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Digital Twin Technology for Smart and Sustainable Railway Planning and Management

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ABSTRACT

Sustainable and intelligent transportation systems are essential for achieving resilient infrastructure and efficient resource utilization in modern economies. The railway industry, a crucial component of Turkey's economic structure, shows a great need for intelligent development as the globe moves into an era dominated by the information economy. In fields like digital modeling, simulation, and predictive analysis, digital twin technology is a valuable tool for increasing productivity. Building a Digital Twin Railway makes it feasible to accomplish thorough lifecycle perception, analysis, and interaction of railway operations, hence offering dependable technical assistance for the wise development of railroads. By offering a virtual reproduction of physical systems, Digital Twin (DT) technology is transforming the railway industry by facilitating real-time monitoring, predictive maintenance, and improved decision-making. This systematic literature review examines the status, enabling technologies, applications in Turkey, and frameworks for DT applications in railway systems with 651 selected papers from Web of Science. The most recent research on DT applications in railway systems is thoroughly reviewed in this work. Compared with the existing surveys, this study covers research articles from a holistic DT and railway system standpoint, spanning a broad variety of DT areas like 'Construction and Building Management', 'Smart Cities and infrastructure', 'Automotive, transportation and logistics'. Additionally, we perpetuated the research with the design of a strong four-layer architectural framework for Digital Twin Railway (DTR) systems, which was successfully validated using a functional prototype interface.

1. Introduction

Digital Twins (DTs) have emerged as a transformative technology, with remarkable capabilities for monitoring, optimizing, and forecasting real-world system behaviour across multiple domains. Although there are various definitions for DTs, a comprehensive definition should include three key aspects of Digital Twins: personalized product representation, dynamic real-time model updates throughout the product lifecycle, and the provision of diverse services, particularly decision-making abilities. As such, a Digital Twin is described as a digital version of an individual/unique physical item

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that has the same structure, context, and behaviour as its real-world counterpart. It is dynamically updated with data from its physical twin throughout its existence and can provide a variety of services, including value-generating decision-making. Enabling technologies and tools for DTs in railway systems. Throughout its existence, it is dynamically updated with data from its physical twin and can provide a variety of services, including value-realizing decision-making. By gathering and/or producing data, processing data in a virtual domain, and making judgments in real time, DTs contribute to value-realizing decisions. They are the intersection of computational engineering, data science, and the real world (Fig. 1).

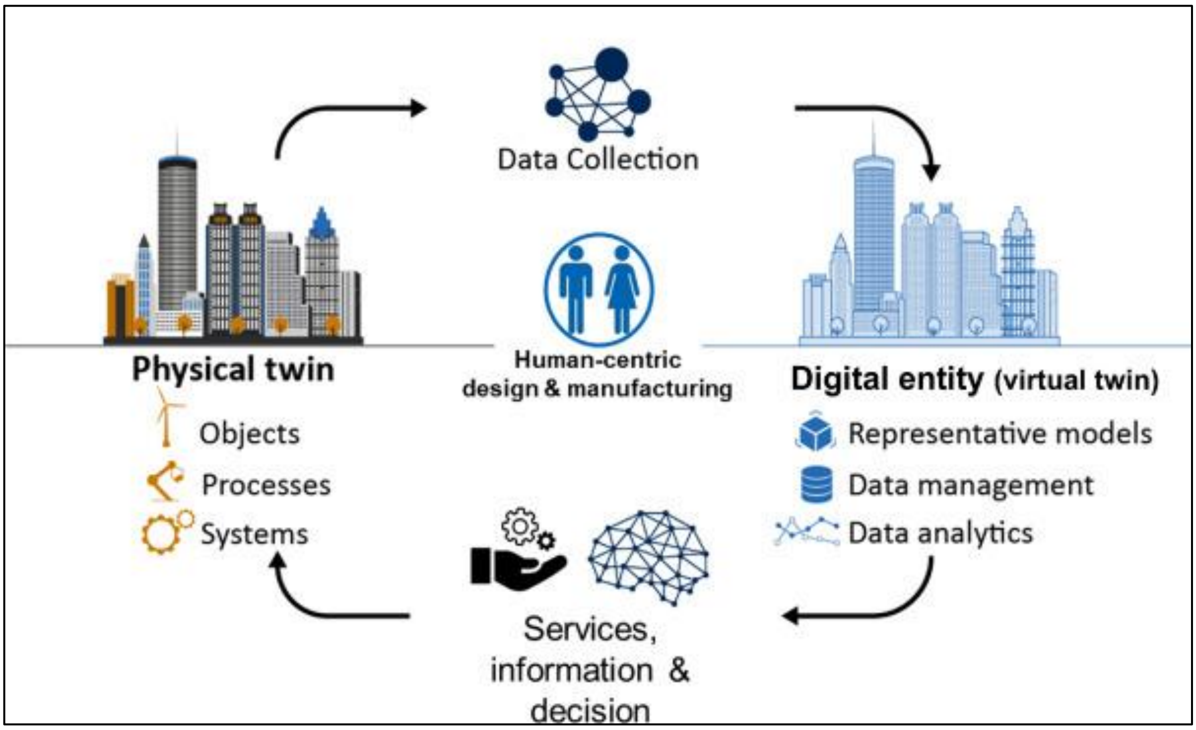

Fig. 1. Digital Twins [1]

In Turkey, efforts are underway to build digital twin models. Kuş et al. [2] created a digital twin model of a station under operation in rail systems. Within the scope of the digital twin study, the aim is to manage the data from all systems of Metro İstanbul A.Ş. (SCADA, SAP, Signaling, Energy Management) and BIM (Building Information Modelling) models on a common web-based platform, and to operate the stations more sustainably and efficiently by performing the necessary analyses throughout their life cycle after they are put into operation. Additionally, Akdeniz and Ofluoğlu [3] studied on sustainability-focused facility management (FMD) in metro station structures. The use of the BIM (Building Information Modeling)-supported digital twin approach in sustainable facility management is discussed. The study provides information on the architectural typology of metro stations and the electromechanical operating systems used, and explores the interoperability of these systems with BIM and facility management. Additionally, it includes examples of successful facility management projects in terms of sustainability. Metro Istanbul which is established by the Istanbul Metropolitan Municipality to operate urban rail systems, is aming to link the design, construction, and operation phases through regular data updates from the live model, ensure integration of existing software with API (Application Programming Interface) programs, process and update data into the model during the station management phase, perform regular monitoring of equipment using sensor data, and display data on dashboards. Aktürk [4] conducted a comprehensive synthesis of the literature on the digital twin through the lens of construction project management, in the second part, a quantitative questionnaire survey was created with the digital twin services that can go beyond BIM and address an enhanced construction project management.

