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Digital Twin for Railway Infrastructure and Historic Stations: State of the Art, Technological Architecture, and Development Perspectives

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Abstract
In recent years, Digital Twins (DTs) have emerged as a key element in the digitalization of railway infrastructure. This review article analyzes the main enabling technologies, operational challenges, and applications of DTs in the railway sector. The integration of Light Detection and Ranging (LiDAR) surveys, deep learning algorithms, Building Information Modelling (BIM) models, IoT sensors, and collaborative platforms enables the creation of dynamic digital twins, useful for monitoring, predictive maintenance, and optimization. However, critical issues remain, including the quality of point clouds, the management of heterogeneous data, and the lack of shared standards. The study identifies major research gaps, such as the need for annotated datasets, more robust AI models, and interoperable frameworks. In conclusion, DTs offer significant potential in terms of efficiency, safety, and sustainability, but bridging the gap between current technologies and their full-scale operational implementation is still necessary.

I. INTRODUCTION

Digital transformation is profoundly reshaping the railway transport sector, driving the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, and 3D modeling. In this context, the concept of the Digital Twin (DT) initially introduced by Grieves in the field of Product Lifecycle Management [1] and later consolidated by Glaessgen and Stargel as a multi-physics and multi-scale simulation of a real system [2] has taken on a central role. DTs are dynamic virtual representations of physical assets, capable of updating in real time through a bidirectional flow of data, with the aim of supporting monitoring processes, predictive maintenance, and optimized resource management.

Recent literature highlights how the application of DTs to transport infrastructures is evolving toward a systemic and cyclical approach, capable of covering the entire lifecycle of roads, bridges, tunnels, and railway networks [3]. The adoption of DTs allows for overcoming the traditionally reactive logic of maintenance, enabling predictive strategies that reduce downtime and operational costs [4]. Specifically in the railway sector, the digitalization of trains and infrastructure is now recognized as a key driver for increasing safety, reliability, and sustainability, in line with the principles of Industry 5.0, which is oriented toward human-centric and resilient models [5].

However, alongside these opportunities, significant challenges are emerging. The management of large volumes of heterogeneous data, the integration of legacy systems with digital platforms, the standardization of formats, and the cybersecurity of OT (Operational Technology) networks are critical factors hindering widespread implementation [3]. Historic stations, a distinctive part of Europe's railway heritage, present additional complexities related to architectural preservation and the need for non-invasive sensing technologies, with direct implications for modeling practices (HBIM) and the interoperability between BIM and GIS environments [6].

In light of this scenario, the present work aims to provide a critical review of the state of the art of Digital Twins in the railway sector, with particular attention to infrastructures and historic stations. The objectives are fourfold: to outline the main technological and organizational challenges limiting adoption; to propose a conceptual architecture structured into functional levels for the integrated management of railway networks; to analyze the enabling technologies and their role within the DT ecosystem; and finally, to identify research gaps and future development prospects, with reference to industrial standards for safety and interoperability (CENELEC EN 50126/50128/50129, IEC 62443, UIC/EULYNX) [7].

II. CHALLENGES

The adoption of Digital Twins in the railway sector is hindered by a range of challenges involving technological, organizational, and cultural aspects. The first major difficulty concerns data management. Railway infrastructures generate heterogeneous information from sensors, BIM models, lidar surveys, SCADA systems, and historical archives. Integrating this data into a coherent, unified platform is complex due to the lack of shared standards and the limited interoperability among proprietary formats. This issue is particularly evident in European railway systems, where networks of varying age and type coexist, often with incomplete or inconsistent digital archives [3].

A second critical area is data quality. Advanced acquisition techniques such as laser scanning or drone photogrammetry produce high-density point clouds that are not always suitable for automated processing. For example, the semantic segmentation of tunnels and underground infrastructures still suffers from limited and poorly annotated datasets, making it difficult to train deep learning models. In the study by Park et al. [4], the overall accuracy of PointNet applied to railway tunnel data reaches 93% in cross-validation across different tunnels, but with Intersection over Union (IoU) values dropping to as low as 0.67 for some classes. These results show how the lack of labeled data hampers performance and highlight the need for publicly available datasets specific to the railway domain.

