ASSESSING THE IMPACT OF LEVEL OF DETAIL FOR PLANNING OF TUNNELLING PROJECTS USING BUILDING INFORMATION MODELLING

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The use of Building Information Modelling (BIM) in tunnel projects is becoming increasingly common, but the impact of different Levels of Detail (LoD) on schedule accuracy remains underexplored. This paper investigates how LoD influences planning outcomes using two real-world tunnel projects, with a focus on schedule prediction. The findings show that higher LoD improves decision making but increases complexity, particularly in the early stages of design. 4D BIM further enhances planning by enabling spatial-temporal coordination of activities. Based on these findings, a phased approach to LoD implementation is recommended, applying higher levels of detail progressively as project complexity increases. The study also proposes LoD 2 as a baseline standard, with LoD 3 reserved for high-risk or sensitive phases. While limited in sample size and focused solely on schedule data, this research provides a replicable framework for broader validation using larger tunnel datasets.

Keywords: digitalisation; building information modelling; levels of detail; tunnel construction

INTRODUCTION

As cities become increasingly dense and the demand for underground infrastructure increases, tunnelling has emerged as an important strategy to support sustainable urban development. Tunnels enable efficient transport, energy distribution and utility networks, but their design and execution remain complex due to variable geological conditions, spatial constraints and the coordination of multiple stakeholders. Paraskevopoulou and Boutsis (2020) note that these challenges often lead to project delays, highlighting the importance of improved planning and risk mitigation strategies.

In response to these challenges, Building Information Modelling (BIM) has gained traction as a tool to support more reliable planning and execution of tunnel projects. BIM provides a collaborative, data-driven approach to infrastructure design, integrating geometric, temporal and geotechnical information in a shared digital environment. As highlighted by Lozano *et al.* (2023), BIM improves tunnel design by enabling predictive modelling and better geotechnical risk assessment, especially when combined with time-based (4D) simulation capabilities. By visualising

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construction sequences and identifying temporal conflicts in advance, BIM helps reduce scheduling uncertainties and optimise construction workflows.

A key factor in the effectiveness of BIM is the Level of Detail (LoD), which defines the depth and reliability of information included in the model at different stages of the project. Higher LoDs allow for more precise planning and sequencing of tasks but also require more extensive data and modelling resources. According to Abualdenien and Borrmann (2022), an optimal LoD strategy should balance modelling effort with project needs, ensuring that the right level of detail is used at the appropriate stage. For tunnelling projects, where minor deviations in excavation timing can cause significant disruption, matching LoD to project complexity and phase is particularly important.

The relevance of this study lies in the growing need to validate BIM design outputs against actual tunnel construction schedules. While the benefits of BIM and LoD are widely discussed, most studies remain theoretical or simulation-based and do not examine how predicted schedules generated at different LoDs compare with actual performance. Ergun *et al. (*2023) explicitly identify this gap and call for empirical studies that quantify the accuracy of BIM-derived predictions. Without such validation, it remains difficult for project managers and decision makers to determine what level of detail is most appropriate for effective planning.

This study addresses this gap by comparing the predictive accuracy of LoD 1, 2 and 3 models with the realised timelines of completed tunnel projects. The aim is not to confirm the intuitive notion that more detailed models are more accurate but rather to assess how each LoD performs in relation to design effort and output reliability. This approach recognises that higher LoD may not always provide proportionate benefits and that strategic use of detail could improve design efficiency without compromising project outcomes.

The primary research objective is to evaluate the impact of different LoD levels on the temporal accuracy of BIM-based design in tunnelling. This includes analysing how closely schedule predictions match actual project performance and identifying which levels of detail provide the most effective balance between modelling effort and design accuracy. By basing its analysis on real project data, this study contributes to the development of more evidence-based guidelines for the use of BIM in complex infrastructure contexts, helping practitioners to make informed decisions about model granularity throughout the project lifecycle.