The Ministry of Environment, Urbanization and Climate Change (ÇŞİDB) designed 3D digital twins for 81 provincial centers as part of the "Creating 3D Topography and Building Models in Urban Settlement and Development Areas" project [5], using information obtained from the General Directorate of Geographic Information Systems between 2016 and 2019. The city's built and natural environment was recorded using drones, and changes that occurred during the process were examined. In parallel with the acquisition and processing of drone data, the development of a "point cloud" and a "3D building and terrain model" was also considered. The 3D modeled data is expected to be integrated with "cadastral parcels" and the "Spatial Address Registration System" and used in urban information systems and urban planning, as well as in disaster risk scenario development. Furthermore, the assessment results are expected to guide relevant institutions and organizations in the protection and promotion of historical and cultural heritage, transportation regulation, energy security and conservation, mine control, and the prevention of environmental degradation (Yıkıcı, 2023) [6].

Digital twin characteristics can be listed as: (liu et al.) [7] (1) Data-driven: The dual mapping and dynamic interaction between physical entities and virtual models are achieved through data, driving iterative updates of the twin models. (2) Model support: Digital models enable the reproduction of complex system processes and provide three-dimensional visual representations. Various data types can be fully expressed through the twin models. (3) Precise mapping: Information sensing technology allows for dynamic monitoring and comprehensive perception of physical entities, ensuring accurate mapping within the physical space. (4) Software-defined: Twin models are displayed on a digital platform and simulate or monitor the state, behaviour, and rules of physical entities dynamically in software form. (5) Intelligent decision-making: By integrating technologies such as artificial intelligence, the twin models enable simulation, intelligent analysis, and predictive forecasting to assist in production decision-making.

The railway infrastructure management application domain could greatly benefit from the use of digital twins. Three of the primary issues that the railway infrastructure sector is currently facing are listed in this section and can be resolved by using digital twins. These needs have been identified through a review of literature and discussions with engineers in management positions at the Passenger Railway Agency of South Africa (PRASA) by Doubell et al. [8]. These can be listed as Integration of information, Validation of existing maintenance paradigms and Processing large volumes of data.

1.1. Digital twins application areas

The sectors are separated into 7 classes for digital twin application areas, which include manufacturing and industrial processes; health and medicine; aerospace and defense; construction and building management; smart cities and infrastructure; automotive, transportation and logistics; and agriculture and food supply chain. In the following section, we will explain engineering fields; namely, construction, smart cities and automotive [1].

1.1.1. Construction and Building Management

The application of DTs in building management and construction has shown great promise in resolving particular industry issues. For example, maintaining the structural integrity of concrete in various weather circumstances, which can impact its temperature and, consequently, its curing process, is a major difficulty in building construction. In order to address this, DTs have been used to use sensors to monitor the temperature of concrete in real time, enabling predictive actions to maintain ideal conditions.

1.1.2. Smart Cities and infrastructure

The use of digital twins in smart cities is still in its infancy, despite its successful implementation in numerous industrial sectors. By offering a framework that not only improves the intelligence and efficiency of urban systems but also radically alters how physical city infrastructures interact with their digital equivalents, digital twins are seen as the cornerstone of the upcoming generation of smart cities. The lack of trust and privacy issues around the sharing of sensitive data are the primary causes of the slow adoption of digital twins in smart cities.

1.1.3. Automotive, transportation and logistics

In the automotive, transportation, and logistics industries, recent developments in digital twins heavily emphasize performance optimization, improved maintenance techniques, and increased safety. Digital twins are used in the automotive sector to optimize vehicle lifecycle management by simulating real-world conditions, which drastically lowers maintenance costs and downtime. Talk about how real-time monitoring and predictive maintenance, which are essential for improving vehicle dependability and operating efficiency, are made possible by the integration of IoT and AI with digital twins. In the transportation industry, digital twins play a crucial role in controlling traffic flow and infrastructure planning. These systems use comprehensive data analytics to optimize traffic patterns and minimize congestion, which improves the effectiveness of urban transportation networks. The incorporation of blockchain technology, which secures data transfers among Digital Twins and improves the dependability and credibility of these intricate systems, is emphasized in logistics, where Digital Twins simulate networks to facilitate scenario planning and resource management.

1.2. Enabling Technologies

The effective application of DT technology in railway systems depends on a number of cutting-edge enabling technologies and tools that enable real-time monitoring, data analysis, and system optimization. The integration of sensor networks and Internet of Things (IoT) devices, which gather real-time data from actual railway components including rails, trains, and signaling systems, is one of the most important technologies. In order to ensure that the DT model adequately represents the physical system, certain data are supplied into it. By ensuring that railway operators have the most recent information on the state of their assets, tools that listed in Table.1, facilitate proactive maintenance and system management [9].

Table.1.
Enabling technologies for DT in railway systems

Characteristic	Iot and sensors	AI and ML	Simulation and modeling	Cloud and edge computing	GIS
Function	Real-time data collection [10]	Data processing and pattern analysis [11]	Virtual environment for strategy testing [12]	Data management and processing [13]	Spatial anlysis and visualization [14]
Application	Monitoring physical railway components [15]	Identifying infrastructure degradation [16]	Optimizing railway operations [17]	Enabling collaboration and real-time access [18]	Managing railway networks across terrains [19]
Benefit	Ensures accurate reflection of physical system [20]	Enhances operational efficiency [21]	Helps explore best solutions [22]	Supports immediate decision-making [23]	Enhances spatial understanding of railway systems [24]

Processing the enormous volumes of data produced by railway systems also heavily relies on the Internet of Things, sensors, artificial intelligence (AI), and machine learning (ML). These technologies improve operational efficiency by assisting DT models in analyzing trends and forecasting possible system breakdowns or maintenance requirements. Early indicators of infrastructure deterioration can be found by AI-powered algorithms, enabling prompt fixes that avoid expensive disruptions. Similar to this, modeling and simulation technologies are crucial for streamlining railroad operations because they offer virtual settings in which various tactics and situations may be tried out before being put into practice. With the aid of these tools, rail operators can investigate the most effective ways to handle intricate factors in a rail yard, such as train timetables and cargo management.

The management and processing of the massive datasets that DT systems depend on is becoming more and more dependent on cloud and edge computing. Railroad operators can work together and share real-time access to the DT model across many locations thanks to cloud platforms' scalability data storage and analysis capabilities. In contrast, edge computing reduces latency and facilitates quick decision-making in crucial railway operations by processing data closer to the source. Furthermore, to improve spatial analysis, Geographic Information Systems (GIS) are incorporated into DT applications, enabling operators to manage and analyze railway networks across a variety of geographical terrains. As a result, these technologies serve as the foundation of DT systems, enabling railway operators to boost maintenance tactics, optimize performance, and increase system reliability.

