

ASSISTANCE SYSTEMS AS A RISK MANAGEMENT TOOL FOR MECHANISED TUNNELLING

Prof Dr Matthias Flora

FLORA Tunnelling GmbH, Innsbruck, Austria

ABSTRACT: Mechanised tunnelling in urban environments is among the most complex and risk-intensive activities in civil engineering. Geological uncertainty, dense surface infrastructure, and high societal expectations regarding safety and reliability place enormous pressure on tunnelling projects. At the same time, key technical and organisational decisions must be made early, based on limited information, and managed throughout a highly dynamic production process. Under these conditions, traditional static risk management approaches are no longer sufficient.

This paper presents a human-centred digital assistance methodology that transforms risk management from retrospective planning into a continuous, operational process embedded directly into TBM production. The approach combines domain expertise with structured data management and intelligent algorithms. At the core of the methodology lies an integrated assistance system that continuously monitors critical TBM parameters and evaluates them using AI-supported analysis of thresholds, trends, and interdependencies. Rather than generating standalone alarms, the system provides context-aware warnings and actionable operational recommendations.

The paper further demonstrates how holistic advance tunnelling concepts, integrating human factors, TBM and jobsite design, and digital assistance systems from the planning phase onwards, significantly reduce operational risk.

Beyond technical aspects, the presented approach addresses key industry challenges such as increasing system complexity, shortage of experienced personnel, and the need for fact-based decision-making. Assistance systems are positioned not as replacements for human expertise, but as enablers that support operators, engineers, and managers in making better decisions under real production conditions.

1. WHY MECHANISED TUNNELLING NEEDS A NEW RISK PARADIGM

1.1 MECHANISED TUNNELLING IN URBAN ENVIRONMENTS

Large-scale infrastructure projects, such as tunnel constructions, play a pivotal role in shaping modern forms of society and coexistence. They connect regions, facilitate trade and contribute to economic growth. Mechanised tunnelling has become the backbone of modern urban infrastructure. As cities densify and surface space becomes scarce, tunnels are driven ever closer to existing buildings, utilities, transport corridors, and sensitive infrastructure. However, the successful execution of these projects is far from guaranteed. Inner-city tunnelling today represents one of the highest-risk construction activities in civil engineering. Budget overruns, delays, and technical complications are common, raising the question: What separates success from failure in such complex undertakings?

Even minor deviations in tunnel behaviour can result in severe consequences: excessive settlements, damage to historic buildings, disruption of public services, sinkholes, or in extreme cases, surface collapses. Numerous documented incidents in metropolitan areas worldwide illustrate that despite decades of experience, urban tunnelling failures still occur – often suddenly and with little warning. These events not only cause substantial financial damage but also erode public trust and place human lives at risk.

What makes mechanised tunnelling particularly challenging is that it is not a deterministic process. It is a complex, adaptive system, operating underground, out of sight, under continuous geotechnical uncertainty.

1.2 THE CRITICAL SUCCESS QUADRANGLE OF MECHANISED TUNNELLING PROJECTS

For decades, the traditional ‘magical’ project management triangle, balancing scope, time, and cost, has served as a foundational heuristic for planning and controlling projects. While this model has offered clarity and simplicity, its reductionist nature renders it increasingly inadequate in the context of modern, complex project environments. Critical dimensions such as risk exposure, employee satisfaction, technological constraints, or sustainability are not explicitly represented in the traditional framework, despite their decisive influence on project outcomes. These factors do not merely act as secondary variables; they actively shape productivity, resilience, and sustainable, long-term success.

In addition, in mechanised tunnelling – particularly under urban conditions – this framework requires further refinement. Experience from tunnel boring machine (TBM) projects worldwide demonstrates that project success is not governed by the classical project management dimensions alone, but by a second, equally critical system: the TBM Critical Success Quadrangle (1).