LITERATURE REVIEW

The Importance of Tunnelling

Tunnelling has become a critical strategy in modern infrastructure development, particularly in densely populated urban environments. It allows for underground transportation systems, utility networks, and stormwater solutions, thereby relieving pressure on surface infrastructure. Tunnels also help to reduce noise and visual pollution, protect natural landscapes and promote sustainable urban growth by minimising surface land use. From a socio-economic perspective, tunnel projects contribute to regional development, reduce travel time and increase property values. Through a comparative economic analysis, Xie *et al. (*2021) demonstrated that tunnels often generate positive long-term net returns by increasing transport efficiency and stimulating economic activity in connected zones. The results reinforce the value of tunnels as a strategic urban policy tool rather than just an engineering solution.

Tunnel Construction Methods and Challenges

Tunnelling methods are typically divided into conventional and mechanised techniques. Conventional methods, such as drilling and blasting, involve sequential processes of excavation, mucking, and structural support installation. These methods are adaptable to different geological conditions but are often time-consuming and risky in complex ground conditions. In contrast, mechanised tunnelling using Tunnel Boring Machines (TBMs) allows for continuous excavation and immediate support installation, making it suitable for long, linear tunnels in consistent geological environments. As CETU (2016) notes, the use of TBMs requires significant upfront investment and precise geotechnical profiling to mitigate operational risks.

However, both approaches face significant challenges. Raza *et al. (*2023) analysed several large-scale metro projects and found that geotechnical unpredictability - such as water intrusion, unstable strata, or heterogeneity in rock strength - was a major cause of delays and budget overruns. These complications are often exacerbated by fragmented information sharing between stakeholders, lack of real-time monitoring and inadequate scenario forecasting. The authors recommend the adoption of digital planning systems capable of integrating geospatial, temporal and logistical data to improve proactive risk management and stakeholder coordination.

BIM Applications in Tunnelling

BIM has emerged as a promising solution to the coordination challenges of tunnel construction. By integrating geometric, geotechnical, time and financial data into a unified digital model, BIM allows for better project visualisation, simulation and analysis. In their case study of a metro extension, Lozano *et al. (*2023) demonstrated that BIM significantly improved geotechnical risk assessment, enabling early identification of potential soil-related hazards through model-based simulations. This capability supports a more responsive design process and risk-informed construction planning.

The utility of BIM is further enhanced by the integration of 4D (time) and 5D (cost) dimensions. Aredah *et al. (*2021) evaluated a tunnelling project where 4D BIM enabled real-time tracking of construction progress, identifying schedule conflicts well in advance and reducing on-site idle time. Their study showed that the integration of the construction schedule into the model promoted greater synchronisation between the excavation and lining teams.

Fugas (2022) adds that BIM, when properly implemented, becomes a single source of truth for all project stakeholders. In the tunnel environment, where design iterations, logistical constraints and safety considerations must be constantly reconciled, this shared platform helps maintain alignment between disciplines. The complexity of tunnelling increases the importance of tools that enable early detection of conflicts, minimise duplication of effort and support integrated decision-making.

Level of Detail (LoD) and Strategic Implementation

A key concept in BIM implementation is the LoD, which defines the depth and accuracy of information embedded in the model. LoD ranges from LoD 100, used for conceptual massing and alignment studies, to LoD 500, which reflects as-built conditions and includes precise materials and systems data. Abualdenien and Borrmann (2022) emphasize that while higher LoDs enable richer simulations and improved constructability assessments, they require significantly more data input and modelling effort. This can reduce efficiency if not applied selectively based on project stage or complexity.

The International Tunnelling Association's Working Group 22 (2022) advocates the use of the Level of Information Need (LOIN) to guide the implementation of LoDs. Rather than applying a uniform level of detail throughout the model, LOIN encourages tailoring the level of detail based on the decision to be supported. For example, preliminary risk assessments may require only basic geometry and soil data (LoD 100-200), whereas excavation sequencing and logistics planning may benefit from LoD 300 or higher.