Additionally, IoT devices and AI/ML technologies work together in the railway systems DT environment, laying the groundwork for effective real-time monitoring and predictive capabilities. IoT sensors placed throughout railway infrastructure continuously record operating data (vibrations, temperatures, displacements, etc.) from physical assets, as seen in Figure.3. This data is then sent to cloud/edge computing platforms via communication networks. This raw sensor data is then processed and analyzed by AI and ML algorithms to find patterns, abnormalities, and performance trends that human operators would miss. This processed data is converted by the AI layer into useful insights, which are subsequently sent back into the DT model to update the railway system's virtual representation.

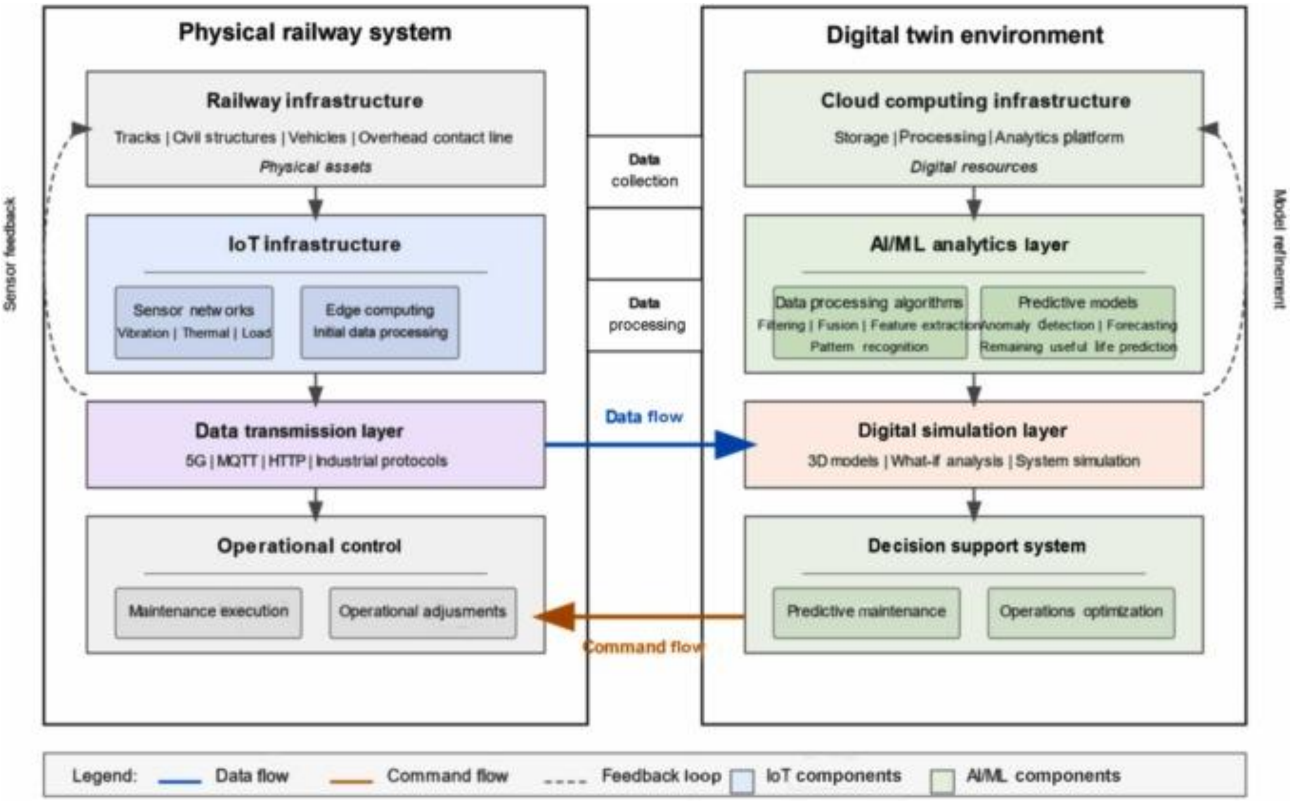

Fig. 3. Interaction framework of IoT and AI technologies in the rail DT ecosystems [9]

2. Bibliometric data search and Screening

The bibliographic data were collected from the Web of Science (WoS) core collection database by Clarivate Analytics. The following search code was used in the WoS advanced search engine: TS=(Digital Twin Technology) OR TI=(Railway System) OR AK=(Smart Systems OR Bibliometric Analysis) Figure 4 shows the review process adopted in this study. The key steps of this process are discussed as follows.

Fig. 4. Bibliometric review methodology

'TI' and 'TS' represent the title and topic of a publication, respectively. 'AK' corresponds to 'Author Keywords'. The time span of the search was set as 2010–2025. In addition, only journal articles in English were used in this study, which has been a common practice of most bibliometric reviews.
In this study, the term 'Article Type' refers to 'Article' and 'Review Article' types. Primary documents are defined as the documents identified from the literature search, namely the 37311 articles retained after two rounds of screening.

According to the refinement of 'Web of Science Categories', we obtained 10304 documents. These categories are 'Transportation Science Technology', 'Engineering Electrical Electronic, 'Transportation', 'Engineering Civil' and 'Computer Science Artificial Intelligence'. Furthermore, we filtered for 'Sustainable Development Goals' and selected 'Sustainable Cities and communities' category. We obtained 2653 documents for this refinement. The last refinement were done by 'Research Areas'. 651 results are obtained for 'Bibliographic data search and screening'.

In our research, the maximum record count obtained from 'Transportation Science Technology' with 568 documents for Web of Science Categories. Engineering Electrical Electronic and Engineering Civil are following categories, respectively. The results are shown in Figure 5.