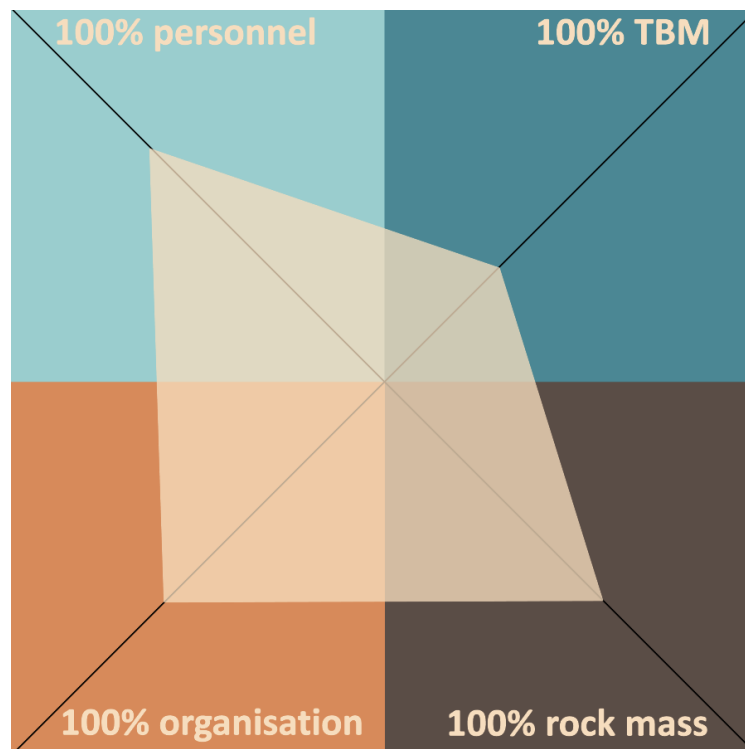


Figure 1: The critical success quadrangle of mechanised tunnelling projects (1).

Unlike the traditional project management triangle, this system (see Figure 1) explicitly acknowledges the strong interdependencies between technical, geotechnical, and human factors inherent to mechanised tunnelling. Deviations in any one dimension – such as unexpected ground behaviour, suboptimal machine configuration, insufficient operational expertise, or inadequate communication between stakeholders – can rapidly propagate across the system and jeopardize overall project performance.

Consequently, successful delivery of mechanised tunnelling projects depends on the balanced management of both the classical project constraints and the TBM-specific success dimensions. Whereas, project risks emerge not from isolated failures within one element, but from misalignments between them.

1.3 FROM STATIC PROJECT CONTROL TO A DYNAMIC RISK SYSTEM

When the traditional project management dimensions (time, cost, quality) are overlaid with the TBM success quadrangle (machine, human, ground, organisation), a dynamic and highly sensitive system emerges.

Yet current risk management practices often fail to reflect this reality. Risks are typically assessed:

1. At project start. Based on limited geological/ geotechnical information,

2. In static risk evaluation files,
3. With mitigation measures defined once and rarely updated.

As tunnelling progresses, these analyses frequently fade into the background of daily operations. The result is a disconnect between formal risk management and actual TBM operation.

This is problematic because underground uncertainty is not static. Geological/ geotechnical conditions evolve, machine wear changes performance, crews rotate, and organisational pressures shift. Consequently, risk itself is dynamic, continuously reshaped by interactions within the success quadrangle.

A static risk assessment cannot adequately capture this evolving risk landscape.

1.4 THE HUMAN AND ORGANISATIONAL DIMENSION – COMPLEXITY WITHOUT ASSISTANCE

Within the critical success quadrangle, the human and organisational dimensions are often the least systematically supported, despite their decisive influence on safety and performance.

TBM operators control machines worth tens of millions of euros, operating in highly sensitive environments. Unlike other high-risk industries such as aviation or rail transport, formalised training standards, simulation-based learning, and real-time decision support systems are often limited or absent. At the same time, modern TBMs generate vast amounts of operational data. While technically available, this data is rarely transformed into actionable, context-aware information that supports operators and site engineers in real time.

Organisationally, responsibilities for risk recognition and response are frequently fragmented across roles and interfaces. Early warning signals may exist but remain unrecognised, uncommunicated, or unprioritized.

This combination creates a structural vulnerability:

High system complexity, high consequence of failure, but insufficient integrated support for human decision-making.

1.5 TOWARDS PROACTIVE RISK MANAGEMENT – THE NEED FOR A PARADIGM SHIFT

The recurring challenges in mechanised tunnelling projects do not primarily stem from a lack of technology or expertise. They arise from the absence of a continuous, integrated understanding of risk across machine, ground, human, and organisation.