Empirical case studies reinforce the benefits of strategic use of LoDs. The West Block rehabilitation project in Ottawa, as reported by PCL (2024), used variable LoDs to address the coexistence of historic preservation requirements and modern building systems. By applying higher LoDs to critical zones and maintaining lower detailing in less sensitive areas, the team avoided over-modelling and maintained schedule discipline while ensuring coordination. Ninić and Koch (2017) similarly argue that LoD decisions should be revisited at key project milestones to ensure that modelling effort is proportionate to value added.

Despite these advances, the literature reveals a persistent gap: very few studies have tested the predictive accuracy of different LoD levels against actual construction outcomes. Most research remains theoretical or simulation-based, limiting the practical applicability of the findings. Ergun *et al. (*2023) explicitly call for comparative analyses that assess how closely BIM models at different LoDs align with actual construction timelines and performance metrics. This study responds to this call by comparing the results of LoD 1, 2 and 3 with real data from completed tunnel projects. In doing so, it contributes both to the empirical validation of BIM strategies and to the refinement of LoD planning in complex infrastructure projects.

METHOD

This study adopts a pragmatic research philosophy, combining empirical observations from real-life tunnel projects with theoretical insights to assess the role of BIM and LoD in schedule accuracy. A quantitative, data-driven approach is used to address the need to objectively assess how different LoDs affect the reliability of construction schedules. The research follows an abductive reasoning process, comparing modelled outputs with actual project schedules to test and refine the conceptual understanding of LoD performance in BIM environments.

Unlike previous studies based on simulated data, this research is based on real design and construction data from two completed tunnel projects provided by the Centre d'Étude des Tunnels (CETU). These real projects form the empirical basis for assessing the predictive accuracy of BIM-based design at LoD 1, 2 and 3. As cost data was unavailable or inconsistent across the projects, this study focuses exclusively on the time dimension - reflecting both the critical importance of scheduling in tunnelling and the availability of reliable as-built schedule data.

Modelling Planning of a Tunnel Project

This section looks at the methods used to produce accurate predictions using BIM software, specifically Revit and Dynamo, to generate parametric models. The tunnels are modelled as straight structures for simplicity, but hypothetical curves and slopes are included in the calculations for time estimation without being visually represented.

The methodology of time estimation differs according to the LoD. For this study, 3 LoDs (LoD1, LoD2 and LoD3) are introduced. While LoD 1 is relying on simplified assumptions based on general ground conditions and assigning corresponding TBM speeds. LoD 2 and LoD 3 offer more precise estimates by examining the project metre by metre, considering factors like TBM specifications, ground variability, excavation phases, and maintenance.

The Revit and Dynamo model formed the core of the methodology, automating the tunnel modelling process and creating a parametric design adaptable to different LoDs. The Revit model began by defining a ring family, the primary structural element of the tunnel, with parameters such as inner and outer diameter, thickness, and ring position. For LoD 2 and LoD 3, additional parameters, including volume, start and end dates, were calculated from imported data. Dynamo, a visual programming tool, was used to automate the modelling process by scripting tunnel parameters based on Excel inputs. This script assigned precise dimensions and properties to each ring, including material quantities and timelines, reducing the need for manual adjustments and ensuring accuracy. The integration of 4D BIM through Navisworks added time data to the model, enabling real-time construction scheduling.

Each model produced a 4D BIM output integrating timeline data, which was exported to planning tools such as Navisworks for comparison with actual project schedules. By aligning the predicted schedules from each LoD with the as-built timelines, the study quantified the deviation in planning accuracy at each level of detail.
In addition to the two validated case studies, a third hypothetical tunnel network was modelled to illustrate the functional benefits of LoD 3 in a more complex setting, particularly in terms of 4D coordination and conflict detection. Although this scenario is not part of the empirical validation, it showcases the potential of advanced BIM uses in complex planning contexts.
By grounding the methodology in real construction timelines and applying a consistent modelling framework, this research offers a robust basis for evaluating the trade-offs between modelling effort and planning accuracy. The insights gained aim to support more strategic decision-making around LoD selection in tunnel projects. Future extensions of this work will draw on a larger CETU database of over 150 tunnel projects, enabling broader statistical validation and deeper exploration of LoD applicability across various project types.