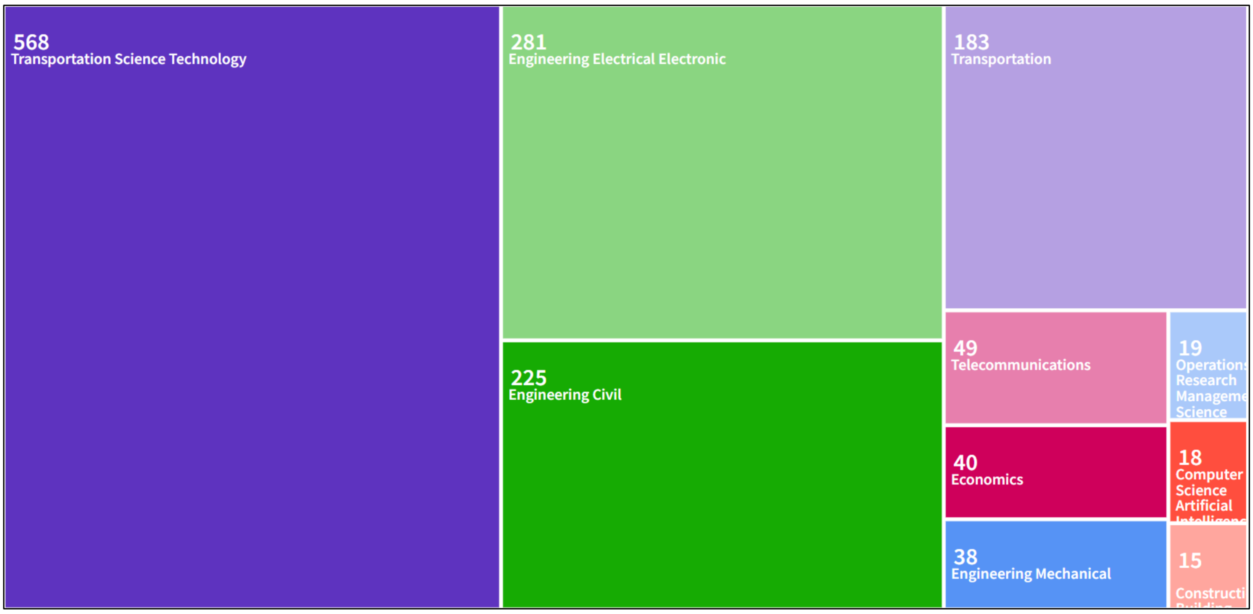

Fig. 5. Web of Science Categories

2.1. Geospatial Analysis

In order to better understand the distribution of research in the field by region, we analyzed the screened literature by geographical region. We marked the research locations of the authors in the literature according to the location of their affiliation, and analyzed the research density in different regions. Figure 4 presents the distribution of research studies by country and continent, highlighting significant regional disparities. The bar chart reveals that China leads with 227 studies, followed by the USA (100) and England (54).

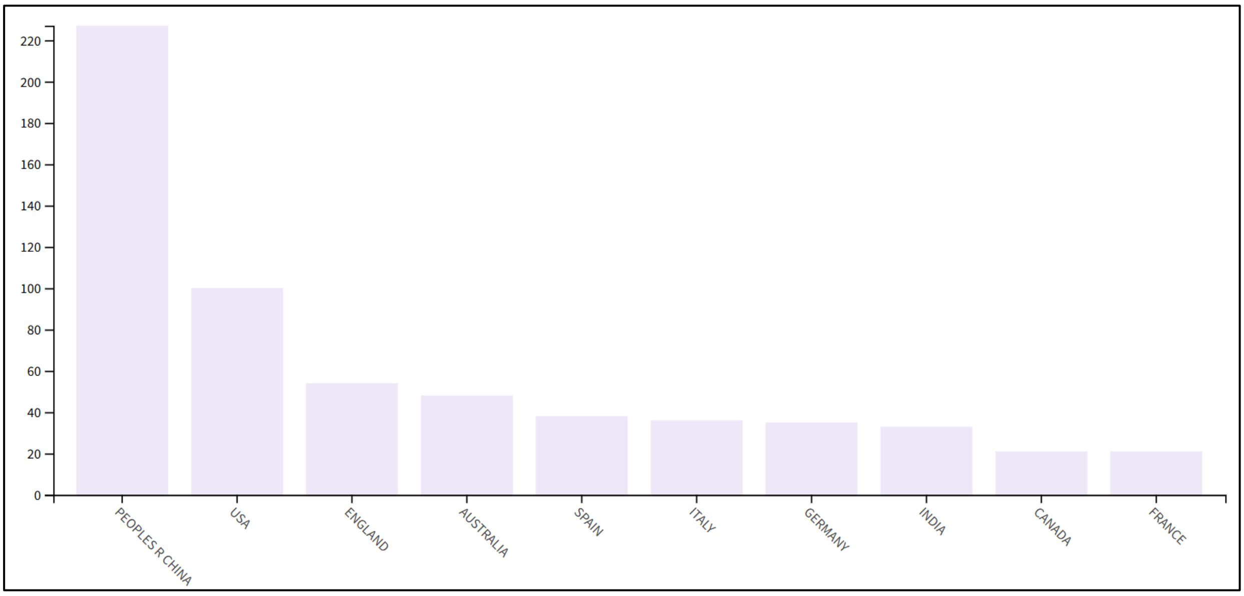

Fig. 6. Global distribution of studies by country and continent

2.2. Temporal Analysis

A temporal analysis was conducted to map the distribution of publication years, as depicted in Figure 7. Overall, the publications have shown a steady upward trend, which reflects the growing academic interest in the field, aligning with the broader development trajectory of digital twin technologies. During this period of 2020–2025, the number of publications increased. The implementation of Digital Twin technologies in construction and building management has demonstrated significant potential in addressing sector-specific challenges. Additionally, DTs still need to tackle several persistent challenges in construction and building management. These challenges include the need for standardized data protocols and improved interoperability between different systems and tools.

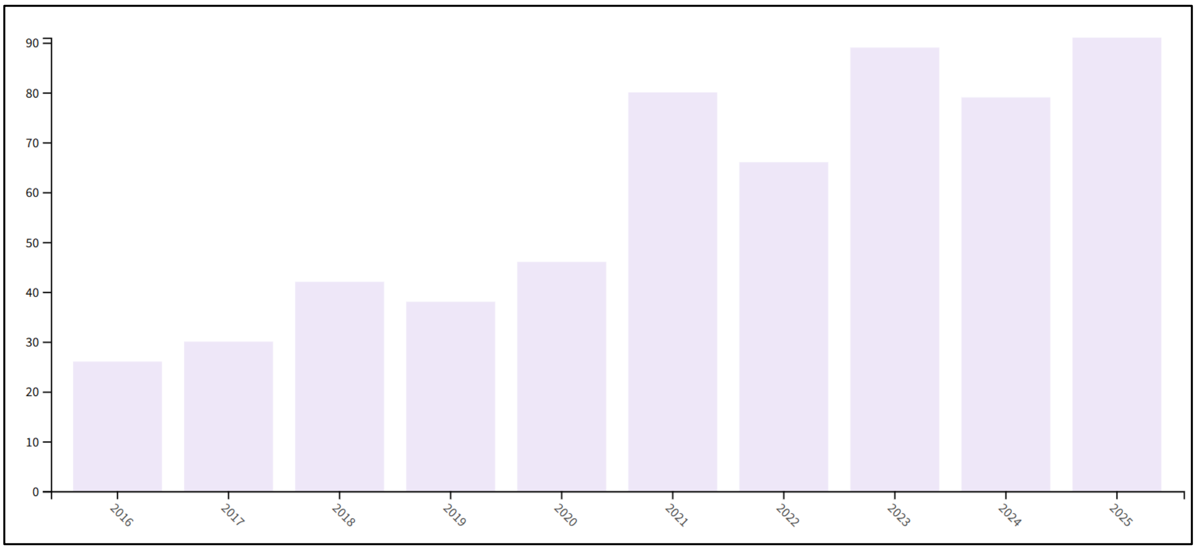

Fig. 7. Number of papers over the years

2.3. Keyword Analysis

We firstly exported the documents as a plain text file (1 to 581 records) and we imported them into VOS viewer program for visualization. Keyword clustering analysis was conducted on the selected literature. The network and density visualization of the keyword co-occurrence map is prepared by VOS viewer as shown in Figure 8 and Figure 9.