The challenges are not merely technical. The digitalization of complex infrastructures requires a profound rethinking of organizational practices. Railway operators are often public entities or state-owned companies, characterized by long-established processes and a strong resistance to change [5]. The lack of internal digital expertise and the difficulty of integrating new tools with legacy systems present significant barriers. In this context, interdisciplinary collaboration must move beyond being an abstract principle and translate into concrete coordination tools among civil engineers, IT specialists, maintenance experts, and cybersecurity professionals.

Historic stations represent a particularly unique issue, as they are part of Europe's architectural and cultural heritage. Implementing a DT in such contexts must contend with strict regulations on preservation, prohibitions on invasive interventions, and the need to ensure aesthetic compatibility of installations. Traditional sensors are not always applicable and require alternative solutions, such as miniaturized sensors or indirect monitoring techniques based on vibrations and imaging [6]. Integrating this data into HBIM models—capable of representing not only geometry but also material properties and degradation states—is still an underdeveloped area.

Additional barriers arise in the field of cybersecurity and data governance. Railway OT networks—which include signaling, telecommunications, and train control systems—are increasingly exposed to cyber threats. The prospect of a fully operational DT, based on interconnected bidirectional communication, amplifies these vulnerabilities. The adoption of security standards such as IEC 62443 and risk management practices in line with CENELEC EN 50126, 50128, and 50129 for Reliability, Availability, Maintainability, and Safety (RAMS) is essential [7].

Finally, the issue of value remains unresolved. Despite the theoretical consensus on the benefits of DTs, a clear methodology for assessing their economic and operational impact is still lacking to support investment decisions. Value-based approaches—such as those recently applied to Portuguese railway networks—demonstrate the potential to integrate financial, performance, and environmental parameters into a unified framework [7]. However, the adoption of such methods remains limited and requires further empirical validation.

In summary, the main challenges relate to data quality and interoperability, the scarcity of annotated datasets, organizational resistance, the specific constraints of historic stations, cybersecurity, and value assessment. These issues are the core obstacles that must be addressed to transition railway Digital Twins from an experimental concept to a reliable, sustainable operational tool.

III. CONCEPTUAL ARCHITECTURE

The implementation of Digital Twins in the railway sector requires the definition of a conceptual architecture capable of transforming raw data into interoperable and operational digital representations. While the literature has already proposed multi-level frameworks for transport infrastructure [3], these are often generic and poorly adapted to the specificities of the railway domain. This work proposes a model structured into six functional levels, which, though inspired by established frameworks, introduces original elements tailored to the railway context and the needs of managing historic assets.

At the foundation lies the **physical level**, which includes tracks, bridges, tunnels, stations, and signaling systems. These assets are the primary sources of data and are characterized by high heterogeneity due to differences in age, materials, and operational conditions. The **second level** involves **data acquisition** through lidar surveys, photogrammetry, and IoT networks. In railway tunnels, for example, point cloud density can reach hundreds of millions of elements per kilometer, generating datasets on the scale of terabytes [4]. Collecting structural, environmental, and operational data is thus a critical challenge in terms of both quality and volume.

The **third level** addresses **intelligent data processing**, where AI algorithms—particularly neural networks—are used for semantic segmentation of point clouds and component classification. Techniques such as PointNet, DGCNN, and KPConv have demonstrated mean accuracies above 90% on railway datasets [4], though they remain sensitive to noise and annotation scarcity. A distinctive feature of this architecture is its **native integration with HBIM models**, which support not only geometry but also the material characteristics of historic stations [6].

The **fourth level** focuses on **informative modeling**. Processed data is transformed into interoperable BIM and HBIM models using open standards such as IFC and

CityGML. The goal is to ensure that digital models can interact with GIS systems and information management platforms, creating a digital continuum between operational infrastructure and architectural heritage.

The **fifth level** is **information management**, involving integration with Common Data Environments (CDEs) and relational databases. This level ensures traceability of changes and semantic consistency across disciplines. The combination of ontologies and standardized vocabularies helps overcome the fragmentation typical of railway systems, ensuring both vertical and horizontal interoperability [3].

Finally, the **sixth level** encompasses **operational applications**, including real-time monitoring, predictive maintenance, and decision support. In the railway sector, this translates into capabilities such as traffic flow simulation, fault prediction in signaling systems, energy optimization, and condition monitoring of historic stations. A concrete example is Deutsche Bahn's "Smart Maintenance" project, which has used Digital Twins for switch systems to reduce unexpected failures by 20% and improve high-speed line availability by 12%, resulting in estimated annual savings of over €30 million [5]. These figures highlight the tangible value of DTs when implemented through a systemic and scalable architecture.

