



A tunnel information modelling framework to support management, simulations and visualisations in mechanised tunnelling projects



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ABSTRACT

A transparent, holistic and detailed design of individual systems and processes in mechanised tunnelling is 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 and the built environment 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, unilateral decisions are made that do not consider all relevant aspects. Existing research has focused either on very general approaches of multi-model container or linked data models 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 integrating four interlinked subdomain 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 concepts of Proxies, Property Sets and Model View Definitions. Based on the proposed framework selected case studies are presented to verify its potential and advantages when (1) interactively visualizing 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 Düsseldorf, Germany.

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 are essential. Mechanised tunnelling is an established flexible and economical construction method for underground structures that is characterised by its trend towards larger shield machine diameters, meanwhile up to 19.25 m, and its constantly growing range of application areas [1].

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 specialised 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, and the above-ground buildings 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 of the machine.

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 of data). Differences in model scale refer 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

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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 (scale of data). 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 of data). Finally, it is important to recognise the life cycle phase in which the data is being created, maintained and used 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.

To use and analyse this diverse data in an efficient and practical manner, a consistent and holistic information model is required. Consequently, diverse software applications need to be 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 an integrated information model. A further advantage of such a model is the ability to provide a 4-dimensional visualisation of the relationships between stored data through mapping in space and time.

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 and linked data approaches that have not yet been adapted to tunnelling projects. To address current shortcomings, this paper presents the development of an integrated tunnel information modelling framework. The overall framework suggests a tunnel information model that consists of several subdomain models, which represent the various data sources of a tunnelling project. To verify the presented approach, a specific tunnel information model is presented with data from a real-world reference project of a subway tunnel in Düsseldorf, Germany. Based on this model selected case studies highlight its potential and advantages when (1) interactively visualizing time-dependent settlement monitoring data in an environment-aware context and (2) generating advanced numerical simulation models to predict settlements.

2. Background

2.1. Current practices in tunnel project data management

Tunnelling project documents are usually available in many different types, scales, and formats, originate from loosely coupled and dispersed resources, but are strongly interdependent. This issue is illustrated in Fig. 1. The type and format of data differs widely (e.g. CAD drawings, text reports, spreadsheets, diagrams and images (Fig. 1)). This complicates their integration in design, simulation and visualisation models, because required data has to be re-organised from multiple resources, and documents have to be scanned for appropriate information and parameters. Additionally, these parameters usually have to be manually integrated and updated in case of design changes. Thus, in tunnelling practice, numerical simulations, for example, are still not being 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 (pre-processing) for settlement prediction simulations [2,3].

In practice, data exchanges between design 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

tunnel construction projects, usually with the goal of monitoring TBM performance data, monitoring geological data, recording material consumption and deliveries, and controlling project costs (e.g. [4]). The focus of these systems, however, is mainly to efficiently structure the large amount of raw data generated during a tunnelling process and provide a basis for further analysis. Performing project data analyses that cover more than a single project component, e.g. settlement visualisation in the context of machine performance and existing buildings, is not possible.

2.2. Current research efforts

To cope with current limitations in practice, several research efforts have been devoted to information modelling of large construction projects. Research activities highly related to the work presented in this paper can be subdivided into infrastructure information modelling, and multi-model data management and linked data.

2.2.1. 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 [5]. Building information models are commonly used as shared data and knowledge resources to support planning, construction, management, utilisation, revitalisation, 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 using standardised exchange formats, such as the Industry Foundation Classes [6].

The use of standardised 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 visualisation 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 hierarchically organised 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 visualisation (geometry) component and a set of semantic information attached to this 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 [7,8] and roads [9,10].

The modelling of tunnels in shield tunnelling using IFC-based multi-scale product model has been presented in [11,12,13,14]. 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, analysis and preparation of measured data, such as settlements or machine performance data, or the modelling of the tunnelling machine itself is not provided. Vossebeld and Hartmann [15] have proposed an information model to support safety professionals that is aimed at maintenance governance and road-user safety evaluation. However, tunnel design support and context-aware visualisation of construction risk have not been addressed.

To model and analyse large-scale infrastructure projects, Geographic Information Systems (GIS) have 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 [16]. Several modelling approaches based on GML are GeoSciML [17], GroundXML based on LandXML [18] and CityGML

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