To master the combined demands of urban tunnelling, projects must transition:

1. from static to dynamic risk management,
2. from reactive response to proactive anticipation,
3. from isolated data sources to integrated system intelligence,
4. from emotional based decisions to human-centered operational support.

This paradigm shift requires digital assistance systems that embed risk awareness directly into TBM operation, transforming data into guidance, uncertainty into transparency, and experience into scalable knowledge.

This is the foundation upon which modern assistance systems for mechanised tunnelling are built.

2. FROM FRAGMENTED DECISIONS TO INTEGRATED TUNNELLING CONCEPTS

2.1 HOLISTIC TUNNELLING CONCEPTS – EARLY DECISIONS UNDER UNCERTAINTY

In mechanised tunnelling, many of the most critical decisions are taken very early in the project lifecycle. The selection of the tunnelling method, TBM type, excavation diameter, lining concept, and site layout fundamentally determines technical feasibility, risk exposure, cost, and schedule performance.

These decisions are inevitably made under conditions of limited factual knowledge. Geological and geotechnical information is sparse, spatially discontinuous, and subject to interpretation. To bridge these

gaps, planners rely on assumptions, buying centres of construction companies use their experience, and probabilistic estimates to enable early-stage design and procurement.

While this approach is unavoidable, it introduces a structural challenge: early decisions carry long-term consequences yet are based on the highest degree of uncertainty.

To address this challenge, mechanised tunnelling projects require holistic advance concepts that integrate technical, organisational, and human dimensions from the outset (Figure 2).

Rather than treating TBM operation, site organisation, and risk management as downstream execution topics, they must be embedded into the design and planning phase. A holistic advance concept (2) therefore explicitly considers:

1. People – roles, competencies, training needs, and decision responsibilities,
2. Design – TBM configuration, backup systems, logistics, and site layout,
3. Assistance Systems – digital tools that support decision-making before and during tunnelling.

This integrated perspective enables risks to be addressed proactively, before they manifest operationally.

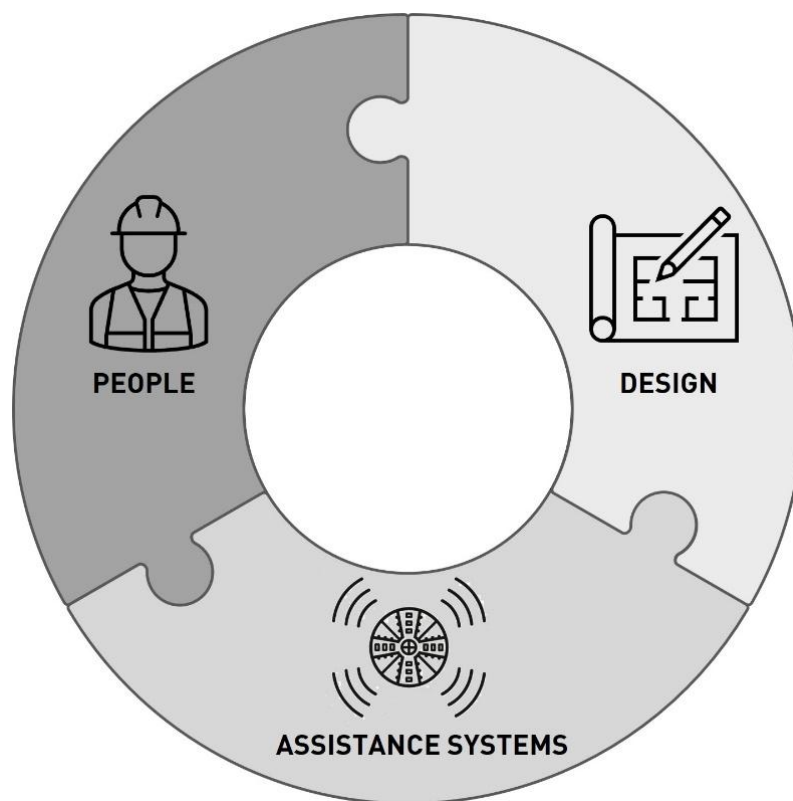


Figure 2: Success factors for holistic project design.

