



## 4D BIM AND VR/AR FOR SUSTAINABLE INFRASTRUCTURE REFURBISHMENT A DESIGN OF METHODOLOGY AND A CASE STUDY OF THE RAILWAY TUNNEL

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### Abstract

This research introduces a methodology leveraging 4D Building Information Modeling (BIM) and Virtual Reality (VR) to promote sustainability in infrastructure refurbishment. Using a railway tunnel as a case study, the study identifies essential data requirements for effective 4D scheduling and carbon footprint analysis, while VR provides immersive visualizations of sustainability indicators. The core objective is to develop a data-driven framework for enhancing sustainability through optimized planning, execution, and control of railway refurbishment projects. Synchro Pro was used for 4D simulation, and LumenRT and Unity were utilized for VR/AR experience development. The findings aim to offer valuable insights for stakeholders adopting innovative technologies for sustainable infrastructure.

### Introduction

Reducing carbon footprint and emissions is a very global priority, pressing the construction industry to minimize its environmental impact and enhance sustainability. BIM has been increasingly recognized for its potential as a tool for sustainability (Singh & Sadhu, 2019; Jalaei et al., 2020; Panteli et al., 2020). Rock et al. (2018) and Li et al (2023) proposed a BIM-based approach for informed, environmentally conscious material and method selection. BIM-based methods for the calculation of embodied carbon have been mostly developed for buildings, e.g., Cang et al. (2020). Given that railway sustainability encompasses numerous interconnected aspects (Ezias et al., 2023), a need for holistic systemic approach was proposed (Setsobhonkul et al., 2017), overall railway energy assessment was developed (Shrubsole et al. 2019), holistic frameworks were proposed (Du & Karoumi, 2014; Vilches et al., 2017), life-cycle analysis for railway passenger transport were applied (Banar and Özdemir (2015), and tools for the transport infrastructure carbon footprint estimation were proposed (Płoszaj-Mazurek et al. 2020).

However, BIM applications in transport infrastructure were generally limited (Bradley et al., 2016; Costin et al., 2018; Bensalah et al., 2018). Limited use of BIM in transport infrastructure has consequently restricted its

application for sustainability, including the application of BIM to the railway refurbishment.

### The potential of BIM and VR/AR in refurbishment

Addressing the gap in advanced BIM applications for the railway refurbishment projects, this research explores the potential of 4D BIM and VR/AR to facilitate achieving sustainable goals in the railway projects. We first explore the potential of 4D BIM and VR/AR in construction in general, then delve into the specifics of railway projects.

4D and VR overcome traditional project documentation challenges. 4D offers dynamic construction visualization, supports contextual communication, collaboration, and informed decision-making (Hardin & McCool, 2015; Hartmann et al., 2008), boosts efficiency (Cheng and Chang, 2018), identifies sequencing conflicts (Dang & Bargstädt, 2016) and risks (Tarar & Dang, 2012). 4D BIM helps in waste management and life cycle assessment (Zhou & Wang, 2009; Choi, 2019). Combining 4D models with VR environments demonstrated several gains in effectiveness and efficiency, or/and opportunities for carbon emission reduction (Ku & Mahabaleshwar, 2011; Sampaio & Martins, 2014; Cruz, 2018). Chong et al. (2016) showcased the integration of BIM with GIS for improved spatial analysis, real-time monitoring, and updating of BIM model progress with the incorporation of BIM with laser scanning. To achieve identified potentials, we have to establish suitable methods.

### Methods

In order to ease the use of 4D BIM and VR to assess the sustainability of infrastructure projects, we tried to identify the minimal needed information using the methods in Figure 1.

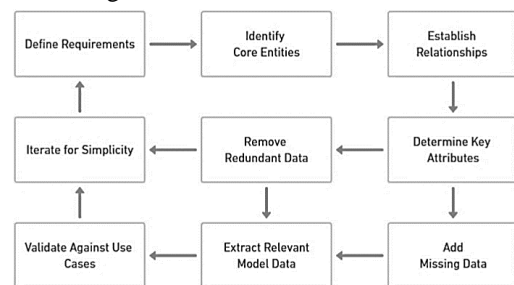


Figure 1: Applied iterative information research methodology

The requirements were identified in iterative assessments:

1. Assessment of the models' Level of Detail (LOD).
2. Assessment of schedules: work breakdown structure, activity durations, sequences, and resources.
3. Assessment of the carbon footprint for each resource.
4. Assessment of relationships between tasks, model elements, resources, and their carbon footprint data.
5. Assessment of 4D model representations.
6. Assessment of the use of VR to ensure sufficient data for visualization and analysis in the decision-making.
7. Assessment of the total carbon footprint of activities and resources over time, visible in 4D and VR.

