Politecnico di Torino
Academic Year 2025–2026

Department of Structural, Building, and Geotechnical Engineering
Master Course in Civil Engineering

Master's Degree Thesis

Application of Digital Twins with Autodesk Tandem in Metro Projects

Supervisor
Prof. Anna Osello

Candidate
Faisal Sami

Contents

List of Figures

List of Tables

Declaration

I, Faisal Sami, hereby declare that the thesis entitled *"Application of Digital Twins with Autodesk Tandem in Metro Projects"* is my original work, carried out under the supervision of Prof. Anna Osello at the Department of Structural, Building, and Geotechnical Engineering, Politecnico di Torino.

I further declare that this work has not been submitted, in whole or in part, for any other degree or diploma at this or any other university.

Date: ____________________

Place: Torino

Signature: ________________________

Name: Faisal Sami

Acknowledgements

I would like to express my heartfelt gratitude to my supervisor, Prof. Anna Osello, for her invaluable guidance, encouragement, and continuous support throughout this research.

I am equally grateful to Daniel Rodriguez Polania (PhD Student, Politecnico di Torino) for his assistance and constructive feedback.

I sincerely thank Infra.To for their collaboration and for providing the professional environment and resources necessary to carry out this project.

I am deeply thankful to my family and friends for their unwavering support and motivation.

Finally, I acknowledge the authors, researchers, and institutions whose work has been referenced and has served as a foundation for this study.

Abstract

Rapid urban growth is putting pressure on metro systems to remain safe, efficient, and sustainable. Digital Twin technology, implemented with Autodesk Tandem, links Building Information Modeling (BIM) with live data streams, creating a dynamic model that can adapt to changing conditions. For example, a Digital Twin model can be applied throughout the whole project life cycle, starting from planning and construction and continuing through operation and maintenance.

This thesis develops a workflow for the pragmatic application of Digital Twins in collaboration with Infra.To, the concessionaire of the Turin Metro. To predict maintenance events, monitor system behavior, and visualize performance, the workflow connects IoT sensors, REST APIs, and Python scripts. Sensors measure environmental parameters, and the information is structured into datasets and uploaded into Autodesk Tandem. Inside Autodesk Tandem, the data are displayed using dashboards and heatmaps. Alerts pop up in real time whenever unusual conditions appear, allowing operators to step in quickly before issues escalate.

To broaden the perspective, studies of the Istanbul and Delhi Metros were reviewed. According to the case studies, digital twins contribute effectively to operational management and to the preliminary phases of design and construction. The research also identifies challenges in integrating data from different sources, maintaining system security, scaling the system, managing costs, and ensuring good governance and ethics.

The thesis concludes with recommendations for greater use of AI/ML, stronger IoT networks, better integration with smart city strategies, and the adoption of AR/VR, predictive maintenance, and sustainability principles. Overall, the findings suggest that Autodesk Tandem-based digital twins can make metro systems more efficient, safer, sustainable, capable of predicting failures, and better prepared for future demands.

Chapter 1

Introduction

1.1 Background of Metro Rail Projects in Urban Transport

Urban transport is the backbone of modern cities. As populations grow and private cars become less practical, mass rapid transit systems (MRTS)—especially metro rail networks—are increasingly vital for moving millions of people each day. Cities from Delhi to Istanbul and from London to Singapore demonstrate how metro systems can reshape urban life by reducing travel times, easing congestion, and promoting sustainability [19, 67, 26, 61, 71].

However, bringing these systems to reality is no easy task. Metro projects are complex, requiring coordination across many stakeholders, years of development, major financial commitments, and constant operational oversight. In the past, they relied on paper records, static design drawings, and manual oversight. The adoption of computer-aided design (CAD) and building information modeling (BIM) has improved planning and project management [22, 28]. Still, challenges remain in areas such as real-time monitoring, predictive maintenance, cost control, and passenger safety [41, 44].

To bridge these gaps, digital twin technology is emerging as a game-changer. By developing a virtual model of the physical infrastructure and linking it with live data from sensors and IoT devices, engineers and operators can simulate processes, monitor performance in real time, and make more informed decisions across the full lifecycle—from design and construction to operation and long-term maintenance [68, 72, 55]. However, there is limited documented evidence on the practical application of Digital Twin technology in real-world metro rail operations [27].

What Are Digital Twins?

A digital twin can be described as a virtual copy of a physical object, process, or system. What makes it different from a traditional model is that it does not stay fixed. Instead, it evolves in real time because it is constantly fed with data from sensors, IoT devices, and other connected sources. In this way, the digital version mirrors the real asset by showing its actual condition, tracking performance, and pointing out issues as they arise [9, 67, 61, 69].

Figure 1.1 illustrates the core components of the Digital Twin technology ecosystem and their interaction through data integration.

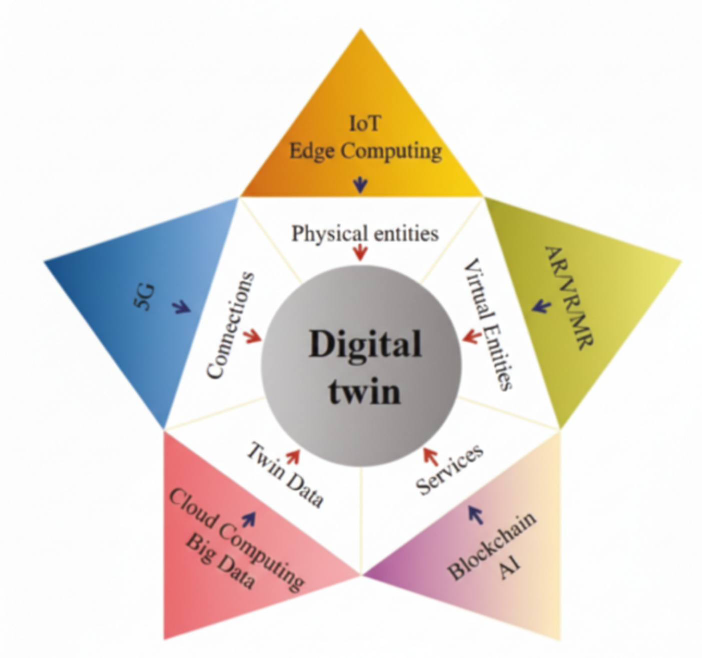

Figure 1.1: Digital Twin Technology Ecosystem [9]

Figure 1.2 presents the operational framework of Digital Twin technology, showing the connection between physical assets, data acquisition, and digital models.