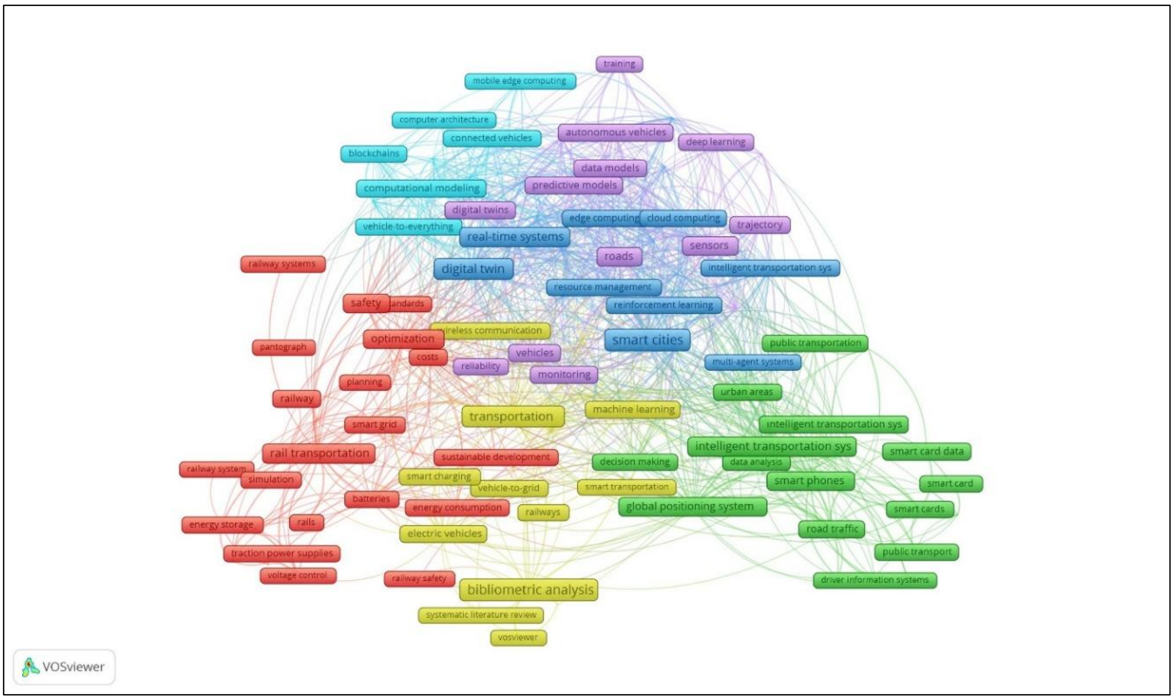

Fig. 8. Network visualisation by VOSviewer

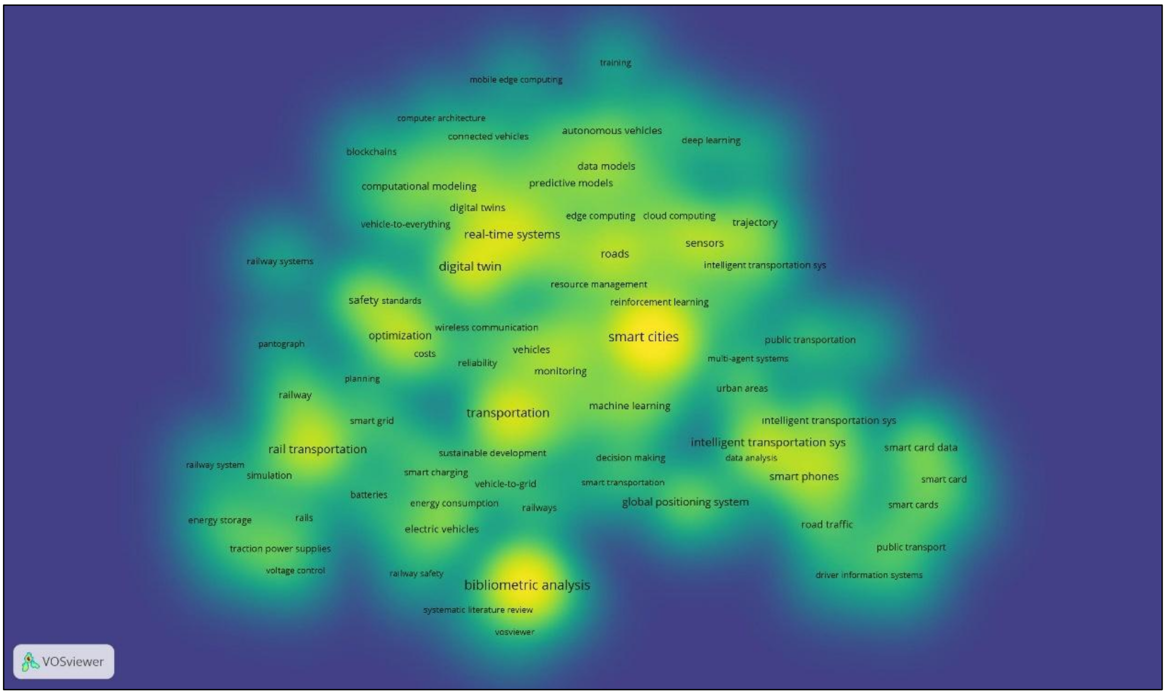

Fig. 9. Density visualisation by VOSviewer

2.4. Citation Network Analysis

We choose citation analysis with documents as the unit of analysis. In this dialog, the type of analysis corresponds to the edges of the resulting network analysis, and the unit of analysis determines the nodes of the analysis. Unit of analysis is selected as ‘Documents’. The results of citation network analysis are shown in Figure 10.