Core railway entities were identified through a case study presented in the results and documented in the Annex. Relationships and key attributes were also studied through different conceptual representations used in construction management and, in particular, in scheduling (Table 1).

Table 1: Scheduling concepts relevant to the railway projects

Scheduling Technique	Application in Railway Projects
Gantt Chart	Clear overview of project timeline, milestones, and potential delays
Critical Path Method (CPM)	Prioritizes activities, manages resources, and mitigates delays of tasks
Program Evaluation and Review Tech. (PERT)	A more realistic estimate of project completion time, considering risks and uncertainties
Linear Scheduling Method (LSM)	Can manage track possessions, optimize crew moves, and minimize train disruptions
Genetic Algorithms	Optimizes train timetabling, resource allocation, and maintenance scheduling
Constraint Programming	Ensures adherence to safety regulations, tracks access constraints, and other specifics
4D BIM	3D planning and progress tracking better communication among stakeholders
VR Simulation	Helps analyze capacity, identify bottlenecks, and evaluate different scenarios

## Results from the case study

The 8 km railway tunnel case study shown in Figure 2 was used to explore the potential of 4D BIM and VR/AR. Tunnel refurbishment included portals, busbar, shotcrete lining, drainage upgrade, track renovation, and single-track conversion for emergency access.



Figure 2: Case Study: Refurbishment of double-track

Figure 3 illustrates the workflow used for making 4D and VR. Initially, the model exported from the BIM authoring environment is imported into Synchro for 4D sequencing. The model then moves to iModel Hub for integration, and after processing, it is visualized in LumenRT. Data from Recap is also processed into high-resolution 3D models via Bentley Context Capture, demonstrating a seamless flow across various software platforms. The model can be tested using VR glasses or/and exported to Unreal Engine or Unity from which it is easy to port to mobile devices.

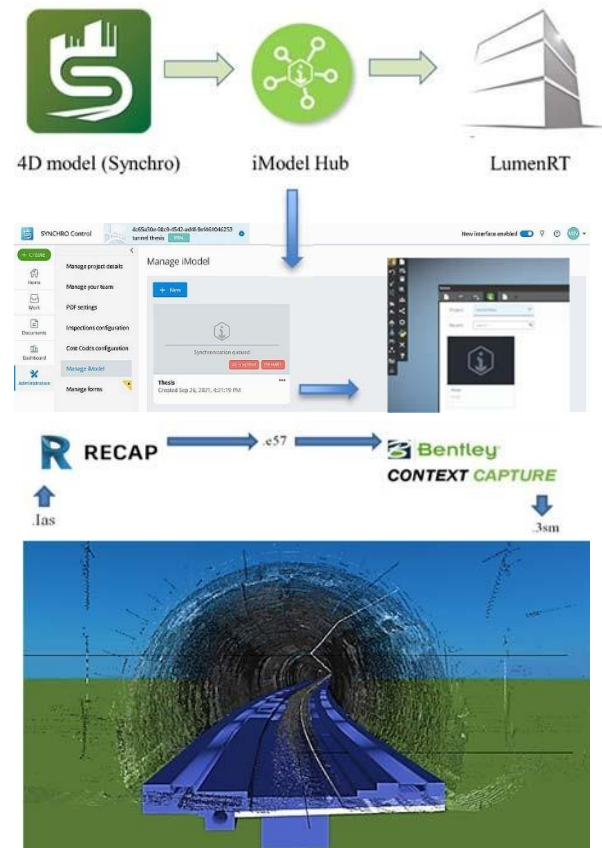


Figure 3: Transfer of 4D from Synchro to the LumenRT With an integrated point cloud and BIM model

For each refurbishment activity, corresponding tasks were identified and required visual representation info of the elements in the model and properties, along with the quantified assessment of their impact on carbon footprint. This approach ensures that each step of the refurbishment process is accounted for in terms of environmental impact, allowing for a more sustainable project option.

## Discussion and conclusion

Precise coordination and meticulous project information management in tunnel projects are needed for effective 4D planning and accurate carbon footprint estimates. This requires consistent geometries that include reliable data while avoiding data overload. Reducing the number of objects and focusing on specific analysis are crucial aspects. The study indicates that ensuring quality data in refurbishment requires very frequent verifications. Future research shall focus on comprehensive life cycle assessments and integrating digital twins for enhanced sustainability. Testing revealed that AI-powered 4D simulations and VR/AR visualizations offer highly promising solutions.

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