2.2 STRUCTURED DATA AS THE BACKBONE OF PROACTIVE RISK MANAGEMENT

At the core of holistic tunnelling concepts lies a structured and reliable data foundation.

The construction industry increasingly employs digital tools to manage and exchange information. Tunnel Information Modelling (TIM) has emerged as a key enabler, not only for geometric representation, but as a framework for structured data management and analysis across the project lifecycle (3).

A well-defined data structure transforms raw information into a strategic asset. It:

1. Enables automation of analyses and workflows,
2. Improves interoperability between planning, construction, and operation,
3. Objectifies decision-making processes, reducing reliance on subjective judgement.

Critically, the structuring of both geometric and alphanumeric information must prioritise machine-readable requirements. This focus allows for seamless information exchange, increases automation potential, and ensures that relevant data is available at the right time and in the right context.

While automated geometric modelling has been extensively researched and implemented in practice, the definition and structuring of information requirements have received significantly less attention, particularly for operational and decision-support use cases.

In many projects, valuable data exists but remains unstructured, inconsistent across disciplines and detached from actual decision processes. This limits its usefulness for proactive risk management and real-time assistance.

To unlock the full potential of digitalisation, data structures must be designed around processes and decisions, not solely around models.

A robust approach is based on a dynamic decision model incorporating three complementary layers:

1. **Feasibility analysis:** Technical compatibility between ground conditions, TBM type, and project constraints.
2. **Qualitative evaluation:** Expert-based assessment of risks, operational flexibility, and organizational capability.
3. **Quantitative evaluation:** Data-driven analysis of cost, time, and performance indicators.

Rather than replacing engineering judgement, such models augment human decision-making by providing transparency, consistency, and traceability.

Cost and time analyses represent natural initial use cases. However, the true strength of a structured data platform lies in its scalability allowing future integration of safety indicators, operational risks, environmental constraints, and real-time performance feedback.

The overarching objective of holistic advance concepts is the creation of a unified information platform that serves as a single source of truth throughout planning and construction. Such a platform could consolidate assumptions, data, and decisions. Furthermore, it would preserve project knowledge beyond individual phases, individuals or teams and finally form the basis for continuous, data-driven risk management.

By systematically structuring tunnelling information within a shared data environment, projects can transition from reactive problem-solving to anticipatory, assisted decision-making.

This shift lays the foundation for operational assistance systems where planning data, real-time TBM data, and human expertise converge to actively support tunnelling performance.

3. ASSISTANCE SYSTEMS AS OPERATIONAL RISK MANAGEMENT TOOLS

3.1 FROM DATA AVAILABILITY TO ACTIONABLE ASSISTANCE

Modern TBMs are equipped with a vast number of sensors and control systems. While the data availability has increased significantly, its practical impact on safety and productivity remains limited if data is not analysed in real time and transformed into actionable guidance.

An initial step toward integrating continuous risk tracking is the automated, ongoing comparison of advance data with the structured data, our backbone, generated during the design phase. This can, for example, be implemented through live-updating charts of key advance parameters. Deviations from expected values can thereby be detected in real time. However, due to the large number of sensors not every value can be tracked manually within a chart. Assistance systems in mechanised tunnelling must therefore go beyond data visualisation. Their purpose is to actively, through alarms and notification, support human decision-making during production by continuously linking machine behaviour, operational context, and project-specific risk profiles. Thus, in contrast to many other industries, assistance systems in mechanised tunnelling cannot be developed by software engineers alone. Tunnelling is characterised by high system complexity, strong interdependencies between machine, ground, human, and organisation, and a level of uncertainty that cannot be fully formalised. An effective assistance system therefore requires deep domain knowledge and operational experience.

FLORA Tunnelling approach to digital assistance systems is therefore fundamentally practice driven. It is based on the conviction that professionals with extensive, hands-on tunnelling experience are capable of identifying which machine and process parameters are truly critical for safety and performance, interpreting data patterns within their specific operational context, distinguishing between normal system variability and early indicators of failure, and ultimately translating complex system behaviour into clear, meaningful operational guidance for site teams. Without this experiential understanding, digital tools risk remaining generic dashboards or alarm systems – technically correct, but operationally irrelevant.

