An integrated platform for design and numerical analysis of shield tunnelling processes on different levels of detail

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ABSTRACT

Building and construction information modelling for decision making during the life cycle of infrastructure projects are vital tools for the analysis of complex, integrated, multi-disciplinary systems. The traditional design process is cumbersome and involves significant manual, time-consuming preparation and analysis as well as significant computational resources. To ensure a seamless workflow during the design and analysis and to minimise the computation time, we propose a novel concept of multi-level numerical simulations, enabling the modelling on different Levels of Detail (LoDs) for each physical component, process information, and analysis type. In this paper, we present SATBIM, an integrated platform for information modelling, structural analysis and visualisation of the mechanised tunnelling process for design support. Based on a multi-level integrated parametric Tunnel Information Model, numerical models for each component on different LoDs are developed, considering proper geometric as well as material representation, interfaces and the representation of the construction process. Our fully automatic model for arbitrary tunnel alignments provides a high degree of automation for the generation, the setup and the execution of the simulation model, connecting the multi-level information model with the open-source simulation software KRATOS. The software of SATBIM is organized in a modular way in order to offer high flexibility not only for further extensions, but also for adaptation to future improvements of the simulation software. The SATBIM platform enables practical, yet flexible and user-friendly generation of the tunnel structure for arbitrary alignments on different LoDs, supporting the design process and providing an insight into soil-structure interactions during construction.

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1. Introduction

Building Information Modelling (BIM) enables the design and analysis of complex, multi-disciplinary systems as often encountered in infrastructure projects and, in particular, tunnelling. Complex projects such as shield-driven tunnels in urban areas require demanding data management as well as analysis during the complete life cycle (design, planning, and construction).

Following the state-of-the-art in engineering practice, the design of a tunnel is assessed by analytical, empirical, or very complex numerical models. In recent years, extensive multi-disciplinary research has been carried out to promote the development and implementation of underground construction. Special focus has been put on the development of numerical models and design concepts to deal with the manifold complex interactions of the components and processes in mechanised tunnelling in urban areas. This allowed to move from empirical models for prediction of tunnelling-induced effects, which neglected the soil-structure interaction effects [1–3], to modern numerical strategies for the modelling of 3D interaction effects [4–6]. Combining sophisticated simulation models with machine learning tools enables predictions of tunnelling-induced effects and steering of the construction process in real-time [7].

On the other hand, in recent years, BIM has gained increasing attention in infrastructure projects, simplifying the planning and analysis and increasing productivity in design and construction. Although BIM was initially developed for managing building data during the building’s life cycle, recently, the concept has been extended to enable the representation of subsurface construction and geo-related data, such as geological, hydrogeological and geotechnical objects and properties [8]. Moreover, the BIM concept has been used to create a tunnel information modelling framework that creates and interlinks a ground model, a tunnel lining model, a tunnel boring machine model as well as a built environ-

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ment model [9]. The most recent advances in BIM for infrastruc-
ture allow for multi-level information representation of the built
environment with the adequate Level of Detail (LoD) to support
planning and analysis tasks of large tunnel projects [10].

Considering the fact that each project from its early design
stage over construction to the operation phase requires both in-
formation management and numerical analysis, the need for a
unified approach becomes evident. Currently, in engineering prac-
tice, the generation of numerical models based on tunnel design
and reports (even when those are part of a BIM) requires
demanding manual intervention of experts and is thus error-prone.
In addition, the resulting simulations can incur substantial com-
putational effort. Recently, the link between information and nu-
merical modelling for modelling of structures has been addressed
in [11,12] where the Finite Element (FE) method is used for the
analysis of the structural behaviour of design alternatives
generated in the BIM framework. Another example is the Analysis
in Computer Aided Design (AiCAD) concept for integrated design
and analysis of structural membranes, where Isogeometric Analy-
sis (IGA) [13] is applied to non-uniform rational B-Splines
(NURBS) surfaces, i.e. unmodified CAD geometry [14–16]. This approach fully
exploits the benefits of geometrical definitions in design tools
(NURBS surfaces) and makes use of basis functions from CAD for
representing the geometry as well as the solution fields in IGA.
Yet, for geotechnical problems, there is no generic link between
BIM and numerical simulations. Some initial research in this direc-
tion has been presented in [17, 18], where data obtained from a
Tunnel Information Model (TIM) [19] is applied for the generation of
the numerical model for a real-world tunnelling project, namely
the Wehrhahn metro line in Duesseldorf.

