Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering (38th Cycle)

Digital Transition in Mechanized Tunneling Construction

Insights from the TELT Project – Lots 6/7

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Abstract

The tunneling industry is one of the most technologically advanced domains within civil engineering, marked by its inherent complexity, high risks, and demand for precision. Recent years have witnessed a surge in tunneling projects driven by sustainable transport needs, energy transition, and urban growth. Simultaneously, the rapid evolution of digital technologies has opened new opportunities to transform how tunnels are designed, built, and managed. The primary motivation of this research lies at the junction of these two dynamics: (i) the accelerating global demand for tunnels and (ii) the transformative potential of digitalization in tunneling construction.

This study is guided by a central research question: Can digitalization techniques improve processes in mechanized tunneling construction? Complementary questions address which technologies provide the greatest improvements, which project domains benefit most, and what barriers hinder the digital transition. These questions were explored through the assessment of digital strategies implemented in a major European tunneling project: Lot 6/7 of the Turin-Lyon High-Speed/High-Capacity Railway Project (TELT).

The originality of this research lies in two main aspects. First, it provides a comparative assessment of multiple digital solutions within a unified tunneling framework, clarifying their strengths, limitations, and complementarities. Second, it bridges research and practice by embedding technological innovation within one of Europe's most complex tunneling projects.

An initial literature review identified six key domains of digital innovation with significant potential to support the digital transition of tunneling construction: (1) Building Information Modelling (BIM), (2) automation platforms, (3) Internet of Things (IoT), Digital Twin (DT) and Management Systems (4) artificial intelligence, and machine learning (AI/ML), (5) robotics and (6) immersive technologies such as augmented/virtual reality (AR/VR).

To evaluate these domains in a real operational context, the doctoral activities included the development, implementation, and testing of several digital solutions within Lot 6/7 worksite. Automation tools based on visual programming languages were developed to accelerate modelling, analytical calculations, and documentation processes. BIM methodologies were applied to improve the coordination of construction activities and multidisciplinary teams. IoT-based management systems and Digital Twin solutions were implemented to enhance data communication and support decision-making processes, while Virtual Reality simulators were used to improve the training of Tunnel Boring Machine (TBM) operators. Some solutions were directly developed by the author (e.g., visual programming scripts and BIM models) while others required coordination with external technology providers such as tunneling management platforms and professional VR training systems. Artificial intelligence and robotics were not directly implemented during the project phase but were included in the broader analytical framework due to their long-term potential for the industry.

The evaluation phase combined the author's direct project involvement with stakeholder feedback collected from 87 AECO professionals, including tunneling experts, technology developers, academics, and trainees. The analysis focused on four domains where digital technologies can provide measurable improvements -(i) design and modelling, (ii) coordination of works, (iii) project management, and (iv) technical operations- together with perceptions of (v) ease of implementation. Qualitative insights were obtained from the author's experience, while quantitative results were analyzed using average values, Relative Importance Index (RII), and graphical data representations, distinguishing between respondents with and without tunneling experience.

Findings confirm that digitalization significantly enhances mechanized tunneling processes, though benefits vary across technologies and domains. IoT/DT systems proved most effective for real-time decision-making and management; BIM improved work coordination and communication; automation optimized modelling workflows; and robotics enhanced safety and efficiency. Most relevant challenges that limit the implementation of the digital strategies include limited digital literacy among tunneling professionals and organizational resistance to change persist as major barriers to effective adoption.

Overall, digitalization improves both operational and managerial performance, but its success depends as much on human and organizational readiness as on technological maturity. The future of tunneling will rely on the synergistic integration of digital strategies with sustained investment in human capital -through digital training and cultural adaptation. Achieving a fully digital tunneling ecosystem will require not only technological progress but also the institutionalization of digital thinking across people, processes, and organizations, fostering innovation, efficiency, and resilience in underground construction.

Key Words

Digitalization; tunneling; construction; TBM; BIM; Digital Twin; tunnel; Digital Transition