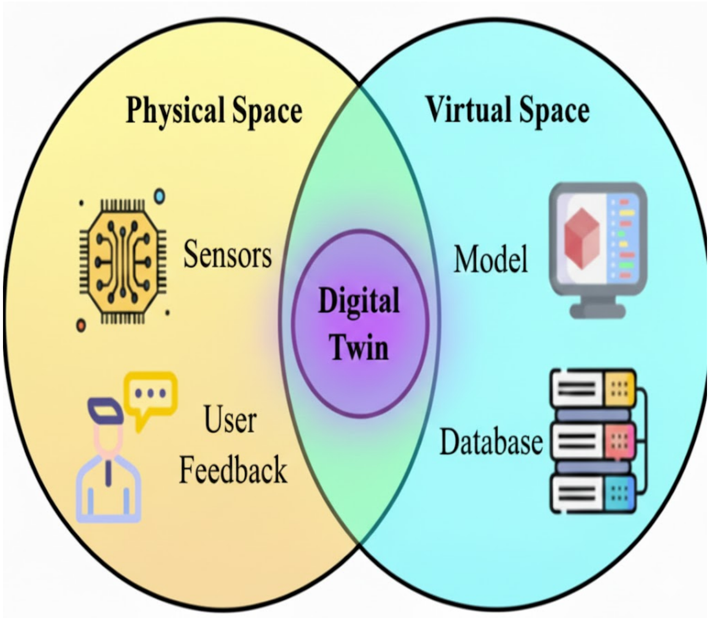

Figure 1.2: Operational Framework of Digital Twin Technology [9]

Within a metro system, digital twins can be applied in different areas:

- **Infrastructure:** tunnels, stations, tracks, and bridges.
- **Rolling stock:** trains, carriages, and signaling systems.
- **Operations:** passenger movement, ticketing, and train scheduling.
- **Maintenance:** anticipate wear and plan repairs before breakdowns happen.

By integrating all these components, the digital twin provides a comprehensive view of metro system performance, improving safety, operational efficiency, and maintenance management [63, 69, 50, 37]. Despite these advantages, metro projects still face several challenges

Metro Project Challenges

- Costs often rise due to design changes or unexpected delays.
- Safety risks during construction and daily operations.
- Managing multiple stakeholders—contractors, engineers, authorities, and the public.
- Maintenance difficulties due to unpredictable faults.

Digital Twin technology helps address these challenges by enabling real-time monitoring, predictive maintenance, and enhanced stakeholder coordination [67, 64, 69, 37].

Benefits of Digital Twins

- Testing and performance checks before system operation.
- Real-time safety monitoring through IoT-enabled sensors.
- Scheduled maintenance alerts based on IoT data.
- Better communication and transparency among stakeholders.
- Support for sustainable expansion in rapidly growing metro networks.

These benefits illustrate why digital twin technology is increasingly considered essential for the efficient management of urban metro systems [31].

Case Relevance to Metro Projects

Digital Twin applications are particularly relevant in metro systems:

- **Delhi Metro**: Predictive maintenance and passenger flow management across a complex multi-line network.
- **Istanbul Metro**: Enhanced safety and efficiency in large-scale underground construction and operation.

- **Denver International Airport**: Use of digital twins for real-time facility monitoring, operational efficiency, and predictive maintenance across a large airport terminal and infrastructure network.

These cases, discussed in detail in Chapter 5, demonstrate how Autodesk Tandem addresses real-world metro challenges.

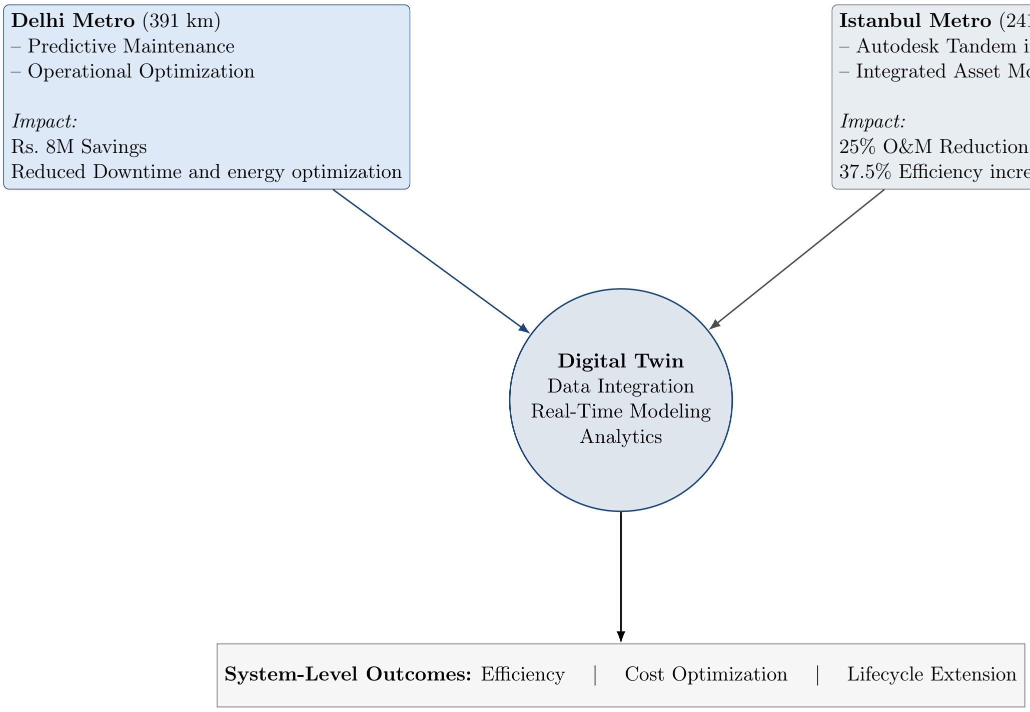

Figure 1.3: Metro System Metrics and Digital Twin Benefits [19, 31, 61, 71]

As Figure 1.3 shows, digital twins are already delivering measurable improvements in operational efficiency and cost savings in metro systems around the world. Detailed case study analysis is presented in Chapter 5.