FINDINGS

This section presents the results of the comparative modelling performed on two completed tunnel projects, using three Levels of Detail (LoD 1, 2, and 3) to estimate construction timelines. The objective was to assess the extent to which increased modelling detail improves the accuracy of planning predictions when compared to the actual as-built schedules. The analysis was carried out exclusively on the temporal dimension, with all cost-related components excluded from the modelling and evaluation.

Each project was modelled in Autodesk Revit with parametric rings generated via a Dynamo script. For each LoD, the script adapted the level of input detail—from basic TBM speed assumptions at LoD 1 to detailed phase breakdowns, including logistics and maintenance, at LoD 3. The timeline data exported from the BIM model was visualised and analysed using 4D simulation in Navisworks, providing both a visual representation of progress over time and a structured schedule for comparison with real-world project data.

Project A: 4.7km main tunnel and 2.2 km service tunnel

Project A corresponds to the construction of a 4.7 km main tunnel and a 2.2 km service tunnel. The as-built records show an average excavation speed of 12.5 m/day with peaks up to 25.4 m/day.

Table 1: Project A, TBM 1 results

	Real project	LoD 1	LoD 2	LoD 3
Start date	03/09/2018	03/09/2018	03/09/2018	03/09/2018
End date	17/11/2020	07/03/2021	03/10/2020	12/09/2020
Planning variation in days		110	45	66
Planning variation in %		14%	6%	8%

Table 2: Project A, TBM 2 results

	Real project	LoD 1	LoD 2	LoD 3
Start date	06/04/2018	06/04/2018	06/04/2018	06/04/2018
End date	13/06/2019	10/04/2019	11/06/2019	04/06/2019
Planning variation in days		64	2	9
Planning variation in %		15%	0%	2%

LoD 1 applied a uniform TBM speed along the entire tunnel, which did not consider the transitions between different soil types, such as green clay and limestone. As a result, it did not anticipate changes in excavation rate or the influence of maintenance cycles, leading to an inaccurate and overly optimistic schedule.

LoD 2 introduced segmented TBM speeds by incorporating known ground conditions into the model. This adjustment improved alignment with actual performance by considering deceleration in difficult strata. However, the model still lacked explicit integration of operational pauses and logistical constraints such as TBM restarts or equipment adaptation periods. However, in this specific case, this did not change the estimates.

LoD 3 provided the most realistic schedule by integrating these critical variables, including three documented TBM stoppages for cutter head replacement and scheduled maintenance events. The modelling also considered minor phase conflicts with secondary works, making the forecast much more robust. Despite being underestimated by a few days, the model closely matched site reality, demonstrating the added value of high-fidelity time modelling. The 4D simulation also facilitated visual tracking of major slowdowns, allowing project managers to anticipate bottlenecks that could affect the continuity of the critical path.

This first project also shows that the more detailed the model, the more information it considers, but it is not necessarily the most accurate.

Project B: 3.2 km urban tunnel

The project examined a 3.2 km tunnel constructed under complex urban conditions, including two station crossings and multiple curved alignments. The project encountered highly swelling clay and logistical constraints related to limited working space. Real progress records indicate an average advance rate of 12.1 m/day, with 256 working days over the excavation period. The results are the following:

Table 3: Project B results

	Real project	LoD 1	LoD 2	LoD 3
Start date	18/05/2020	18/05/2020	18/05/2020	18/05/2020
End date	22/07/2021	10/11/2021	26/10/2021	02/07/2021
Planning variation in days		111	96	20
Planning variation in %		26%	22%	5%

LoD 1's simplified approach did not account for key disruptions such as TBM deceleration near station approaches, limited site logistics, or soil swelling phenomena encountered mid-alignment. Its reliance on average excavation speeds resulted in a substantial planning mismatch. The absence of any segmentation or task-level phasing further limited its reliability.