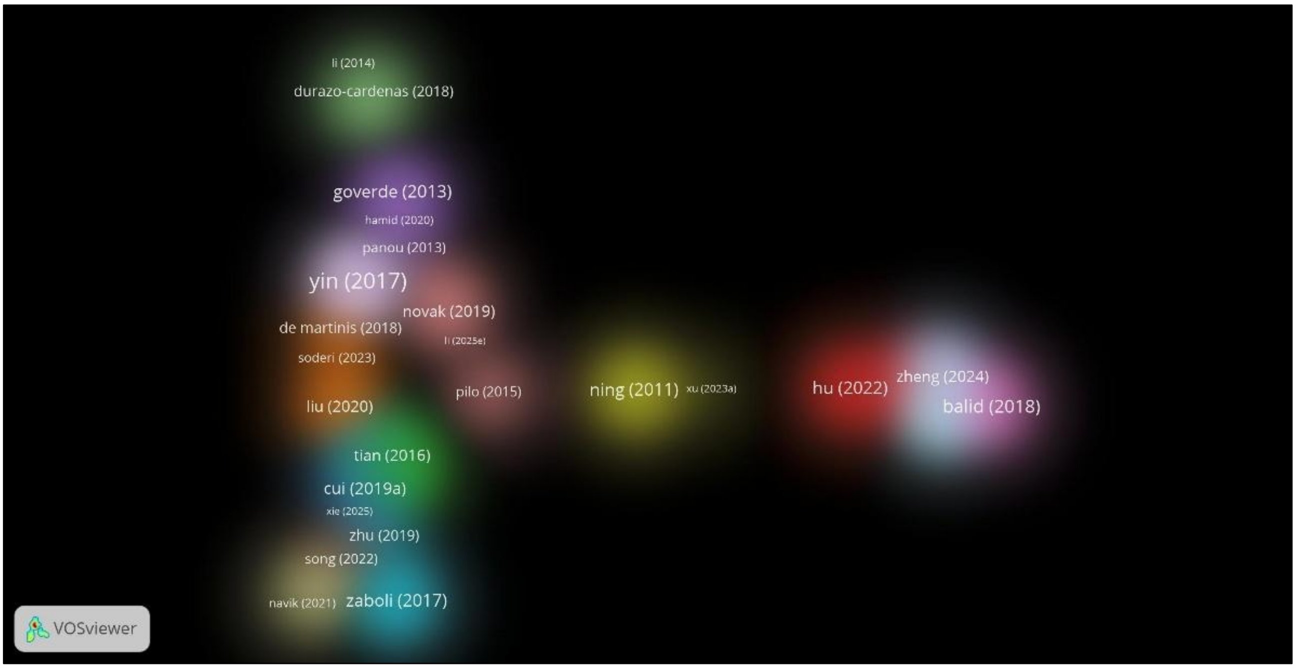

Fig. 10. Cluster of Citations

2.5. Co-authorship Analysis by Countries

Country co-authorship analysis measures a region's academic influence in a field by examining the geographical locations and authors of published articles. This study’s co-authorship analysis results are shown in Fig.11. It reveals collaborative networks, highlighting cooperation between different countries in specific research areas. This analysis is an important indicator of international collaboration and the distribution of academic influence across various regions. It demonstrates how countries work together on research and contribute to the global knowledge base.

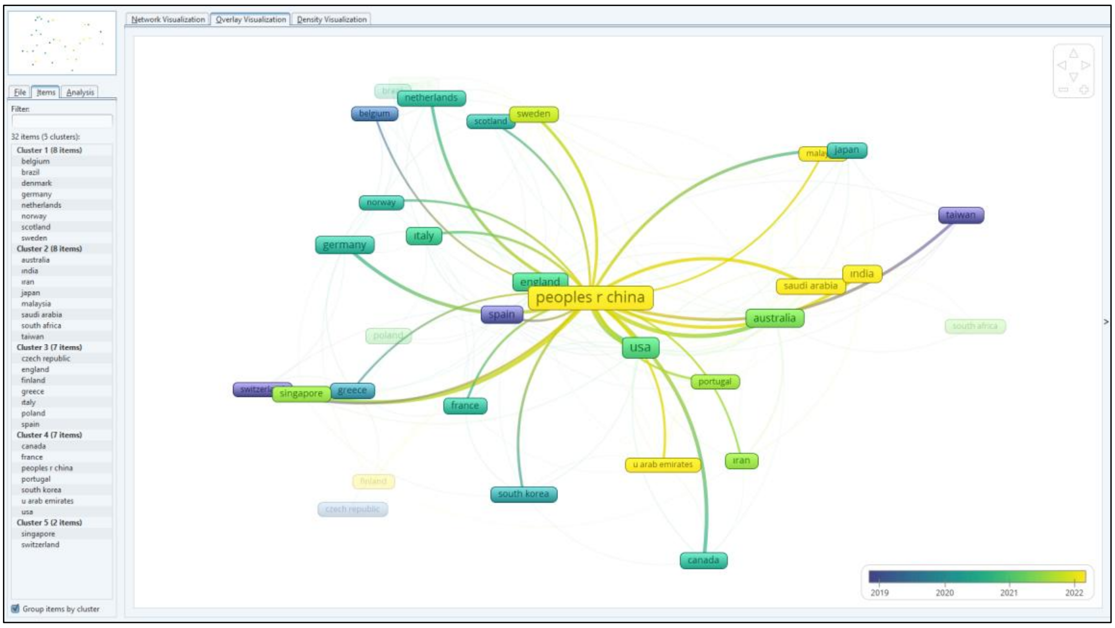

Fig.11. Overlay visualisation by VOSviewer

3. Data Management for supporting the efficient and stable operation of Digital Twin systems

Data management and storage is one of the backbone for the digital twin applications. Therefore, data management technologies are critical for supporting the efficient and stable operation of Digital Twin systems. [7] (liu et al.,2024) Table 2 summarizes the phases for supporting the data management and data analysis.

(1) Data storage and resource scheduling: Optimizing the storage organization of current databases or creating spatiotemporal data indexes are required to guarantee the simultaneous storage of spatial relationships and attribute relationships in spatiotemporal data. The goal of this optimization is to satisfy the requirements for concurrent storage queries and high data access rates. A multi-agent database cluster monitoring mechanism and stream, batch, model, and historical data can also be used to create a resource scheduling management system. The Digital Twin system's requirements for data integration, real-time processing, service direction, and intelligence are met by these actions, which also improve the operational capabilities of database clusters and the access efficiency of enormous spatiotemporal data.

(2) Data fusion and preprocessing: By filtering out aberrant and noisy data and eliminating redundant, duplicate, and incomplete data, preparing raw data improves data quality and guarantees accuracy, completeness, and consistency. Data reduction, data transformation, data integration, and data cleaning are all steps in this process. Additionally, data fusion is accomplished at the data level, feature level, and decision level through the synthesis, filtering, correlation, and integration of multi-source data. This method successfully lowers redundant data and improves reliability, offering a solid data basis for further activities like data mining.

(3) Data mining and visualization: Deep data features are mined by using statistical analysis, neural networks, and other techniques to process data, allowing situational awareness of physical entities. Additionally, data visualization techniques are used to effectively, simply, intuitively, and clearly portray the outcomes of data analysis.