Introduction to Autodesk Tandem

Autodesk Tandem is a cloud-based platform created by Autodesk that integrates IoT, lifecycle management, and BIM data in a single environment [4].

Key Characteristics of Autodesk Tandem

- Works smoothly with BIM processes.
- Provides centralized data access for all stakeholders.
- Updates models with real-time IoT sensor data.
- Supports 3D digital visualization of assets.
- Enables full lifecycle management (design, build, operate, maintain).

Other digital twin platforms, such as Bentley iTwin, provide similar BIM integration; however, Autodesk Tandem is preferred due to easier accessibility, simpler licensing, and a user-friendly interface [50, 61].

1.2 Research Questions

- How do digital twins compare with traditional approaches (BIM/CAD)?
- How does Autodesk Tandem, integrating BIM and IoT, enhance project management, and why might it be preferred over other platforms?
- What benefits and challenges have metro systems faced in adopting digital twins?
- How might digital twins, supported by IoT, shape the future of urban transport and smart cities?

1.3 Research Objectives

The primary objective of this research is to investigate the practical application of Digital Twin technology in metro rail systems using Autodesk Tandem as a case study platform. The study aims to evaluate how the integration of Building Information Modeling (BIM) and Internet of Things (IoT) technologies can enhance lifecycle management, operational efficiency, and decision-making in urban metro projects.

Specifically, the objectives of this research are:

- To evaluate the effectiveness of Digital Twin technology in improving monitoring and management of metro infrastructure.
- To assess the role of Autodesk Tandem in integrating BIM and IoT for lifecycle management.
- To analyse the benefits and challenges of implementing Digital Twin solutions in metro systems.
- To identify best practices and strategic recommendations for future metro digitalization.

1.4 Research Gap

Although Digital Twin technology has gained significant attention in recent years, there is limited documented research focusing on its practical implementation in operational metro rail systems. Most existing studies concentrate on conceptual frameworks or isolated pilot projects, with relatively few investigations examining real-world integration of BIM, IoT, and lifecycle management platforms in large-scale metro infrastructure.

Furthermore, there is a lack of structured evaluation of Digital Twin platforms in terms of operational performance, stakeholder coordination, and long-term asset management. This thesis addresses these gaps by providing a practical case-based analysis of Digital Twin implementation in metro systems using Autodesk Tandem, contributing empirical insights into its effectiveness and limitations [71, 69, 50].

1.5 Scope of the Study

This study focuses on the application of Digital Twin platforms in metro rail projects, with primary emphasis on Autodesk Tandem and comparative reference to Bentley iTwin. Case studies are drawn from metro systems in Delhi, Istanbul, and Turin. The research examines the full lifecycle of metro infrastructure, including design, construction, operation, and maintenance. While the study concentrates on metro rail systems, other transport modes such as buses and monorails are outside its scope.

Study Limitations

This study is subject to several limitations. The analysis focuses primarily on selected metro case studies and on a single Digital Twin platform (Autodesk Tandem), which may limit the generalizability of findings to other platforms or transport systems. In addition, some operational data are based on case study documentation and simulated scenarios rather than full-scale long-term operational datasets. Simulated scenarios were used in instances where real-time operational data was unavailable, providing a practical means to assess Digital Twin implementation. These limitations are acknowledged while interpreting the results and recommendations.

Significance of the Study

- Academic contribution: insights on digital tools in large-scale infrastructure.
- Practical contribution: guidance for metro authorities and planners.
- Policy contribution: supports policies for smarter and more sustainable metro systems.
- Industry contribution: demonstrates Autodesk Tandem as a practical tool for improving costs, safety, and efficiency.

Overall, this chapter has introduced the background of metro rail systems, outlined the concept of Digital Twin technology, and discussed the role of Autodesk Tandem in modern metro projects. It has also presented the research objectives, questions, scope, and significance, establishing a foundation for the subsequent chapters. As illustrated in Figure 1.4, design methodologies in metro projects have evolved from traditional CAD through BIM to Digital Twin platforms integrated with IoT. The roadmap highlights key stages including Autodesk Tandem implementation, results and discussion, case studies and research gaps, governance and ethical frameworks, and finally future directions.

