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Digital Transformation in Tunneling – A Project Report on TransIT

Abstract

The digital transformation has significantly affected many industries. Recently, it has gained momentum in the Architecture, Engineering, and Construction (AEC) sector in general and tunneling in particular. To support these developments, TransIT represents an inter-university and interdisciplinary research initiative with the goal of advancing digitalization in tunneling. This article discusses the challenges connected with the digital transformation of the tunneling sector. We examine this topic with different use cases demonstrating solutions to those challenges.

Keywords

tunneling, digitalization, digital transformation

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1 Introduction

The Brenner Base tunnel, currently being built between Austria and Italy, will be the world's most extended underground railway connection. In addition to this engineering masterpiece, multiple other gigantic tunneling projects are underway in Austria. Digital technology, such as Building Information Modeling (BIM), Artificial Intelligence (AI), and Augmented Reality (AR), is attributed to improving productivity, lowering costs, and increasing quality (HUYMAJER & WINKLER, 2018). The research community has made significant efforts to apply digital technology to challenges in the Architecture, Engineering, and Construction (AEC) sectors while the industry made substantial progress in its implementation. Despite these remarkable achievements, the tunneling sector continues to face challenges in achieving a level of digitalization comparable to other sectors within AEC. TransIT's primary goal is to change this and to demonstrate some state-of-the-art digital technologies in the tunneling domain prototypically. Another goal of TransIT is to bring different stakeholders from teaching, research, and industry closer together to foster the digitalization of the tunneling sector.

Tunnel construction, or tunneling for short, can be understood as a sub-discipline of civil engineering with connections to surveying, geology, and hydrology, among others. Historically, tunneling has developed from mining and occupies a unique position within civil engineering. Modern tunneling can be discerned between conventional tunneling (or cyclic method) and mechanized tunneling (or continuous method). In conventional tunneling, heavy equipment and explosives are used to drive the tunnel, whereas so-called tunnel boring machines are employed in mechanized tunneling. Both methods have specific strengths and weaknesses, and the choice of the method depends on many parameters.

TransIT focuses on the digitalization of conventional tunneling projects. TransIT is an inter-university research project with a strongly interdisciplinary character that aims to apply computer science concepts to tunnel construction (MAZAK-HUEMER, GALLER, WENIGHOFER et al., 2020). Those concepts are evaluated using data from the Zentrum am Berg (ZaB) , an underground facility for research and development, education, and training (GALLER, 2016). The project is a collaboration between Montanuniversität Leoben, TU Wien, and Johannes Kepler University Linz. In this project, the tunneling domain is represented by the Chair of Subsurface

Engineering , the Institute of Construction Process and Construction Economics , and the Institute of Material Technology, Building Physics, and Building Ecology . The Institute of Information Systems Engineering and the Institute of Business Informatics – Software Engineering represent the computer science domain. TransIT demonstrates the digital transformation of tunneling with several different use cases.

This article provides a concise overview of TransIT's achievements up to its third year and discusses our future work. The article is structured as follows: Sections 2 to 7 discuss various use cases examined in the project, and Section 8 concludes the article with a summary and future outlook.

2 Tunnelling Hub

A collaboration of different research areas, such as civil engineering, geology, hydrology, and computer science, is crucial for the digital transformation of the tunneling sector. However, it has been shown that there is limited cooperation between different fields within the scientific tunneling community (HUYMAJER, WOEGERBAUER, WINKLER et al., 2022). Moreover, there is insufficient collaboration between teaching, research, and industry.

This project introduces the Tunnelling Hub to tackle this challenge. The Tunnelling Hub is a cross-domain platform to connect the community in the field of digitalization of tunneling. The community consists of stakeholders from teaching, research, and industry. The open character of this platform is essential, which is achieved through the use of concepts such as open-source software, open data, and open science. A publication repository gives all stakeholders an overview of the current research on digitalization in tunneling. The publication repository collects information from different online sources and compiles a list of relevant publications. The list contains essential meta-data and links to publishers to access full-text versions. A use case repository allows project members and stakeholders to share their contributions with the community. The project members currently maintain the use case repository, which allows the presentation of digital media, such as texts, images, videos, or general data for a specific use case related to digitalization in tunneling.

