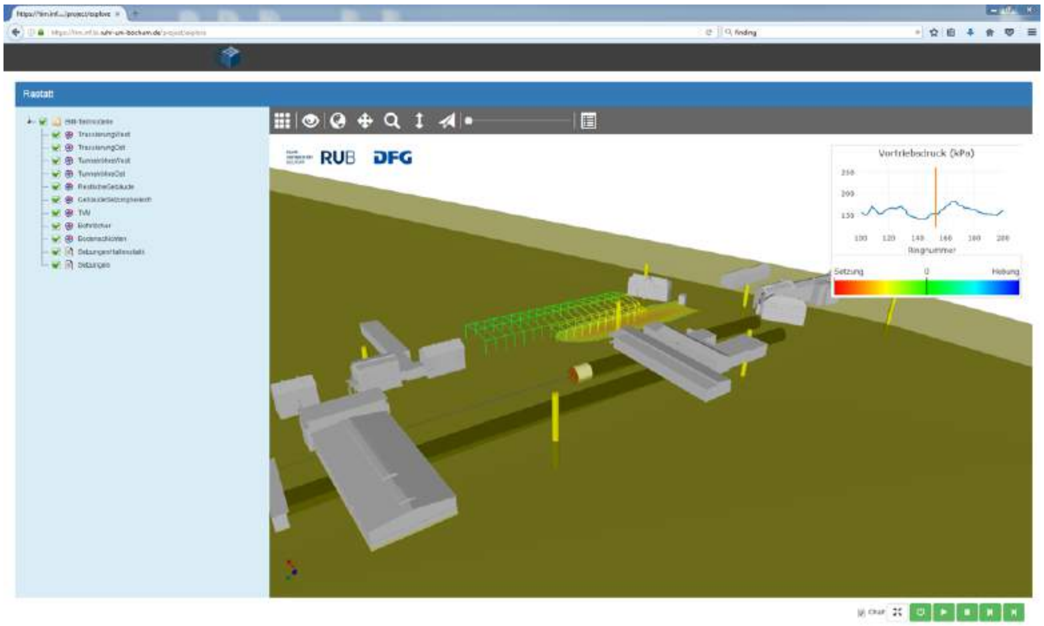

Figure 19: Visualisation of settlement simulation results in time-dependent construction process

is used to effectively visualise selected simulation input and outputs, the history of operational parameters and settlements of the ground and the frame structure, respectively.

4.4. Multi-level modelling: from kilometre to meter scale

The SATBIM approach allows for an effective and computationally efficient way of design alternatives exploration, as the modelling LoD can be increased for particular tunnelling sections where potential risks are identified from an initial low-LoD analysis (see Fig. 20).

In this example, we employed the SATBIM framework to generate a tunnelling scenario using real data, including the 3D topology of the ground based on bore-hole data, 3D tunnel alignment, and building models created based on city model data, to create and analyse a large tunnel section of approximately 1 km length. Fig. 20 (top left) shows how the SATBIM framework is used for the fully automatic generation of the information model based on the CAD data. This model is then further used for the generation of the simulation models and the design assessment of the tunnel construction as illustrated in Fig. 20. Initial calculations of a large tunnel section