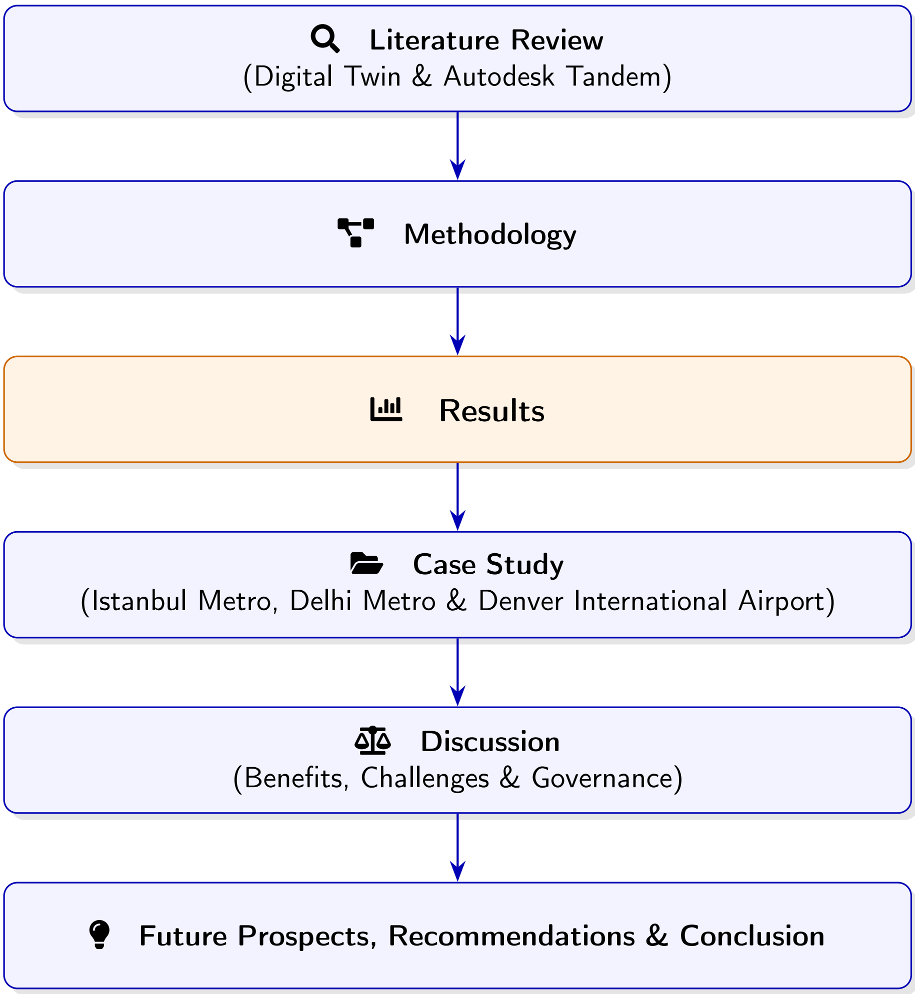

Figure 1.4: Roadmap of the thesis showing the progression of chapters following the Introduction. Each chapter highlights the key focus areas, from literature review to methodology, results, case studies, discussion, and the final recommendations and conclusion.

The next chapter presents the literature review, examining the evolution of metro project management, BIM, Autodesk tandem and Digital Twin technologies, and identifying research gaps that this study addresses.

Chapter 2

Literature Review

Introduction

A literature review is a key step in placing this study within the wider field of research. It helps to trace how digital tools have developed over time, showing both the theoretical foundations and the practical applications of Digital Twins in metro projects [22, 9, 36, 57]. The review not only summarizes what has been achieved so far but also highlights the gaps that remain—gaps which this research aims to address.

This chapter reviews how tools for managing and designing infrastructure projects have evolved over time. It begins with traditional methods, then examines the impact of Building Information Modelling (BIM), and finally explores the more recent shift toward Digital Twins. The role of Autodesk Tandem within this technological transition is also discussed. Among global examples, metro projects in India and Turkey receive particular attention. Comparing these two contexts provides a useful perspective for the case studies presented later in this thesis.

2.1 Evolution of Project Management in Metro Infrastructure

Metro rail projects are among the most complex forms of infrastructure development. They involve large investments, multiple stakeholders, and long operational lifespans. As a result, project management approaches have continuously evolved to respond to increasing technical and organizational challenges.

Initially, metro projects relied heavily on paper-based documentation such as blueprints, sketches, and written reports. While these methods were standard at the time, they made information sharing slow and error-prone. The introduction of Computer-Aided Design (CAD) improved drafting accuracy and allowed faster revisions. However, CAD remained largely a two-dimensional representation tool and did not integrate cost, time, or performance data.

The adoption of Building Information Modelling (BIM) marked a major shift. BIM enabled three-dimensional modelling enriched with detailed information, improving coordination between disciplines and reducing design conflicts. In metro projects, BIM supported better visualization and constructability analysis. Despite these advantages, BIM models remained largely static and focused on design and construction phases [9, 48, 38, 11].

As noted by Azhar [9], BIM significantly improved collaboration but did not fully address the dynamic nature of infrastructure systems. Metro projects evolve continuously during construction and operation, requiring tools that can respond to real-time conditions. This limitation has driven the increasing interest in Digital Twin technology, which integrates live data to support monitoring, prediction, and decision-making throughout the asset lifecycle.

Figure 2.1 shows the traditional CAD vs BIM process.

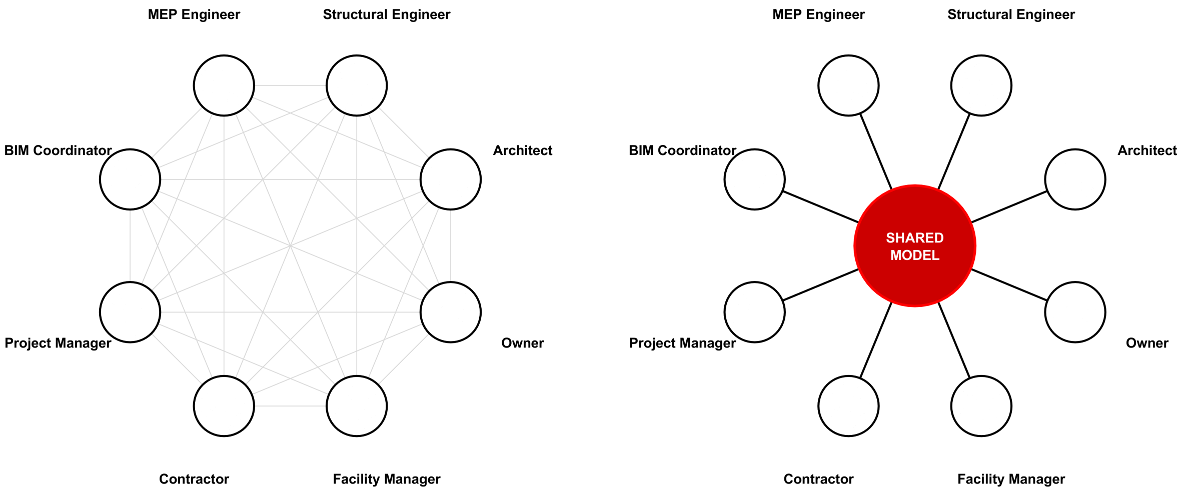

Figure 2.1: Traditional CAD vs BIM [48]

2.2 Evolution from BIM to Digital Twin

For many years, metro projects relied heavily on Building Information Modelling (BIM) during planning and design. BIM enabled detailed three-dimensional models containing both geometric and descriptive information. However, its application was largely limited to the design and construction phases, and models often became static after project completion.