From a technical point of view, the Tunnelling Hub is an interactive website built on modern and open technology. Only free software components are used in the implementation, and data will be offered in machine-readable form via interfaces. The main focus is flexibility, which allows future requirements to be taken into account in an agile manner. Compared to the technology employed in the Tunnelling Hub, which is domain-independent, the managed content on the Tunnelling Hub exclusively focuses on the tunneling domain. A continuation of the platform after the end of the project should make a sustainable contribution to the digitalization of tunnel construction. Ready-made software components are used wherever possible during development to keep future maintenance costs low. Web technology can usually be divided into a backend component, typically running in a data center, and a frontend component, running in the user browsers. The Tunnelling Hub utilizes a web framework employing the model-view-template paradigm on the backend (SHAW, BADHWAR, GUEST et al., 2023). A modern JavaScript library is used as a frontend technology (YIN, 2020). The selected technology allows for a so-called single-page application, which means that the content of the viewed website is dynamically changed upon user interaction. This gives a better user experience compared to websites where the browser has to load whole pages.

The current level of development can be accessed online[2]. Figure 1 shows a web browser accessing the Tunnelling Hub. The implementation of the publication repository and use case repository are both finished.

Future work includes extending the Tunnelling Hub with a benchmarking functionality. Furthermore, we plan to add functionality for using the Tunnelling Hub as a digital twin environment. We are also working on enhancing the user interface.

2 https://v2.tunnellinghub.at/

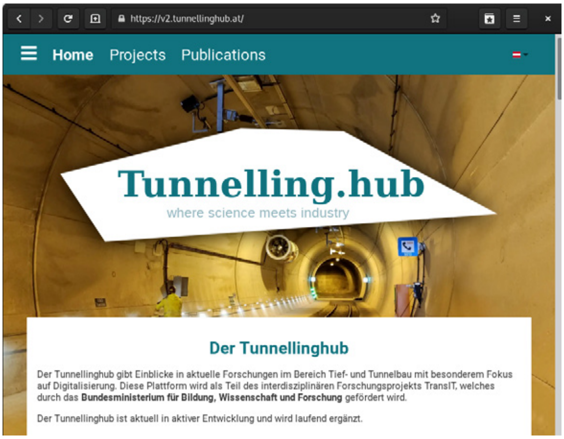

Figure 1: The Tunnelling Hub

3 Data drop platform

The realization of large-scale projects such as tunnels is tied to the creation, management, and review of an enormous amount of documents that include technical data (e.g., BIM models, construction plans), legal files (e.g., land and nature surveys, legal documents) and other, more generic files (e.g., work schedules, resource planning). Over the long course of large projects, these documents are continuously updated and extended by individual project partners but often need to be reviewed and agreed upon by a consortium. In practice, the so-called data drop concept (Figure 2) emerged as a best practice of document management, where each data drop represents a snapshot of an updated, reviewed, and accepted version of all (or a large set of) managed documents (PASKALEVA, NIEDERMOSER, VIERHAUSER et al., 2022).

We might compare such document versioning and management to common version control best practices for software projects, where releases (i.e., specific versions of all files) are made available regularly after a thorough testing and review phase.

Hence, one work package of TransIT encompasses the development of a platform that will bring modern versioning and similar techniques to the tunneling domain. We have developed a research software tool tailored to the tunneling domain, designed to support a modern file management and versioning system. The tool also seamlessly integrates a customizable review process for the review and release of data drops.

In the development process, we implemented a proof-of-concept application as a starting point for a full-fledged application. Primarily, the application focuses on file versioning and review process modeling. File versioning is the ability to create, edit, and update files while keeping older versions for reference. Additionally, a tagging mechanism is required to create a data drop, i.e., a common label for a set of file versions. Currently, this system is based on a Git backend, but in future versions of the platform, we plan to incorporate versioning systems better suited for the documents used in tunneling projects. Business Process Modeling (BPM) is often used to express and specify workflows in a system. The data drop platform allows modeling the review process using the Business Process Model and Notation (BMPN). This is implemented with Camunda[3], a popular BPM engine. Users can thus employ graphical tools to design and alter review processes that can then be integrated into the frontend application.