A unified integration of all information in one multi-level model
not only facilitates technical design and construction aspects, but
also can be employed in cost estimates, accounting, quality con-
trolling, production management and, last but not least, in claim
management for the project. For these economically important
elements, every investment in the configuration of the model and
the supply of suitably processed data pays off as soon as any tech-
nical or contractual problem occurs and information needs to be
retrieved fast and reliably. A seamless documentation along with
clear definitions of times, locations and components of the tunnel
are a prerequisite for that. To this end, the here proposed BIM can
be linked to a process controlling system [20] in the construction
phase of the project to allow for a real-time update of the project
information.

During the design and analysis of major infrastructure projects
such as shield-driven tunnels, different scales have to be consid-
ered: from the kilometre scale for the general alignment of the
track, down to the centimetre scale for detailed design of connec-
tion points, as illustrated in Fig. 1. Moreover, both the planning
and the design phase require data analysis, modelling, numerical
analysis, and visualisation. These tasks are supported by Geographic
Information Systems (GIS), BIM tools, and software for numerical
simulation.

To carry out those tasks with high consistency when chang-
ing scales and modelling the components on different LoDs, a
sound foundation for handling such multi-level representations is
required. Multi-level modelling is already well-established in the
GIS field [21], where most often the “bottom-up” approach is used,
generalizing detailed models to more abstract ones [22]. Besides,
multi-level modelling has become standard for modelling build-
ings [23,24] as well as an integral part of CityGML [25]. However,
there is only a very limited number of examples where the multi-
level approach is used to support the planning, design, and analysis
of large tunnel projects [10].

Multi-level concepts naturally arise from the information quant-
ity and flow at different project stages (planning, design and con-
struction), allowing to build different LoDs from a low to high-
detail representation. For example, the planning process typically
provides only rough information in the early stages (low LoD), but
increasingly detailed and fine-grained information in later stages
(high LoD). The proof of design has to be conducted throughout
all those phases. Nowadays those analyses are usually conducted
using different models and software on different stages, and there-
fore the link between them is not generic and may suffer from in-
consistencies. Therefore, multi-level concepts would be extremely
useful in the context of numerical analysis for such projects.

To enable information and numerical modelling preserving the
consistency of data on different LoDs, this paper presents SATBIM,
a comprehensive platform for incorporating multi-level represen-
tations into BIM and numerical analysis. A particular focus of this
paper is the link between (i) the geometric-semantic modelling of
shield tunnels on different LoD, (ii) the numerical analysis and (iii)
the visualisation of central results of the numerical analysis.

This paper is organised as follows: Section 2 introduces the
case for parametric multi-level information modelling as a basis
for numerical analysis, giving an overview on the software archi-
ecture and the data flow. Section 3 presents the automatic mod-
eller SatBimModeller for the generation of multi-level numerical
simulations for soil-structure interaction in tunnelling based on
the multi-level information model. Moreover, in Section 3, the
visualisation of simulation results within the BIM design environ-
ment and our strategy for real-time design optimisation is intro-
duced. Section 4 gives examples of integrated information and nu-
merical modelling, demonstrating the capabilities of the proposed
concept. In Section 5, we conclude, summarizing the central find-
ings of this paper.

2. Integrated multi-level information and numerical modelling
for design support

2.1. Multi-level parametric information and numerical modelling

2.1.1. The concept

Nowadays, large infrastructural projects require both in-
formation management and numerical analysis on different LoDs
throughout the complete project life cycle. To facilitate the tasks of
design, analysis and assessment of different design solution, SAT-
BIM provides a unified platform for information and numerical
modelling (see Fig. 2a). The central goal of SATBIM is to develop
a multi-level simulation model for the tunnel-structure interaction
integrated in the framework of BIM to support engineering deci-
sions in the planning and design phase. This allows for the sub-
sequent evaluation and minimisation of risks on existing infrastruc-
ture. Our approach also enables the general evaluation of the ef-
ciciency of such a multi-level simulation approach in other fields
related to engineering design and risk assessment.

The appraisal of different design alternatives is essential for
ensuring an optimal design alternative. The current state-of-the-
art process for dealing with alternatives involves repeated man-
ual changes of the simulation model, re-simulation of the com-
plete model, and manual evaluation of the results. This is cumber-
some, error-prone, and requires significant computing resources
and time. Note that in the conceptual phase, a designer often only
needs approximate estimations for many different scenarios, e.g.
tunnel track alternatives. Moreover, different design objectives re-
quire different approaches for assessing the safety and stability. For
example, minimising the overall risk of damage to buildings needs
high LoD for structures and low LoD for lining, while estimating
stresses in the tunnel structure needs high LoD for lining, while
low LoD for buildings is sufficient (see Fig. 2b).

To ensure a seamless workflow, the analysis time should be
minimised, i.e., the simulation model should be configured such

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