Table.2.
Methodological Framework of the Digital Twin Phases

Phase	Layer	Workflow Description	Key Technologies & Outputs
Data Acquisition	Information Perception	Collection of raw data from physical assets (rolling stock, tracks, stations) using on-site sensors.	IoT Sensors, LiDAR, GNSS, 5G/GSM-R, UAV (Drones)
Data Integration	Data Management	Filtering, cleaning, and synchronizing raw data based on time and spatial location (chainage).	SCADA, Big Data Storage, Data Mining, Data Fusion
Model Construction	Model Assembly	Enhancing static 3D models (BIM/GIS) with dynamic real-time data and kinematic behavioral rules.	CityGML, BIM (LOD 300/400), Kinematic/Physical Models
Analysis & Decision	Integrated Platform	Processing data via AI and simulation to generate operational insights and forecasts.	Predictive Maintenance (PdM), 3D Visualization, Fault Diagnosis
Operational Optimization	Feedback Loop	Translating insights into direct actions or improvements in the physical rail system.	Automated Work Orders, Speed Restrictions, Energy Efficiency

We prepared an example real-time simulation of the Digital Twin Railway (DTR) ecosystem by Python programming language. By using the tkinter library, it simulates the four layers of the digital twin like a "Control Panel". The four-layered digital twin architecture presented in this study aims to transform raw sensor data into actionable operational intelligence for railway systems. By ensuring the spatiotemporal synchronization of physical data within the Information Perception layer, fusing dynamic IoT streams with static BIM geometry in the Data Management layer, and executing physics-based risk simulations in the Model Construction layer, the system transcends simple monitoring to provide predictive insights, such as the quantified 71% critical failure probability. Ultimately, the Integrated Platform layer distills these complex engineering computations into high-priority 'Predictive Maintenance Alerts', offering a holistic decision-support mechanism designed to enhance railway safety and prevent imminent failures through optimized maintenance life-cycle costs.

Layer 1: Information Perception (Sensing): This part certifies the successful acquisition of multimodal data. The mention of "KM 42+500" is essential because it illustrates Spatiotemporal Datum Unification, which means that the system correctly synchronizes sensor data to a specific physical position on the train line.
Layer 2: Data Management (Processing): This stage confirms the Data Fusion method. It implies that raw IoT streams are not handled in isolation but are combined with static BIM (Building Information Modeling) geometry and past maintenance logs to provide context to the vibration or strain data.
Layer 3: Model Construction (Simulation): This is the "Analytical Engine" of the twin. The "CRITICAL RISK (Risk: 71%)" output indicates the outcome of the Behavior/Rule Model simulations. It implies that the system is running complicated kinematic and physical calculations in the background to calculate the possibility of failure across all integrated assets (trains, tracks, signaling, and power), indicating a high-priority risk level that exceeds safety criteria.
Layer 4: Integrated Platform (Apps): Integrated Platform (Action) is the final output layer. The green status "System Healthy - Monitoring..." implies that the risk score (54%) is lower than the critical level (e.g., 70%). This depicts the Condition Monitoring application in steady-state operation.

Figure 12 shows an example of a "Conceptual Application Interface" that translates the theoretical layers of a Digital Twin Rail (DTR) architecture into an operational flowchart. There are four steps which illustrates how data transforms from the sensing layer to a decision output at the integrated platform layer.

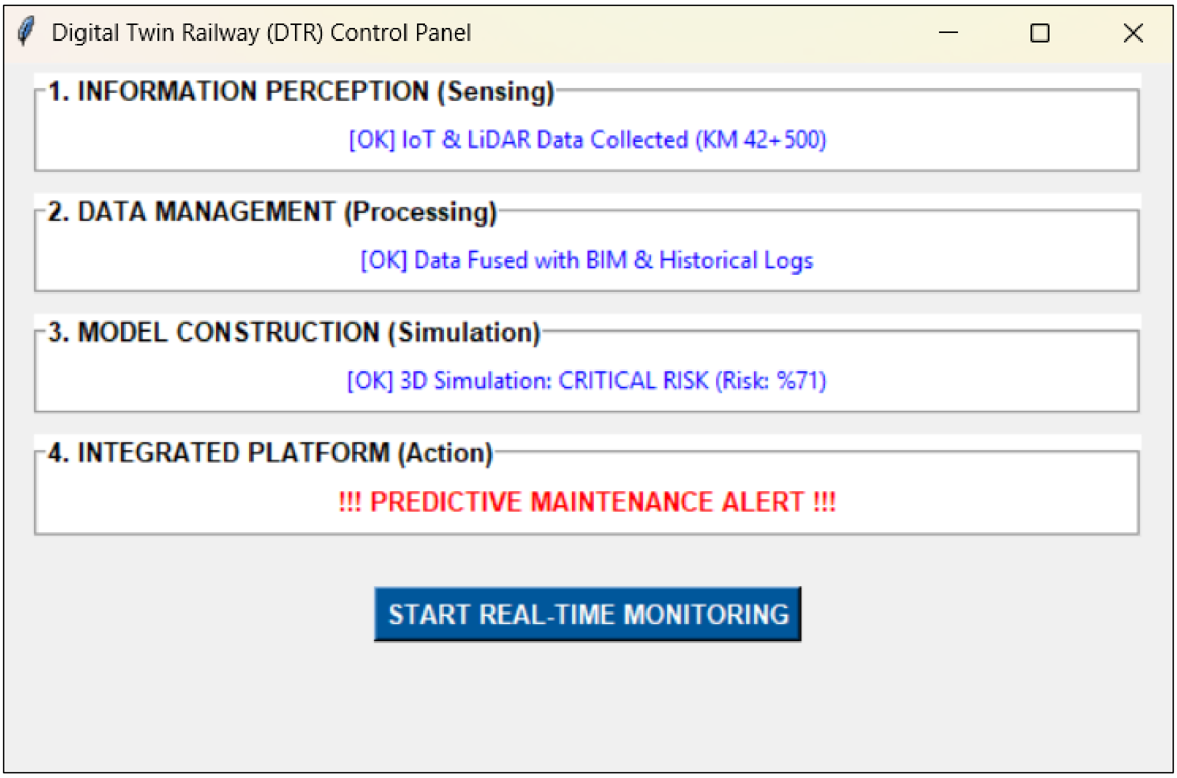

Fig. 12. Control Panel of railway digital twin

Additionally, Future directions should be developed by scrutinizing the interaction of information management issues. The following five strategic areas are vital for digital twin applications for rail transportation: (Ghaboura et al.,2016) [25]

- **Spatiotemporal Knowledge Integration**: Some studies emphasize the construction of conceptual, logical, and ontology models. By using a knowledge graph approach, these cases aim to map the complex spatiotemporal relationships between railway infrastructure characteristics, enabling a holistic understanding of how different features interact over time and space.
- **Urban and Environmental Simulation**: Another significant approach utilizes standardized 3D formats (specifically CityGML) to integrate railway data into broader city planning. These case studies demonstrate that a data-analytics-embedded digital twin can effectively visualize and analyze urban metrics such as building energy performance, air quality, and pedestrian movement near transit hubs.
- **Semantic Standardization and Redundancy Control**: In the context of urban planning, research focuses on semantic segmentation using advanced standards like CityGML 3.0, OpenDrive, and INSPIRE. These cases aim to create a uniform 3D representation across various transportation

modes to prevent data redundancy and ensure interoperability between different infrastructure systems.