At the moment, we are working towards extending the proof-of-concept into a prototypical data drop platform. This platform can showcase the benefits of modern document versioning to practitioners and as a foundation for further evaluation and research.

3 https://camunda.com/

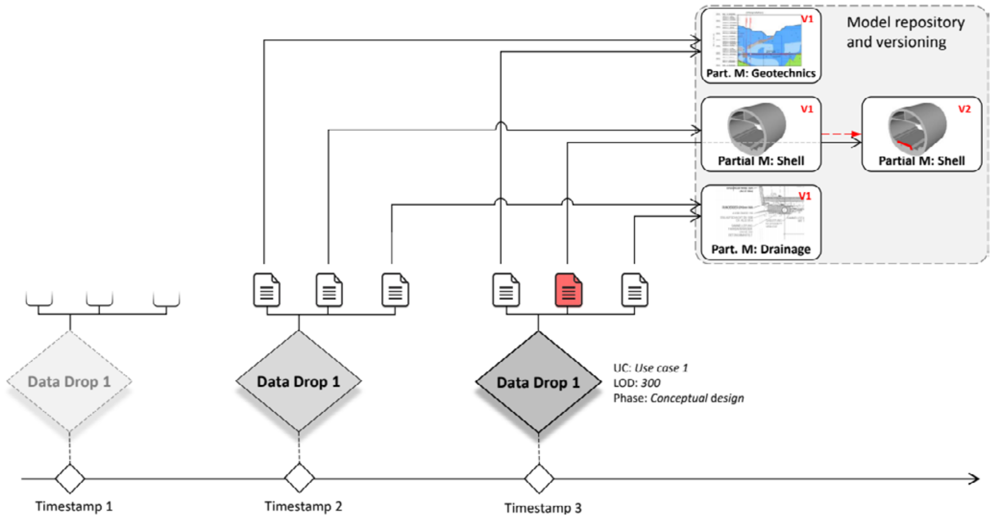

Figure 2: The data drop concept

4 Tunneling Information Management System

The execution of today's tunneling projects requires a substantial amount of documentation (MELNYK, RAAB, & LULEI, 2023). Due to the extensive use of BIM, the design phase of tunneling projects is already mostly digitalized. On the other hand, the construction phase still frequently employs paper documents or unstructured data, such as spreadsheets and scanned documents, for data storage and exchange (KVASINA, 2018). The main issue with unstructured data is that they do not express the semantics and are thus generally not comprehensible by machines. Therefore, such data cannot be automatically processed but requires human involvement, which is costly and error-prone.

We implemented a Tunneling Information Management System (TIMS) to solve these issues (HUYMAJER, OPERTA, MAZAK-HUEMER et al., 2022). TIMS is a software tool for managing data from the tunnel drive. These data typically include detailed recordings of the activities performed and labor, material, and heavy equipment employed. The data are organized according to a data model with precise semantics and can, therefore, be understood by machines and thus automatically processed. A streamlined interface allows users to record these data directly where they arise, at the tunnel face. After the data have been checked, corrected, and confirmed by project management, the data can be exported to established software tools. This facilitates end-to-end digital data flow.

TIMS is based on state-of-the-art and free software platforms. The utilized Tryton framework[4] enables rapid application development by offering a broad range of functionality found in modern software, such as object-relational mapping, user management, access control, a workflow engine, a view engine, a report engine, and functionality for internationalization. We decided to implement two different user interfaces. One user interface is optimized for hassle-free data entry directly in the tunnel using a mobile device. The second user interface, depicted in Figure 3, offers a broader functionality range and is typically used by project management and supervision using a desktop computer. All the data is accessible in a machine-readable format via an application programming interface (API).

We imported one month of tunnel construction data from ZaB into TIMS to evaluate our BIM approach (MELNYK, HUYMAJER, HUEMER et al., 2023). The evaluation has shown that the complete invoicing process could be digitalized.

Industry Foundation Classes (IFC) has become the de-facto standard as an open and vendor-neutral data exchange standard (BORRMANN, KÖNIG, KOCH et al., 2018). We are currently working on extending TIMS's functionality to generate IFC data from construction data.