LoD 2 introduced variable TBM rates and partially accounted for hydrogeological variations. The model improved significantly over LoD 1 by factoring in specific zones with constrained advancement. However, it still missed the finer details of execution phasing, particularly in areas requiring reduced speed or split shift working cycles.

Then, LoD 3 integrated all major project constraints, including operational slowdowns during station bypasses, logistical downtime from limited shaft access, and reduced TBM productivity due to equipment repositioning. The model also allowed detailed sequencing of interface works, offering a temporally consistent projection closely aligned with the actual excavation sequence. The 4D output gave a clear view of complex interdependencies, enhancing the predictive quality of the planning process.

Project C: Hypothetical Complex Tunnel

To further illustrate the planning potential of LoD 3, a hypothetical multi-branch tunnel network was modelled, including intersecting alignments and overlapping excavation phases. Although not validated against real data, this scenario served to visualise how 4D modelling supports coordination, especially in identifying sequencing conflicts and simulating construction logistics. The outputs underscore the benefit of LoD 3 in planning-intensive projects.

In such complex projects, it is not enough to have only a 3D visualisation or only a temporal visualisation. A 4D BIM model is then required, and this implies a necessary high LoD (LoD2 or LoD3). For this scenario, the 5D model helps to understand the crossing of two tunnels. The model displays planning and cost information as shown in Figure 1, Figure 2, Figure 3 and Figure 4.

With the 4D model, it is much easier to understand the project, and it is also possible to identify time clashes. A 4D clash in BIM occurs when scheduling conflicts arise within the 3D model where construction activities are planned to take place in the same space at the same time, leading to potential problems with logistics, safety, and efficiency. These spatiotemporal conflicts can be identified early by integrating time into the 3D model, as can be done with LoD3 in this scenario, allowing project teams to adjust schedules, re-sequence tasks, and avoid delays.

By resolving 4D conflicts, projects benefit from better coordination, reduced risk, and optimised resource allocation while improving communication and decision-making between stakeholders, leading to more efficient and successful project delivery.

Cross-Project Insights

The comparative analysis confirms that higher LoD consistently improves schedule prediction accuracy. However, the results also support a more nuanced view: LoD 2 often offers a high return on modelling effort with significant improvements in forecast quality, while LoD 3 offers marginal gains that are justified primarily in complex or high-risk environments. LoD 1, while faster to produce, systematically underestimates durations and should be limited to preliminary studies.