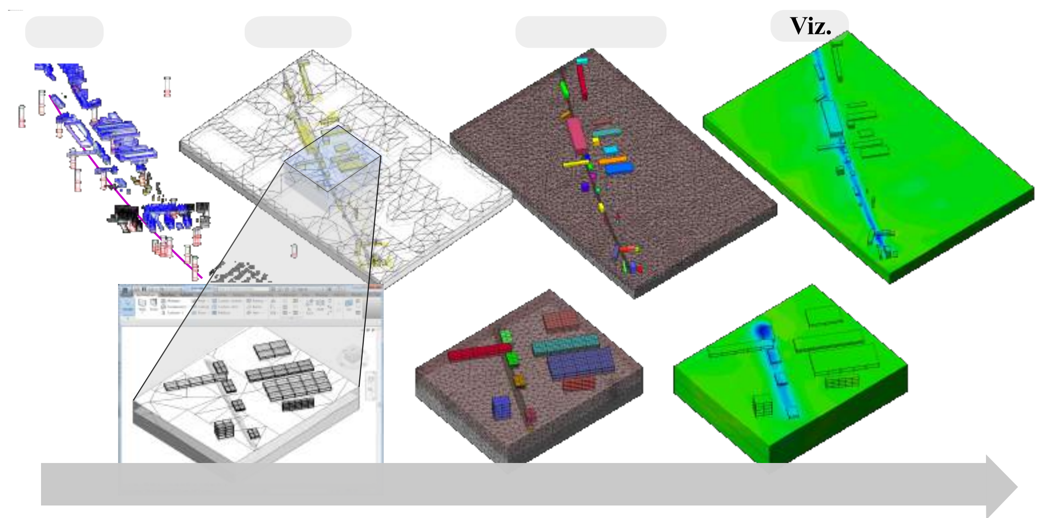

Figure 20: SATBIM: transition between different LoDs depending on simulation scale and identified assessment requirements.

were conducted with a low LoD for the structural components (lining LoD 1, buildings LoD 2 and TBM LoD 1). The evolution of tunnelling induced settlements and their effects on the existing infrastructure were evaluated as illustrated in Fig. 20 (top right). Secondly, for the tunnel section, where potential risks on the existing structure have been identified, a more detailed analysis was conducted, adopting higher LoDs for the structural components (lining LoD 2, buildings LoD 3 and TBM LoD 2) as illustrated in Fig. 20 (bottom).

4.5. BIM-to-IGA: efficient modelling of large tunnel sections

In this example we show how the BIM-to-IGA concept allows to analyse large tunnel sections on the kilometre scale, without compromising the accuracy of the geometrical representation and the achieved numerical solution. This will allow flexible and efficient explorations of a large number of design options in early design stages and therefore contribute to project safety and cost efficiency. Fig. 21 shows two different tunnel alignments specified by B-splines. Upon model generation, i.e. using the SATBIM framework, the geometry is reconstructed to contain volumetric B-splines representations, and therefore can be analysed directly using the IGA approach. The only items to be defined by the user are the tunnel lining geometry (outer and inner radius, ring length, conicity, number of segments, angles describing

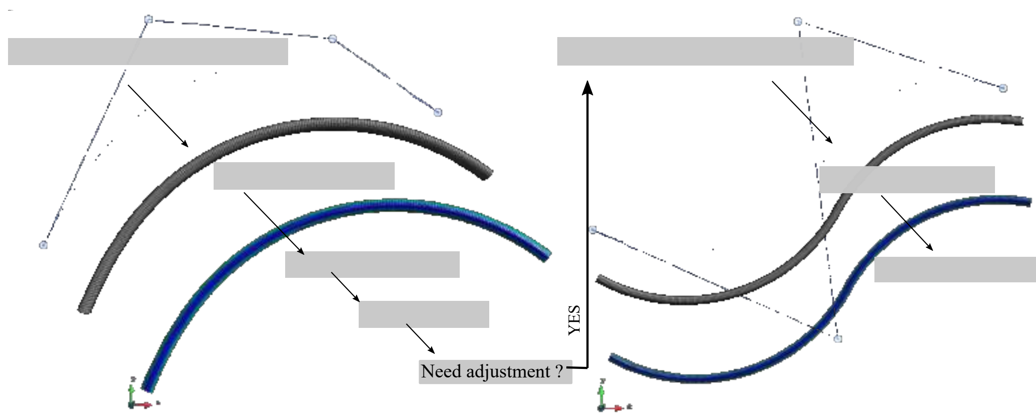

Figure 21: Investigation of different design alternatives using automatized design-through-analysis workflow for segmented tunnel linings.

segment shapes), and the semantic parameters describing the lining and soil materials. In Figure 21 (left), it is shown how, based on ring parameters and the tunnel alignment described with an approx. 300m long spline, the tunnel design model can be automatically generated using the parametric lining model described in Section 3.1 ($\approx$ 240 sec), and then assessed using the workflow described in Section 3.3 (150 sec). Figure 21 (right) shows how the user can simply adjust the shape of the spline in the Revit model, which in this case is S-shaped and more than 600 m long. Again, the design model is automatically generated within $\approx$ 450 sec and analysed within $\approx$ 292 sec). This means that the whole process of creating, changing and assessing a new design of a large tunnel sections is performed within less than 20 minutes. The results, including macro deformation and stress resolution, can be improved by applying hpk-refinement, without altering the geometry.