4 https://www.tryton.org/

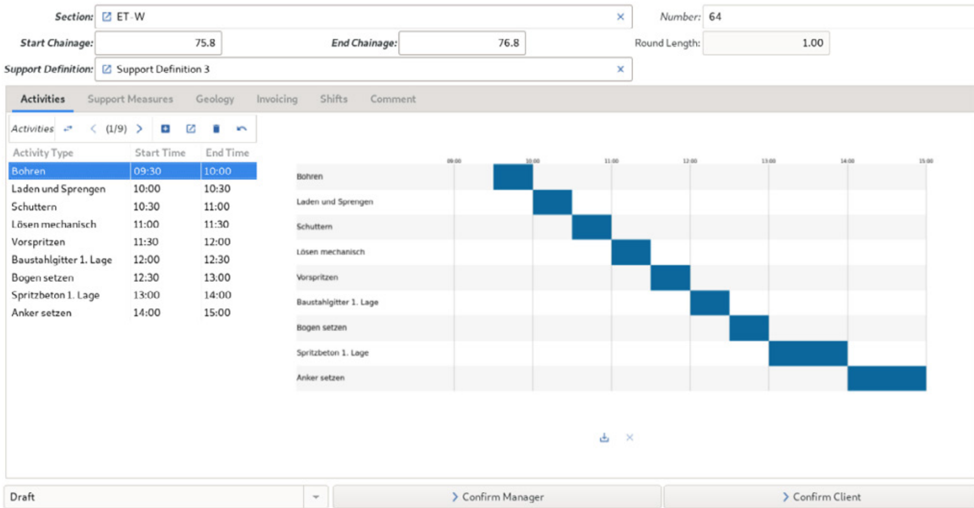

Figure 3: The TIMS user interface

5 Digital Twins for Tunneling – Use case ventilation simulation

One of the major challenges both during the planning and operational phases of a tunnel is the need to store all kinds of information in a common data environment (CDE). CDEs allow building operators to monitor their buildings and compare the measured results to the expectations of the planning process. The findings can then be used to control the building's system, thereby forming a digital twin (BORRMANN, KÖNIG, KOCH et al., 2018). The use case's main goal is to build a digital twin environment for tunneling, which allows tunnel operators to use simulation results and measured sensor data to control the tunnel's ventilation system.

The example workflow that shows the capabilities of the digital twin starts with importing a tunnel model from Civil3D (Figure 4a), a commercial software tool used in the tunneling industry, into the SIMULTAN data model (Figure 4b). Based on the imported tunnel geometry, a specialized simulation geometry for the ventilation simulation is generated (Figure 4c). The heat transfer is simulated using a computational fluid dynamics simulation in OpenFOAM[5] (Figure 4d). The simulation geometry, together with the simulation results, are then stored in the initial SIMULTAN model, both for documentation and future reuse of the simulation geometry.

The digital twin is modeled in the open-source data model SIMULTAN[6] (PASKALEVA, LEWIS, WOLNY, STEINER et al., 2019; PASKALEVA, WOLNY & BEDNAR, 2018), which has been successfully used for digital twins of buildings (STEINER, SARKANY, JÁROSI et al., 2023; BÜHLER, STEINER & BEDNAR, 2022; PASKALEVA, LEWIS, WOLNY & BEDNAR, 2019) and is developed by TU Wien, Research Unit of Building Physics. SIMULTAN is also a data modeling tool that allows users to organize their data more flexibly compared to traditional data models, such as IFC[7]. This enables fast prototyping in research projects. Since SIMULTAN has not been used in the tunneling domain before, it is a part of the project to extend its capabilities to include tunnel-specific requirements. We identified the need to store multiple geometric representations of the tunnel (tunnel alignment, tunnel sections, and simulation geometry used for the ventilation simulation) simultaneously as a missing key feature and extended the SIMULTAN modeling tool with a multi-geometry system.

Finally, a physical model of a tunnel will be built as a testing environment for the coupling with the actual tunnel. It should enable users to experiment with the digital twin, including simulations and sensor data, and other IoT (Internet of Things) equipment, like the control unit of an air fan. This prototype will allow experts to test different algorithms without the risk of operating in a real tunnel environment.