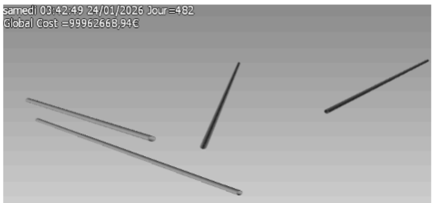

Figure 1: 4D view at day 482

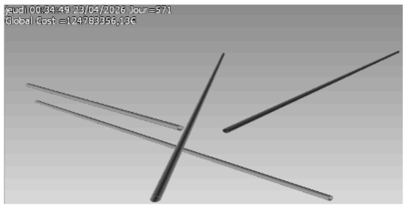

Figure 2: 4D view at day 571

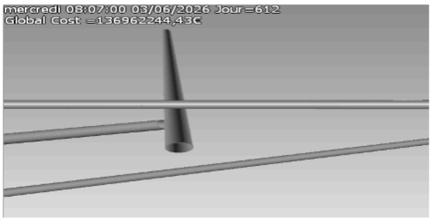

Figure 3: 4D view at day 612

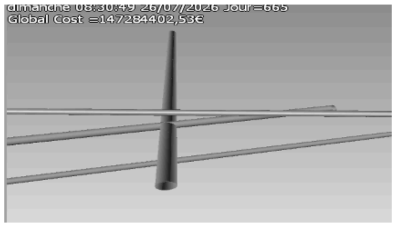

Figure 4: 4D view at day 665

Future Expansion and Dataset Scaling

This study forms the basis of a wider research initiative. The modelling framework developed here is currently being scaled up to analyse a dataset of over 150 completed tunnel projects held by CETU. Future work will focus on automating the comparative analysis of LoD predictions against realised durations, providing statistically robust insights into when and where higher LoD adds most value.

By grounding the analysis in real project schedules and combining this with structured 4D modelling, this research provides new empirical evidence for the effective use of LoD in tunnelling. It supports a strategic, risk-based approach to LoD selection, enabling project managers to optimise modelling effort relative to project complexity and constraints.

DISCUSSION

The case studies highlight the substantial impact of different LoDs on the accuracy and reliability of schedule predictions in tunnel planning. For the Project A, a relatively straightforward tunnel with constrained urban logistics, LoD 1 resulted in an error exceeding 120 days—demonstrating the limitations of average TBM speed assumptions. In contrast, LoD 2 offered a near-exact prediction, capturing basic zoning variations and thus validating its effectiveness for standard projects. The more detailed LoD 3 marginally improved this accuracy but at the cost of additional modelling effort, suggesting diminishing returns in low-to-moderate complexity contexts. The 4D simulation outputs reinforced the benefit of temporal visualisation for both technical planning and stakeholder coordination. By sequencing tasks along the project timeline and integrating ground condition data, higher LoDs provided clearer insight into risk points and logistics management. Although cost analysis was excluded from this study, previous findings (Aredah *et al.,* 2021; Butkovic *et al.,*

2019) suggest that integrating 5D BIM can further enhance project control when paired with high-fidelity LoD inputs.

These findings confirm that LoD should not be treated uniformly but adapted to project complexity. LoD 2 is suitable for baseline planning in most cases, while LoD 3 adds critical value in high-risk or phase-sensitive environments. A phased LoD strategy, escalating detail as the design matures, offers the most balanced and effective use of BIM in tunnelling.

CONCLUSIONS AND RECOMMENDATIONS

This study provides empirical validation of how different Levels of Detail (LoD) influence planning accuracy in tunnel projects using BIM. Through two real-world case studies, the research demonstrates that simplistic models like LoD 1 lack the precision required for execution planning and often produce significant errors. LoD 2 strikes a balance between accuracy and effort, proving sufficient for many tunnelling contexts. LoD 3, while demanding, becomes essential in projects involving complex geotechnical, logistical, or operational phases, particularly when supported by 4D visualisation tools.

The analysis supports a phased and adaptive approach to LoD implementation. Early planning stages can rely on lower LoDs to enable rapid decision-making, while critical sections of the project should progressively integrate more detail as risks and interfaces become clearer. This allows for targeted resource use, reducing unnecessary modelling effort and improving project efficiency.

Based on these findings, a phased and targeted LoD strategy is recommended: start with LoD 1 for concept design, shift to LoD 2 for baseline planning, and use LoD 3 only in instances where critical sections demand precision. LoD should also be adapted to the importance of specific project elements to optimise effort and impact. This strategic approach supports more efficient resource allocation and better decision-making in complex underground infrastructure development.

Nevertheless, the study has several limitations. It is based on a limited number of real projects, which may restrict generalisability. Only the schedule dimension was analysed, excluding cost-related data. In addition, the effectiveness of LoD 3 relies on access to high-quality, detailed input data, which may not always be available during early project phases. Future research will address these gaps by applying the methodology to CETU's broader database of over 150 tunnel projects, supporting the development of robust and scalable LoD strategies for infrastructure delivery.

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