3.2 AN INTEGRATED ASSISTANCE SYSTEM – RISK-BASED PRODUCTION BOOST

The assistance system is implemented as an integrated digital application that combines several functional components into a coherent operational production optimisation and risk management tool. Rather than addressing isolated use cases, the system supports the entire decision chain – from real-time monitoring to expert-supported intervention.

At its core lies the ‘**COCKPIT**’, which provides continuous, real-time insight into the operational state of the TBM. Relevant machine parameters are monitored 24/7 and evaluated against individual, project-specific thresholds and behavioural patterns. Advanced algorithms and AI-based methods are applied to analyse trends, correlations, and interdependencies between parameters. This allows the system not only to detect simple limit exceedances, but also to identify complex risk constellations that emerge from interacting effects between machine behaviour, operational settings, and ground response.

When thresholds are exceeded or abnormal patterns are detected, the system generates context-aware warnings and intelligent recommendations. Rather than issuing generic alarms, the assistance system provides action-oriented guidance, supporting operators and engineers in selecting appropriate countermeasures.

When anomalies occur, the ‘**DIAGNOSIS**’ module supports TBM operators and PLC specialists in a structured and systematic fault analysis process. Based on observed machine behaviour and contextual information, the system guides users through possible causes and recommended checks. This diagnostic support enables site teams to resolve issues efficiently and independently, strengthening operational competence in line with a ‘help-to-self-help’ philosophy. In parallel, digitalised maintenance functions ensure that interventions are documented, traceable, and aligned with actual machine condition, thereby improving operational reliability and quality control.