5 https://www.openfoam.com/

6 https://github.com/bph-tuwien/SIMULTAN

7 https://standards.buildingsmart.org/

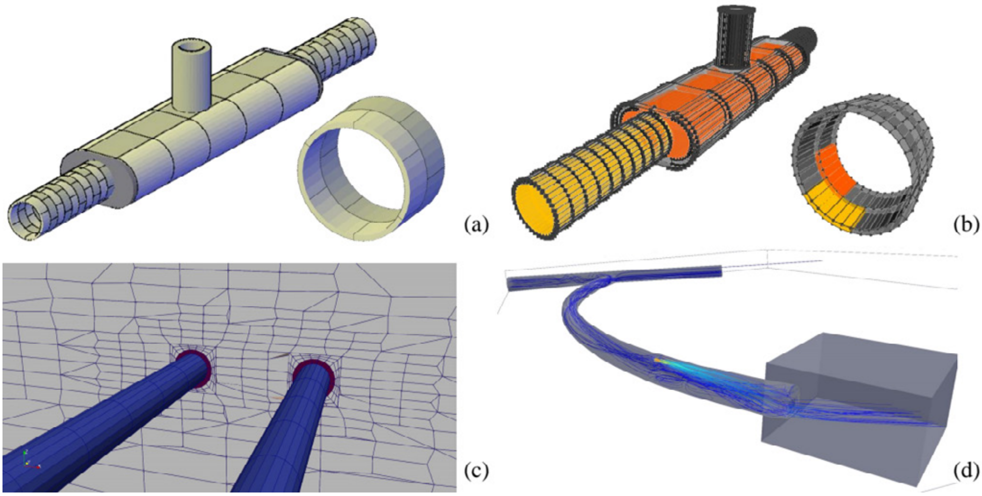

Figure 4: The initial tunnel model (a) is imported into the SIMULTAN MDM (b). A simulation grid (c) is generated and OpenFOAM is used to calculate the air flow (d)

6 Augmented Reality

Augmented reality (AR) is expected to become an integral part of the Architecture, Engineering, and Construction (AEC) industry. Incorporating AR technology into the construction process can enhance spatial awareness, visualization, and animation, offering valuable benefits without replacing traditional materials (CHACÓN, 2021). Multiple platforms, such as "AR-supported Teaching", could facilitate the creation of interactive AR scenes using BIM models, facilitating distance learning and collaboration (URBAN, PELIKAN & SCHRANZ, 2022). The positive impact of AR extends beyond education, as it improves motivation, learning experiences, and understanding of complex issues (THOMS, 2019; KHAN, JOHNSTON & OPHOFF, 2019; NIEDERMEIER & MÜLLER-KREINER, 2019; JOAN, 2015). Numerous studies have further demonstrated the favorable learning outcomes associated with

AR compared to conventional textbooks (JAN, NOLL, BEHRENDS et al., 2012; PATHANIA, MANTRI, KAUR et al., 2021; ALBRECHT, FOLTA-SCHOOFS, BEHRENDS et al., 2013). Integrating mixed reality (virtual reality – VR and AR) with BIM further enhances the learning environment in construction engineering training (VASILEVSKI & BIRT, 2020). Despite the proven benefits of AR in learning outcomes, its utilization in higher education remains limited due to resource constraints and accessibility issues (YUEN, YAOYUNEYONG & JOHNSON, 2011). As demonstrated by (URBAN, PELIKAN & SCHRANZ, 2022), AR holds significant promise for the future of the industry with the potential to revolutionize tunnel construction and other AEC disciplines. In addition to education, AR brings numerous benefits to the tunnel construction industry (GU, SINGH & WANG, 2010; ZOLLMANN, HOPPE, KLUCKNER et al., 2014). AR can provide real-time visualizations and overlays of digital information onto the physical environment, allowing engineers and construction workers to better understand and interpret complex tunnel designs (MESAROS, SOLTES & MESAROSOVA, 2014). By superimposing virtual models, plans, and data onto the construction site, AR enables precise alignment of tunnel components, reducing errors and improving overall accuracy during construction (GIMENO, MORILLO, CASAS et al., 2011). Additionally, AR can provide on-site guidance and instructions, displaying step-by-step procedures and safety information directly in the workers' field of view (KATIKA, KONSTANTINIDIS, PAPAIOANNOU et al., 2022). This ensures that construction tasks are executed correctly and according to specifications, improving productivity and minimizing errors. Moreover, AR can be employed for the effective maintenance and inspection of tunnel structures. By overlaying digital information onto physical components, inspectors can quickly identify potential issues or anomalies, such as cracks, corrosion, or structural deformations (SHIN & DUNSTON, 2010). This enables timely detection of problems, facilitating proactive maintenance and ensuring the longevity and safety of the tunnel infrastructure.