The emergence of Digital Twin technology extends BIM into a dynamic environment where digital and physical systems interact continuously.

Figure 2.2 illustrates the core formula of BIM. BIM modelling is defined as the combination of a BIM model and interoperability between systems and software. For the model to be effective, interoperability must be non-zero, meaning that the model must be able to exchange and integrate data across platforms [46].

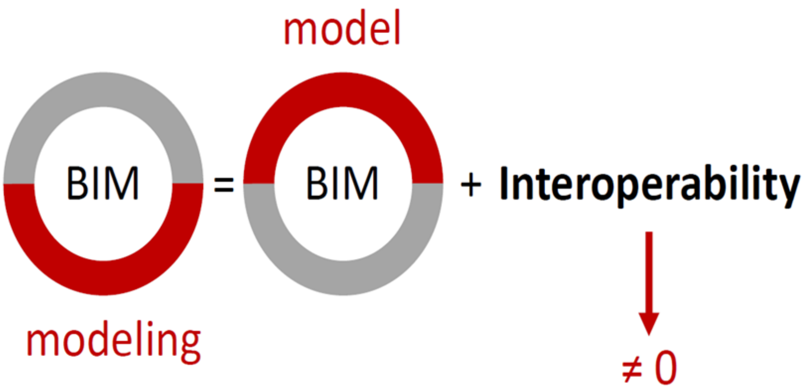

Figure 2.2: Formula of BIM [46, 49]

Figure 2.3 illustrates the different BIM dimensions, ranging from 3D geometric modeling to advanced dimensions such as 4D (time), 5D (cost), 6D (sustainability), up to 10D, showing how various aspects of building information are integrated for design, construction, operation, and maintenance.

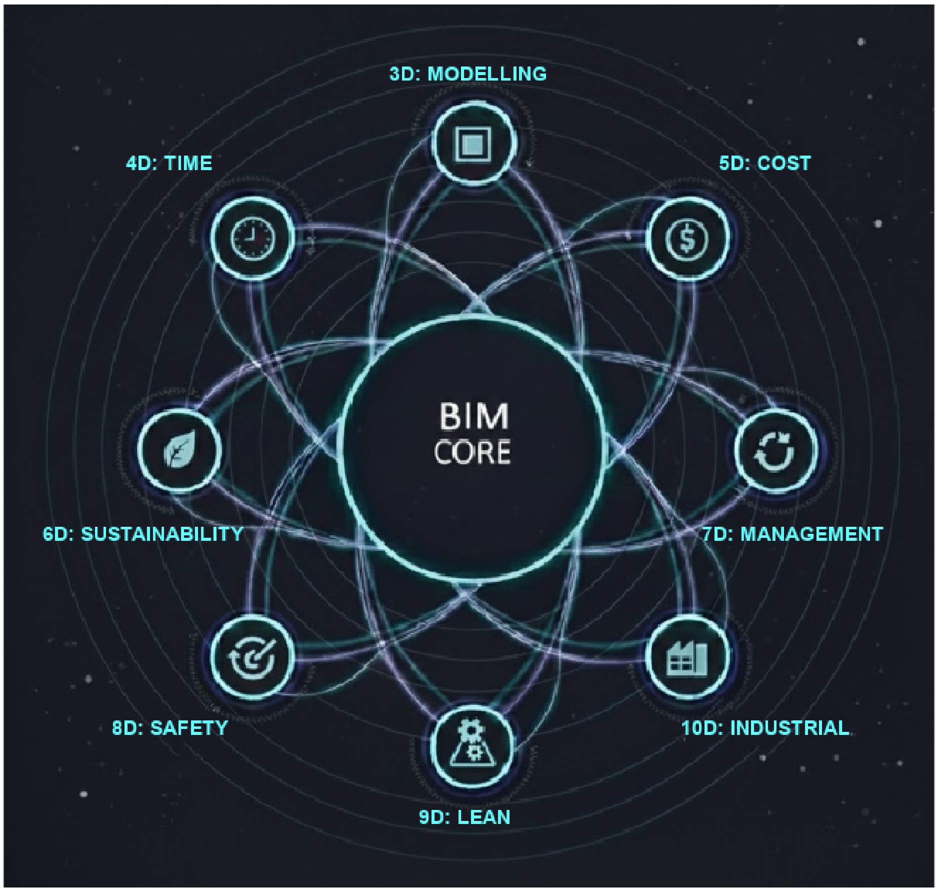

Figure 2.3: BIM Dimensions from 3D to 10D [47]

$$\text{BIM} = (D + C + M) \times (T + Q) \times (I + C_x) \tag{2.1}$$

where:

- D = Design (conceptual and technical designs, including 3D modeling)
- C = Coordination (MEP coordination, clash detection, interdisciplinary collaboration)
- M = Management (data management, project documentation)
- T = Time (scheduling, project timelines, phasing)
- Q = Quality (design quality, adherence to standards, value engineering)
- I = Information (material properties, energy analysis, cost estimates)
- C_x = Collaboration (communication among stakeholders, Lean construction principles)

Aspect	**BIM**	**Digital Twin**
Representation	Static 3D / 4D / 5D model	Dynamic real-time model
Data input	Design and construction data	Continuous IoT and sensor data
Updates	Manual or periodic	Automatic real-time synchronization
Lifecycle coverage	Design to construction	Full lifecycle including operation and maintenance
Predictive capability	Limited and reactive	Strong predictive and analytical capabilities

Table 2.1: Conceptual comparison between BIM and Digital Twins [47, 36, 57, 24]

BIM is often described as a digital prototype, whereas a digital twin is considered a living model that evolves alongside the physical asset [25, 13, 39, 33]. According to Grieves [25], digital twins represent the next stage in engineering digitalization. By integrating Internet of Things (IoT) devices, artificial intelligence, cloud computing, and data analytics, digital twins enable improved efficiency, resilience, and sustainability in infrastructure systems.