- **Virtual Performance Mirroring:** A data-driven approach is also used to evaluate the effectiveness of the digital twin itself. These studies simulate virtual spaces to reflect the real-time performance of physical assets, proving that a well-constructed digital twin can accurately mirror the behavior of real-world transportation infrastructure products.
- **Sustainable Asset Decision-Making**: Finally, some case studies treat data as a core engineering tool for smart infrastructure. This approach focuses on the curation of railway asset data specifically to support sustainable decision-making, ensuring that maintenance and operational choices align with long-term environmental and economic goals.

4. Conclusion

An initial exploration of the topic was conducted using Web of science, aimed at establishing a preliminary direction and gaining a broader understanding of the research landscape. This bibliometric search provided insight into the topic by using Geospatial, Temporal, Keyword, Citation Network Analysis and Co-authorship Analysis by Countries in Railway System Planning and Management. The topic of publication is “Digital twin technology” and the title of a publication is “Railway System”. Keywords are refined as “smart systems” and “bibliometric analysis”. Documents search were employed within the context of digital twin processes.

Digital Twin refers to the construction of a digital model within an information platform, where the model dynamically operates and self-learns based on multiple feedback data sources. This allows for real-time representation of the physical entity’s actual changes within the digital world. Building on this foundation, technologies such as big data and artificial intelligence are comprehensively employed to monitor the system’s state, conduct simulation experiments, and perform predictive analyses. When well-managed, data enables improvements in safety, productivity, efficiency, and innovation, organizations that leverage the power of data analytics gain a competitive edge, allowing them to adapt to changing circumstances, make informed decisions, and achieve their goals more efficiently. However, given the rapid expansion of this topic with a multitude of ideas and concepts emerging, it is crucial to take a step back and analyze the role of digital twin Technology as a smart application. This capability is vital for data-driven modelling, three-dimensional visual representation, precise mapping, software-formation and intelligent decision-making.

Digital Twin technology primarily encompasses information perception technology, data management technology, model construction technology, and integrated platform technology. Digital twin and emerging technologies can be categorized as ‘Digital twin and artificial intelligence’, ‘Digital twin and 5G’, ‘Digital twin and cloud-fog-edge computing’, ‘Digital twin and virtual reality’, ‘Digital twin and blockchain’ and ‘Digital twin and the metaverse’.

Countries around the world are seizing this opportunity to accelerate the implementation of Digital Twin initiatives. Nations such as the United States, the United Kingdom, and Germany have elevated Digital Twin technology from localized exploration to national strategy, planning the long-term development of Digital Twins at the national level and establishing corresponding standards, principles, and development roadmaps. Countries like France, Russia, Japan, Singapore, South Korea, and Australia have also embarked on Digital Twin city construction, creating urban models across temporal and spatial dimensions to simulate extreme and anomalous events, thereby significantly enhancing urban infrastructure construction and operational management capabilities.

In the realm of digital twin technologies in Turkey, The digital twin can be applied in different application areas such as Manufacturing and industrial processes, Health and medicine, Aerospace and defense, Construction and building management, Smart cities and infrastructure, Automotive, transportation and logistics, Agriculture and food supply chain etc. Examples of good practices regarding the digital twin used in the world show that solutions are produced in accordance with the needs of metropolitan cities like Istanbul. In spite of this, it is important to point out that the degree of practice that is now being realized within the framework of digital twin city technology has not yet reached the level that is in accordance with the expectations that have been set in Turkey. It is important to note that in the background of this, there are security challenges, as well as technological and economic deficiencies. From this point of view, it can be interpreted that digital twin technology is utilized at many stages from the planning of cities to the implementation and development of smart city applications.

Digital twin city applications in Turkey do not fully reflect the digital twin city model. The methods and tools used in updates contribute to this situation. However, the other digital twin city projects mentioned utilize 5G infrastructure and IoT-based sensors to reflect instantaneous changes in physical objects onto the digital copy. In this context, receiving support from software companies experienced in digital twin city projects, digital twin railway projects and from city administrations implementing these projects can contribute to increasing the effectiveness of digital twin city applications in Turkey and the benefits they can generate. Furthermore, examples of projects and applications from around the world related to the construction of digital city twins, as well as the methods and tools used in these projects, can guide future projects in Turkey in this regard. On the other hand, the fact that digital twin cities are being developed concurrently with technical advancements, as well as the growing significance and providing the impetus to move further on, suggests that the gap will be closed. It is noteworthy that this study has vital importance in terms of shedding light on the ongoing operations to be carried out in the relevant field. The current paper establishes a significant baseline by articulating clear concepts and offering a critical perspective on the existing state of digital twin technology within railway systems.

The study concludes with the design of a strong four-layer architectural framework for Digital Twin Railway (DTR) systems, which was successfully validated using a functional prototype interface. The project demonstrates the feasibility of transforming heterogeneous raw data into usable engineering intelligence. The prototype GUI acts as a proof-of-concept, demonstrating how integrating BIM, GIS, and real-time IoT streams may greatly improve operational transparency and transform railway maintenance paradigms from reactive to predictive techniques.

Future research should focus on five essential areas to improve the usefulness of railway digital twins. First, spatiotemporal knowledge integration and knowledge graphs must be prioritized in order to unravel the complex spatial and temporal linkages between infrastructure assets. At the urban scale, including railway data into environmental simulations utilizing CityGML standards would allow for more inclusive planning strategies that take into consideration variables such as air quality and pedestrian mobility. Furthermore, prioritizing semantic standards is critical for reducing data redundancy and ensuring cross-system interoperability. Advances in virtual performance mirroring will be important in ensuring that digital models accurately reflect real-world asset behaviour in real time. Finally, integrating these digital workflows with sustainable asset decision-making will be critical in meeting long-term economic and environmental sustainability targets. Also, it would be interesting to use recent AI and ML technologies [26-30].

Author Contributions

Author Contributions: Conceptualization, B.Ç. and I.G.; methodology, B.Ç.; software, B.Ç.; validation, B.Ç. and I.G.; formal analysis, B.Ç.; investigation, B.Ç.; Python coding, B.Ç.; resources, B.Ç.; data curation, B.Ç.; writing—original draft preparation, B.Ç.; writing—review and editing, B.Ç. and I.G.; visualization, B.Ç.; supervision, I.G.; project administration, B.Ç.; funding acquisition, I.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

"The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper."

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