TransIT has made progress in addressing the research issues surrounding AR in conventional tunneling (Figure 5a). The conducted study specifically investigates the potential use of AR for achieving localization within tunnels and explores the application of AR-based site inspection for documenting tunnel construction problems (FENZL, 2022). The study also aims to evaluate the effectiveness of the developed prototypes in a tunnel environment and their ability to improve traditional site inspection procedures. The localization prototype (Figure 5b) developed in this research shows promising results, offering reliable solutions for mapping tunnels using the world lock tool framework and space pins (FENZL, 2022). Incorporating physical markers provides a backup solution in cases where the prototype fails to recognize virtual markers, ensuring robustness across diverse environments. User testing and focus group interviews indicate that the prototype is intuitive to use, although some issues requiring improvement were identified in AR-based tunneling applications. These include enhancing guidance information on the user interface and addressing the slow input speed associated with keyboard interactions. The research highlights the viability of AR applications for tunnel localization and site inspection using currently available hardware, such as Microsoft's Hololens 2. AR offers benefits such as spatial mesh detection, GPS-free localization, and hands-free operation, expediting various documentation processes during construction. However, challenges related to hand gesture recognition, spatial mesh detection, low frame rate, and a narrow field of view need to be addressed in future iterations. Advances in AR device technology are expected to resolve these issues.

Figure 5: AR headset user in a tunnel (left) and AR software prototype (right)

7 Digital Academic Program

In the digital transformation of the construction industry, new tools and solution approaches for ecologically optimized and sustainable planning, design, and manufacturing processes are imperative. Future development will occur at the interfaces between computer science and the classic disciplines of civil and environmental engineering and will require engineers with strong interdisciplinary training.

In order to accommodate these new job profiles, new educational programs are needed. TransIT may play a pivotal role in shaping these new profiles and programs in this field. Based on the experiences gained during TransIT, TU Wien and Montanuniversität Leoben decided to establish a new inter-university master program digital civil engineering sciences. This program represents a significant leap forward in addressing the demands of the digital age, extending well beyond tunneling to encompass the broader spectrum of digitalization within engineering.

In this master program, the students are trained in an interdisciplinary manner. This means that they acquire all the necessary basic knowledge from computer science and civil engineering to build on this with targeted interdisciplinary knowledge of digital planning, construction, and operation. They can thus apply various concepts of computer science, which serve as drivers of digitalization, in the context of civil engineering. They not only recognize the potential of these concepts for the construction industry but also possess the expertise to implement them effectively. Importantly, they develop the capability to assess the associated risks and consequences, considering factors such as life cycle management and sustainability. With these competencies, they have a holistic understanding of digitalization in the construction industry and drive the digital transformation process in building construction and civil engineering. In this way, they will contribute to enhancing the efficiency, quality, and sustainability within the construction sector.

Currently, TU Wien and Montanuniversität Leoben are drafting the joint curriculum, expected to be announced in 2024. It is expected to start this program based on hybrid learning technologies supported by a corresponding mobility concept in the autumn of 2024.

8 Conclusion

We have outlined some of the challenges in the tunneling sector and discussed how different digitalization concepts can be employed to tackle those challenges. We also reference some of the publications from this project and provide deeper discussions of the project's achievements.

However, the project's impact is more far-reaching than the mere software artifacts and the dissemination within the scientific community. In the course of the project, the cooperation between the domains of tunneling and computer science has been sustainably strengthened. With the increased collaboration between the research domains, the collaboration between the universities has also been strengthened. On the part of computer science, TransIT has contributed to understanding challenges in tunneling. On the part of tunneling, it has been possible to gain an overview of computer science concepts and how tunneling could profit from them. This collaboration of the domains is reflected at all levels of the research areas – from the professorial level to the student level.

The project is still ongoing, and we are confident to present further contributions to the digital transformation of the tunneling domain in the near future.

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