4.6. Real-time assessment of design alternatives

We exemplify the capabilities of the SATBIM concept for real-time design assessment with the design of tunnel alignments in urban areas to minimise the impact on an existing building. To this end, the SatBimModeller is used for the generation and execution of a large number of simulations in order to obtain the data set for meta model training. In this example, we investigate the impact of tunnel construction on an existing building in terms of the distance of the tunnel from the building and the tunnel depth. The depth of the tunnel crown w.r.t. the foundation of the existing building is in the range of 0.5–2.5 of the tunnel diameter (D) as shown in Figure 22 (a). The tunnel distance from the building in Y direction is 0–6 D for the straight tunnel (Figure 22 b), and is specified as a 1–5 design option (DO) for the curved tunnel (Figure 22 c).

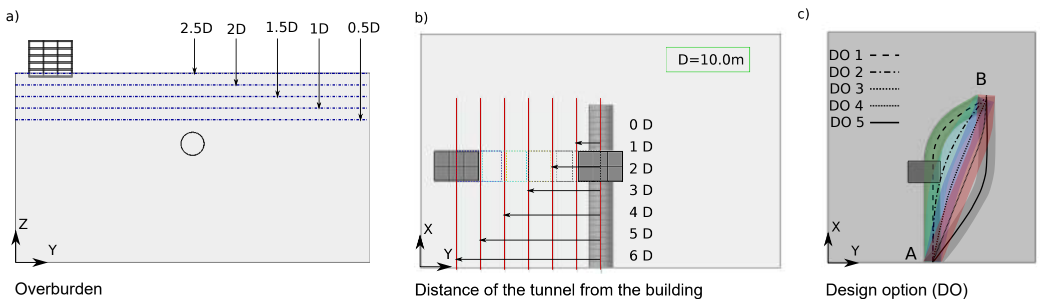

Figure 22: (a) Overburden of tunnel w.r.t. foundation of the existing building; (b) design options for the straight tunnel in terms of distance of the tunnel alignment from building; (c) design options for the curved tunnel.

The meta models for the prediction of tunnelling-induced effects are generated using the workflow described in Section 3.4. These meta models are implemented in Revit by developing a Dynamo node for the forward calculation based on the tunnel model parameters. The trained meta model is imported as a text file, while design parameters are set using value boxes or sliders. Figure 23 illustrates how the simulation-based meta models are used for real-time prediction and design assessment in Revit. In this example, the influence of the tunnel construction onto the existing building is evaluated directly in the design tool. Figure 23a shows the first scenario of the straight tunnel (corresponds to alignment from Figure 22b), where the influence of the tunnel construction on the existing building decreases when the distance from the tunnel and the tunnel depth increase. When the distance of the building and the tunnel depth are large enough, the effect of tunnelling on the existing building is negligible, hence the LoD of the building can be reduced. The second example of the curved tunnel in Figure 23b, for the alignment options shown in Figure 22c, shows similar results in terms of the effect of tunnelling on the building when moving from DO 1 (tunnel below the structure and small cover depth) to DO 5 (tunnel far from the structure with larger cover depth). Moreover, in the second example, meta models are trained to predict both the deformation of the building and the tunnelling induced settlements. It is important to emphasise that in both cases, using the meta model, the results of the analysis are obtained and visualised near instantaneously, while simulations would have taken hours to be calculated using computational models.