Key Differences Between BIM and Digital Twin

- **BIM**: Primarily static, focused on design and construction coordination.
- **Digital Twin**: Dynamic and real-time, integrating BIM with live operational and sensor data for monitoring, analysis, and predictive management.

Digital Twin

In essence, Digital Twins represent the next evolutionary step of BIM by combining IoT connectivity, analytics, and continuous feedback to transform static models into living systems that mirror real-world performance. In recent years, the concept of Digital Twins has gained significant attention in the fields of transportation and infrastructure planning. Although the idea itself is not entirely new, its application has expanded rapidly as cities seek smarter and more integrated approaches to managing public systems. In metro networks, where design, construction, and daily operation often overlap, a Digital Twin functions as a live digital representation of real-world conditions. Engineers can observe asset behaviour, compare real-time data with design intent, and adjust operational strategies while the system remains in service [63].

Among the companies advancing this approach, Autodesk has played a key role in transforming the Digital Twin concept into a practical engineering tool. Autodesk Tandem connects information generated during design and construction with operational and maintenance data. The following sections explain how this technology works in practice and how it can support safer, more efficient, and more manageable metro systems [4, 60, 3].

Theoretical Framework of Digital Twins

A Digital Twin is generally defined as a digital replica of a physical object, system, or process that continuously evolves based on incoming data. Unlike static drawings or conventional BIM models, a Digital Twin remains synchronized with its physical counterpart through constant data exchange. Information from sensors, IoT devices, and control systems ensures that both the digital and physical systems remain aligned.

This dynamic nature allows engineers to monitor system behaviour, simulate alternative scenarios, and optimize performance while the physical asset continues operating [63, 64].

Main Elements of a Digital Twin

The core components of a Digital Twin include:

- **Physical asset**: The real-world infrastructure element, such as tunnels, tracks, trains, or stations.
- **Digital model**: A virtual representation developed using BIM, CAD, or GIS tools that reflects geometry, materials, and asset condition.
- **Data link**: Continuous data flow from sensors, SCADA systems, and maintenance records connecting the physical and digital environments.
- **Analysis and prediction**: Performance trends are analysed using simulations and analytics to anticipate failures and optimize responses.
- **Feedback mechanism**: Insights from the digital model support operational adjustments and proactive maintenance planning [63, 65, 67, 64].

Conceptual Framework for Digital Twins

The Digital Twin framework is typically described using three interconnected layers [57, 24, 10, 20]

- **Physical layer**: Represents the real metro system, including stations, tunnels, tracks, and rolling stock.
- **Digital layer**: A virtual representation consisting of 3D models, design data, and engineering information.
- **Connection layer**: Links the physical and digital layers through sensors, IoT devices, and cloud platforms, ensuring continuous data flow.

In metro systems, these layers support several key functions:

- **Simulation**: Testing operational scenarios such as train schedules, passenger flow, and emergency responses.
- **Monitoring**: Real-time tracking of system performance, energy consumption, and asset condition.
- **Prediction**: Early detection of faults to enable predictive maintenance.
- **Optimization**: Identification of opportunities to improve safety, efficiency, and user experience.

Key Functions of Digital Twins in Metro Projects

Digital Twin technology supports all phases of metro development, from early design to long-term operation and maintenance.

- **Design validation**: Designers can test station layouts, passenger circulation, and ventilation strategies virtually, reducing the likelihood of costly design changes during construction.
- **Construction monitoring**: Real-time data from sensors and drones allows project teams to compare actual progress with planned schedules and identify deviations early.
- **Operations management**: Digital Twins integrate signalling, train scheduling, and passenger information systems, improving service reliability and responsiveness.
- **Predictive maintenance**: Continuous monitoring of assets such as escalators, HVAC systems, rolling stock, and tracks enables early fault detection.
- **Energy optimization**: Real-time observation of lighting, ventilation, and train operation supports energy efficiency improvements.

- **Emergency preparedness**: Virtual simulations of emergency scenarios enhance evacuation planning and safety procedures.

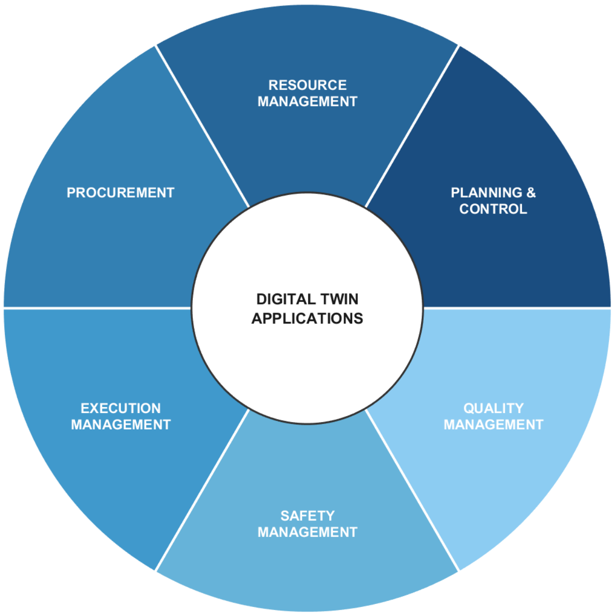

Figure 2.4: Operational parameters and workflow of Digital Twin integration in metro systems [63, 14]