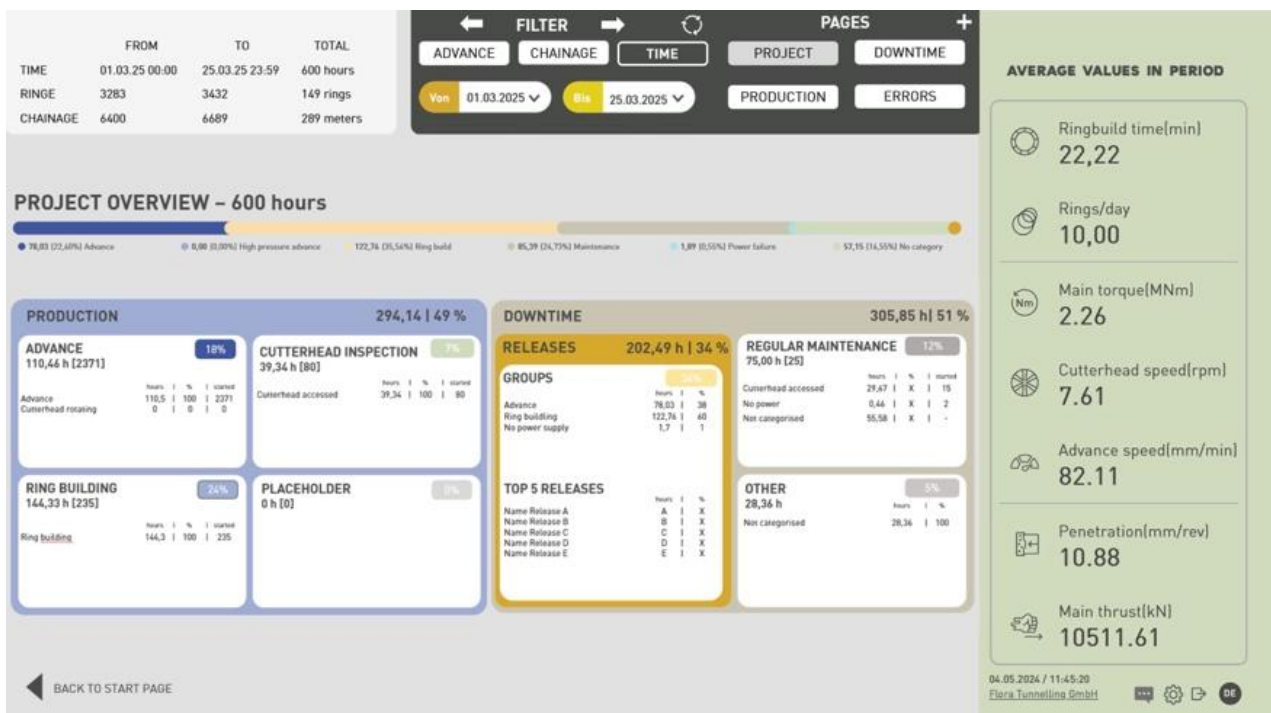


Figure 3: A sample dashboard focusing on productivity and reducing downtime

For project and construction management, the system provides a project-specific '**DASHBOARD**' (Figure 3) that consolidates operational data into meaningful performance indicators. Production rates, stoppage times, and efficiency losses are transparently analysed and visualised. This dashboard serves as a controlling instrument, supporting both short-term operational decisions and longer-term performance optimisation. By linking production metrics with risk indicators, management gains a consistent understanding of how operational behaviour influences project objectives.

In situations where on-site troubleshooting reaches its limits, the assistance system seamlessly integrates a **PLC Remote Service**. Through secured online access, tunnelling experts can analyse the TBM control system in real time, identify root causes of critical situations, and recommend targeted corrective actions. This immediate access to expert knowledge significantly reduces reaction times and prevents risks and prolonged downtime, particularly in complex or unfamiliar operating conditions.

The true strength of the system lies in the interaction between human expertise and algorithmic intelligence. Real-time monitoring, AI-supported diagnostics, performance transparency, and expert intervention are not isolated features, but interconnected elements of a unified operating model. Complemented by regular expert reviews and joint evaluation sessions with the project team, the system ensures that data is not only observed but interpreted and translated into concrete actions.

In this way, the assistance system embeds artificial intelligence as a supportive layer, enhancing human decision-making rather than replacing it. Risk management becomes continuous, proactive, and directly linked to production—enabling safer, more stable, and more efficient mechanised tunnelling.

4. OUTLOOK – HUMAN-CENTRED DIGITALISATION FOR SAFER AND MORE EFFICIENT TUNNELLING

4.1 ASSISTANCE SYSTEMS BEYOND MONITORING

The assistance systems described in this paper represent an important step towards proactive, data-driven risk management and decision-making in mechanised tunnelling. However, they also form the foundation for the next generation of TBM assistance technologies such as automated steering or assisted ring building. These systems increasingly rely on interconnected sensors, Internet of Things (IoT) architectures, and intelligent control algorithms. Together, they transform the mechanised tunnelling jobsites into a networked production system, capable of adapting TBM to its environment while remaining under human supervision.

The integration of TBMs into broader IoT-based project ecosystems will further enhance transparency and decision quality. Machine data, ground information, monitoring results, and organisational inputs can be linked across disciplines and project phases. Such interconnected data environments enable consistent, fact-based decision-making across planning and construction, improved traceability of assumptions and interventions as well as continuous learning across projects and organisations.

In this context, data is no longer a by-product of production, but a strategic asset for managing risk and performance.

4.2 KEEPING HUMANS AT THE CENTRE

Despite increasing automation and algorithmic intelligence, people remain the central success factor in mechanised tunnelling.

The industry is currently facing a growing shortage of experienced personnel. At the same time, the complexity of projects continues to increase. Assistance systems play a crucial role in addressing this tension by reducing cognitive load on operators and engineers, supporting less-experienced personnel with structured guidance and preserving and scaling expert knowledge through digital tools.

Successful tunnelling has traditionally relied heavily on individual experience. While experience remains invaluable, it must increasingly be complemented by fact-based, data-supported decision-making. By making decision processes transparent and explainable, assistance systems increase confidence, motivation, and acceptance among site teams, especially considering the changing environment in Joint Ventures.

Experience from implemented projects clearly demonstrates that successful tunnelling is not the result of chance. It is the outcome of well-structured processes, informed decisions, and effective collaboration between humans and technology.

Assistance systems that integrate data, algorithms, and expert knowledge transform mechanised tunnelling into a controlled, transparent, and continuously improving production process.

By placing people at the centre and supporting them with intelligent digital tools, mechanised tunnelling can become safer, faster, and more reliable, meeting the growing demands of urban infrastructure development.

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Prof Dr Matthias Flora

FLORA Tunnelling GmbH

m.flora@flora-tunnelling.com