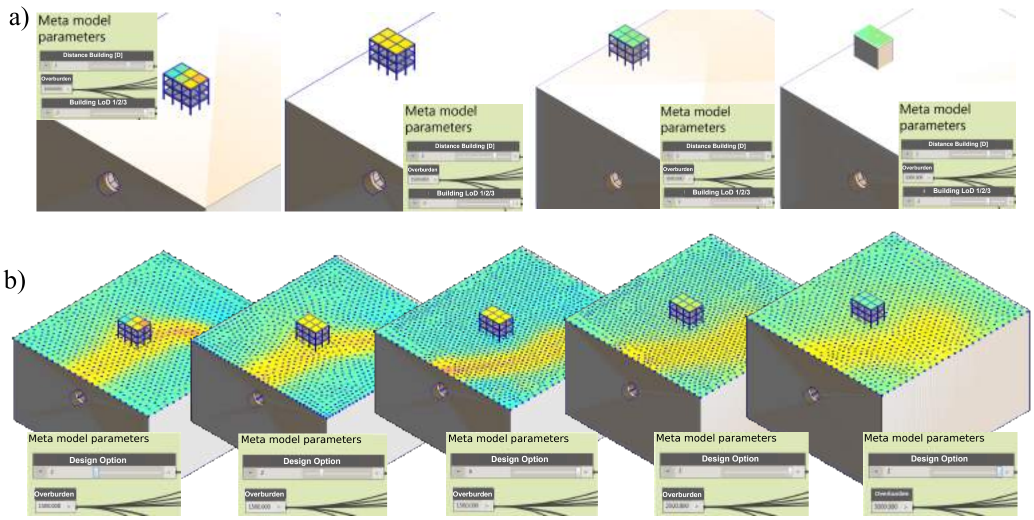

Figure 23: On-demand design assessment of the building deformation in Revit based on simulation-trained meta models for: (a) straight tunnel, including dynamic change of the building LoD; (b) for the curved tunnel, including ground settlements.

5. Conclusions

The design of safe and sustainable tunnelling projects, in particular in urban areas involves complex interactions between the tunnel construction, the ground and existing buildings. To cope with the large amount of interlinked data structure involved large infrastructure projects, using high fidelity computations for prognoses in the design stage, both information and efficient computational modelling strategies are required.

Integration of information modelling and computational simulation requires additional effort in creating a bridge to seamlessly connect the data from a digital information model to an analysis-aware framework. In this contribution, a systematic summary of two approaches has been conveyed. The first one is based on a Tunnel Information Modeling (TIM) concept, in which data is wrapped into multiple layers using IFC representations (i.e. proxies, property sets and model views). Upon user demand, necessary information can be conveniently extracted from IFC for different use cases. Particularly for numerical analysis, the data regarding geology, alignment, lining, material and process parameters are extracted and exchanged to the analysis framework ("ekate") using the standardised ACIS format. It was shown, that enhancing the computational efficiency by using taylor-made paralellisation strategies for mechanised tunneling projects is indispensible when integrating high fidelity simulation models for tunnel advancement into the TIM environment. The second approach, denoted as SATBIM, allows users to directly create and edit the representation of the tunnel model in a user-friendly BIM-enabled design environment (Autodesk Revit). In combination with the visual programming plugin Dynamo, this approach enhances the flexibility in modelling by enabling different LoDs. As a result, models for different analysis scenarios can be generated quickly and on-demand. For instance, the NURBS representation of the lining can be extracted and analysed using isogeometric analysis.

In situations where rapid decisions are required or several design alternatives have to be explored, design assessment has to be performed in near real-time. To solve this problem, in the SATBIM framework, we have proposed a novel concept for on-demand design assessment for mechanised tunnelling using simulation-based surrogate models. Examples have shown, that these models can be built efficiently using a hybrid machine learning approach and can be used for real-time predictions and further analysis such as sensitivity studies.

The presented concepts offer clear advantages compared to the traditional manual modelling approach in terms of modelling efficiency, error-free data exchange and efficient visualisation of simulation data within the BIM context. It is noted, that the quality of predictions also depends on various factors, including availability and quality of data, choice of the constitutive model for the ground and calibration of the prediction model, which has not been specifically addressed in the paper. Our concepts have been shown to be particularly useful to improve the design and decision making workflow of engineers, as verified by a number of representative examples. These concepts are extensible, and more sophisticated data layers can be incorporated. Further aspects, such as the computational efficiency of holistic, TIM-integrated computational models, is subject for further research and development.

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