The proposed architecture stands apart from generic models because it explicitly incorporates the constraints of the European railway context: the coexistence of modern infrastructure and historic stations, the need to comply with safety standards such as CENELEC EN 50126/28/29, the centrality of UIC/EULYNX protocols for interoperability, and the relevance of HBIM models for cultural heritage. It is therefore not a simple transposition of existing frameworks but a **critical and contextualized adaptation** that offers a conceptual foundation for the implementation of truly operational railway Digital Twins .

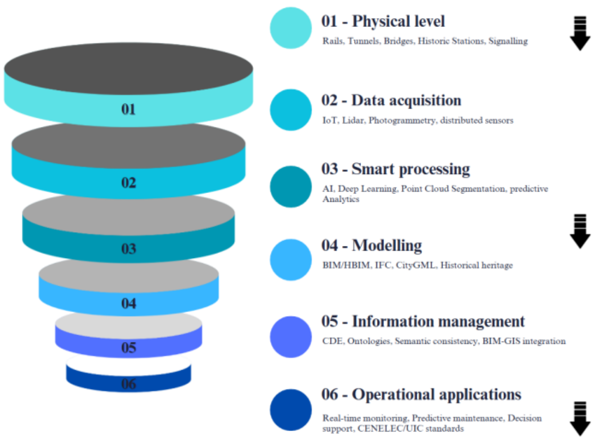

Figure 1 - Six-level conceptual architecture for Railway Digital Twins

IV. ENABLING TECHNOLOGIES

The development of effective railway Digital Twins is grounded in a set of enabling technologies that must not be viewed as isolated components, but rather understood in relation to the functional levels of the conceptual architecture. It is precisely in the integration of these solutions that the transformative potential of DTs lies.

At the foundation are the **Internet of Things (IoT)** and **distributed sensing technologies**, which enable continuous and multimodal data collection from railway assets. Sensors installed on tracks, signaling equipment, and vehicles allow for the monitoring of operational conditions, vibrations, deformations, and environmental parameters. Recent studies have shown that IoT is the key element for the transition from Digital Shadows to true Digital Twins, ensuring a **bidirectional data flow** between the physical asset and its digital counterpart [3,5].

Closely connected to sensing technologies, **artificial intelligence (AI)** and **predictive analytics** play a central role. Deep learning algorithms for point cloud segmentation and component classification have already achieved accuracy levels above 90% in railway contexts [4], although they are still limited by the scarcity of annotated datasets and data noise. The application of AI to predictive maintenance has also proven effective in reducing downtime and operational costs, supporting both **Condition-Based** and **Predictive Maintenance** strategies [4,5].

To consolidate and ensure the interoperability of data, **information models based on BIM and HBIM** form another essential pillar. The integration of parametric models with GIS environments using open standards (such as IFC and CityGML) enables **multi-scale management** of infrastructures, fostering cross-disciplinary collaboration and allowing DTs to encompass both modern infrastructures and historic stations [6]. The adoption of HBIM is particularly significant in heritage contexts, where it is essential to document and monitor material characteristics and conservation status.

Data management infrastructure plays a strategic role in ensuring semantic coherence, traceability, and shared access to information. **Common Data Environments (CDEs)** and **collaborative platforms based on ontologies** help overcome the fragmentation typical of railway systems and ensure an integrated and continuous vision throughout the lifecycle of the assets [3,6].

However, alongside these potentials, **cybersecurity and data governance** issues arise. The bidirectional nature of data flows and the growing interconnection of railway OT networks expose systems to increasing cyber risks. The application of security standards such as the **IEC 62443 series**, along with the **CENELEC EN 50126/28/29** standards for the reliability and safety of railway systems, is essential to ensure system reliability and service continuity [3,7].

Finally, the **technological maturity** of DTs is still evolving. Most existing applications remain limited to **digital models or digital shadows**, with predominantly unidirectional data flows. The shift to fully-fledged DTs—capable of supporting simulations, predictions, and autonomous decision-making—requires not only technological advances but also **process standardization** and the adoption of **shared value metrics** [7].

V. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the growing interest in Digital Twins within the railway sector, the literature highlights a number of gaps that hinder their full implementation and outline a future research agenda.

The first gap concerns the **availability of annotated and shared datasets**. Most studies rely on proprietary and limited datasets, particularly for the segmentation of tunnels, bridges, and switches. This makes it difficult to compare approaches and replicate results. There is a clear need to develop public repositories specific to the railway domain, enriched with semantic annotations and consistent metadata, following the model of well-established databases in other infrastructure sectors [4].

A second limitation lies in the still **partial integration between Digital Twins and Structural Health Monitoring (SHM) systems**. Many applications remain at the level of digital shadows, with unidirectional data flows, without fully leveraging the potential of bidirectionality to optimize maintenance, degradation forecasting, and operational decision-making [4,5]. Future research must focus on defining fully interactive DT architectures, capable of enabling a continuous cycle of data acquisition, analysis, and feedback to physical assets.

A third critical area involves **historic stations and railway cultural heritage**, where there is a lack of established methodologies for integrating non-invasive sensors, HBIM models, and regulatory constraints. The digital management of protected buildings requires the development of monitoring pipelines that are compatible with conservation requirements and capable of combining structural, environmental, and historical data [6].

Another gap concerns the **assessment of the economic and managerial value of DTs**. Digital investments must compete for limited resources, yet there are no standardized metrics to estimate returns in terms of reliability, availability, and maintenance cost reduction. Value-based approaches, such as those recently proposed for national railway networks [7], provide an initial reference point, but require further methodological refinement and empirical validation.

Cybersecurity remains a crucial issue. The progressive opening of railway OT systems to digital flows increases the risk of cyberattacks, while the literature still offers fragmented solutions. Future studies will need to investigate **resilient DT architectures**, based on established standards such as **IEC 62443** and **CENELEC EN 50126/28/29**, capable of ensuring operational continuity even under advanced threat scenarios [3].

Looking ahead, research should focus on building **digital ecosystems** capable of:

A. Ensuring **semantic and technical interoperability** across heterogeneous platforms;
B. Integrating **structural monitoring and predictive maintenance** within a closed loop;
C. Enhancing the value of **historic heritage** without compromising its preservation;
D. Defining **shared value metrics** to support evidence-based investment decisions.

These directions represent the necessary conditions for transforming railway Digital Twins from experimental tools into consolidated digital infrastructures, capable of ensuring **safety, resilience, and sustainability** throughout the entire lifecycle of networks and stations.

VI. CONCLUSIONS

This study has critically analyzed the state of the art of Digital Twins applied to the railway sector, highlighting their potential, challenges, and future development prospects. The review demonstrated that DTs represent a paradigm capable of radically transforming the management of railway infrastructures, shifting from reactive approaches to predictive and integrated strategies, with positive impacts on safety, efficiency, and sustainability.

A six-level **conceptual architecture** has been proposed, tailored to the specificities of the European railway domain and capable of encompassing both modern infrastructure and historic stations. This model integrates data acquisition, artificial intelligence, BIM–GIS interoperability, collaborative environments, and predictive maintenance applications, all in alignment with key standards such as **CENELEC EN 50126/28/29** and **IEC 62443**.

The analysis of enabling technologies highlighted both the potential and limitations of **IoT sensing**, **AI**, **HBIM**, and **data management platforms**, emphasizing the need for their integrated use in accordance with safety and reliability requirements. The review of major challenges revealed domain-specific criticalities: the lack of publicly annotated datasets, limited integration between DTs and SHM systems, the complexities of digital management of protected heritage, the difficulty in evaluating the value of digital investments, and cybersecurity-related risks.

From these insights, future research directions emerge, aimed at the creation of **resilient and interoperable digital ecosystems** that can combine predictive maintenance, heritage preservation, environmental sustainability, and adaptation to climate change. In this perspective, Digital Twins should not be seen merely as technical support tools, but as **reference digital infrastructures** for the entire railway lifecycle.

While not exhausting the complexity of the topic, this work aims to provide a **critical and systematic framework** to guide further scientific and practical developments. The full maturation of railway DTs will require addressing the identified gaps, developing standardized methodologies, and conducting large-scale validation. Only then can the Digital Twin be consolidated as a **strategic driver** to ensure the safety, reliability, and resilience of European rail transport

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