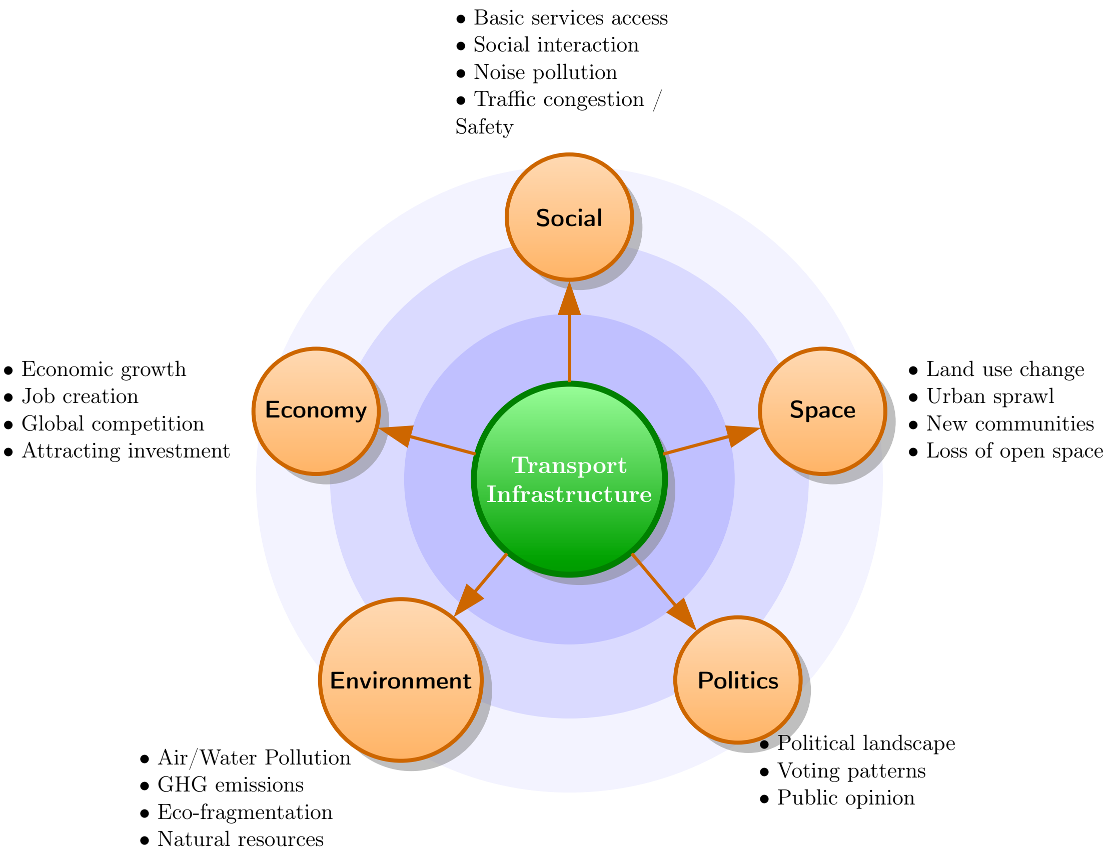

Figure 2.5: Multidimensional impacts of transport infrastructure [63]

Figure 2.4 shows the operational workflow of Digital Twin integration in metro systems, highlighting data-driven design, construction, and operational monitoring to enhance reliability, safety, and passenger experience [63, 14, 70]. Figure 2.5 illustrates the multidimensional impacts of transport infrastructure on society, space, politics, environment, and economy, emphasizing the interconnected effects of metro projects [63].

As shown in Figure 2.6, Digital Twin (DT) technology spans across diverse domains. In Building Construction, it facilitates progress monitoring and safety assessments, while in Urban Management, it supports city planning and HVAC control. The technology further extends into specialized sectors such as Aerospace for failure analysis and Health Care for patient management and heart disease research [63].

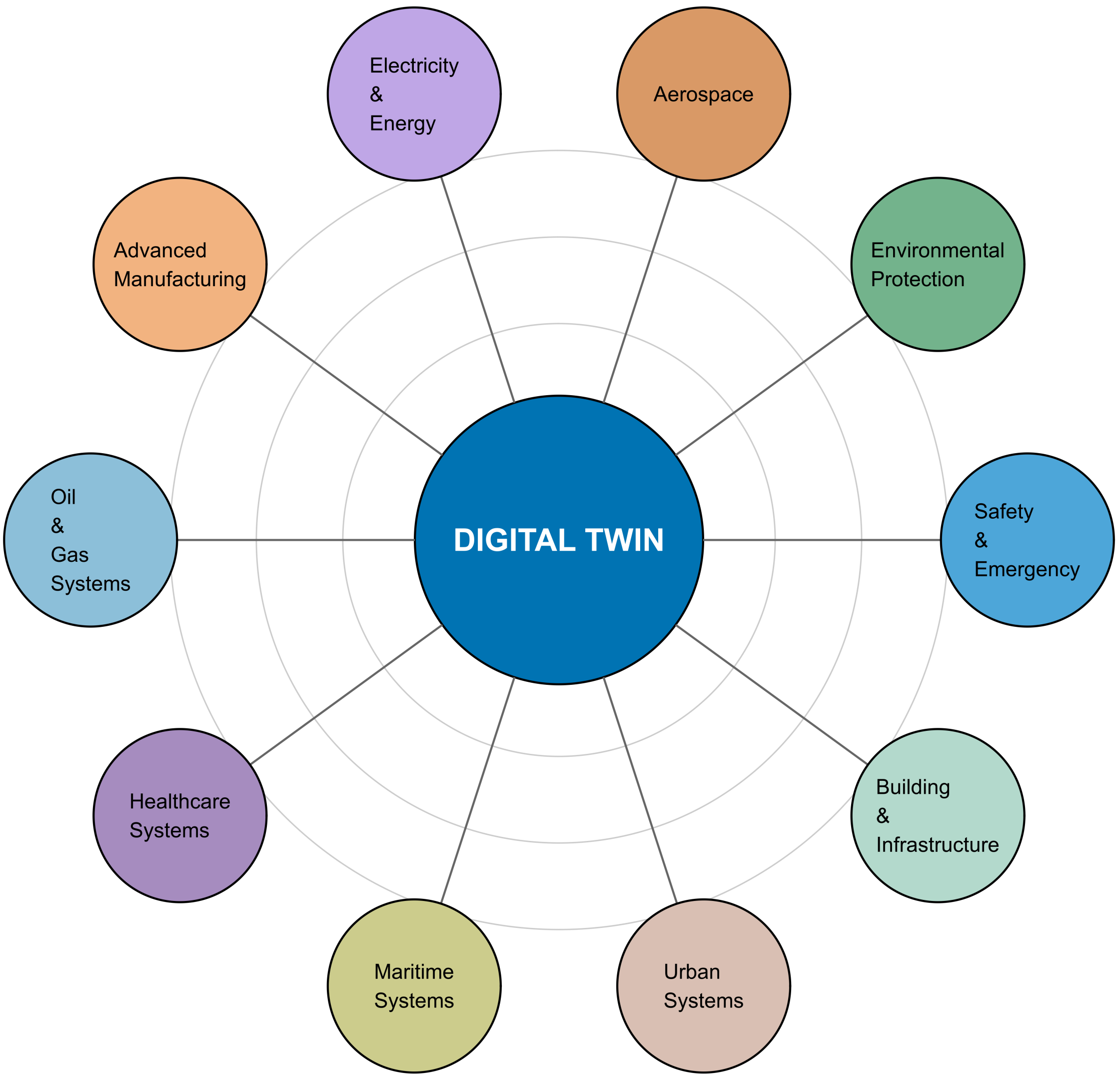

Figure 2.6: Conceptual overview of Digital Twin (DT) application areas across multiple sectors [63]

Together, these capabilities improve system reliability, safety, and passenger experience [63, 70, 14].

2.3 Literature on Autodesk Tandem

Since Autodesk Tandem was introduced in 2021, academic literature on the platform remains limited. Most available information comes from Autodesk publications, industry reports, and early project implementations.

Autodesk [4, 3, 50, 61] describes Tandem as a platform that bridges BIM models and operational data, facilitating smoother handover from construction to operation. A collaborative case study by Autodesk [3] reported improvements in data continuity and efficiency during project handover. Industry reports also suggest that Tandem reduces information loss between lifecycle stages, a common issue in traditional project delivery. Although peer-reviewed studies are scarce, early adoption by major AEC firms indicates strong potential for long-term asset management.

Autodesk Tandem: Overview

Autodesk Tandem is a cloud-based Digital Twin platform designed to operationalize digital asset management. It provides a shared environment where information from design, construction, and operations is integrated into a single, evolving digital record. Autodesk Tandem bridges the gap between building services and digital twins to improve operational efficiency [3, 7, 60].

Figure 2.7 demonstrates the integration of building and services with a Digital Twin framework. In this ecosystem, physical assets like Smart Meters, IoT Devices, and BMS (Building Management Systems) feed data into a Normalized Data Layer, enabling Contextual Visualization, dashboards, and metrics. This transforms a static BIM model into a dynamic operational tool.

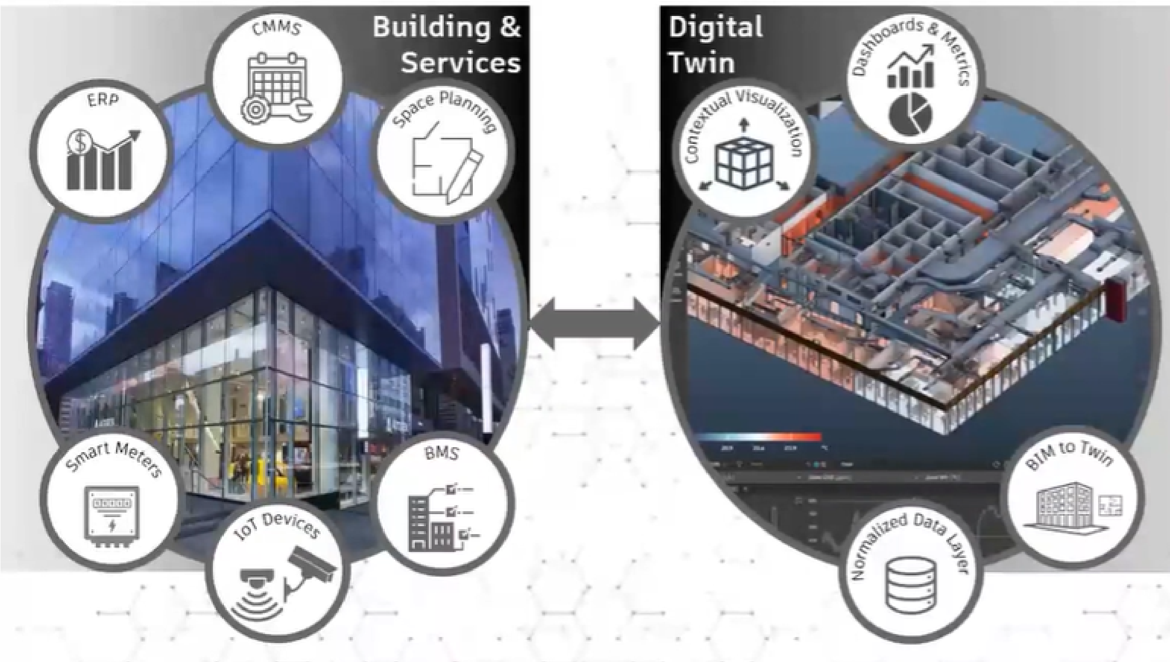

Figure 2.7: Overview of how Autodesk Tandem modernizes operations through Digital Twin integration [4]

- **Unified data environment**: Single, consolidated view integrating BIM, GIS, IoT, and enterprise systems.
- **High-quality asset and system data**: Accurate, structured, and up-to-date information for assets, spaces, and systems.
- **Actionable decision support**: Transforms data into insights for proactive operational decisions.
- **Cloud-native architecture**: Secure, scalable, and remote access for stakeholders.
- **Asset-centric representation**: Each asset has associated performance, condition, and maintenance data.
- **Lifecycle information continuity**: Preserves information flow from design through construction to operations.
- **Open and interoperable standards**: Supports formats such as IFC and COBie for cross-platform interoperability.

Figure 2.8 illustrates the primary outcomes of implementing Digital Twin technology in building systems. The integration of real-time monitoring, data analytics, and simulation capabilities contributes to improved operational efficiency, reduced utility costs, and supports the achievement of net-zero energy objectives. These outcomes demonstrate the strategic value of Digital Twin adoption in sustainable building management.

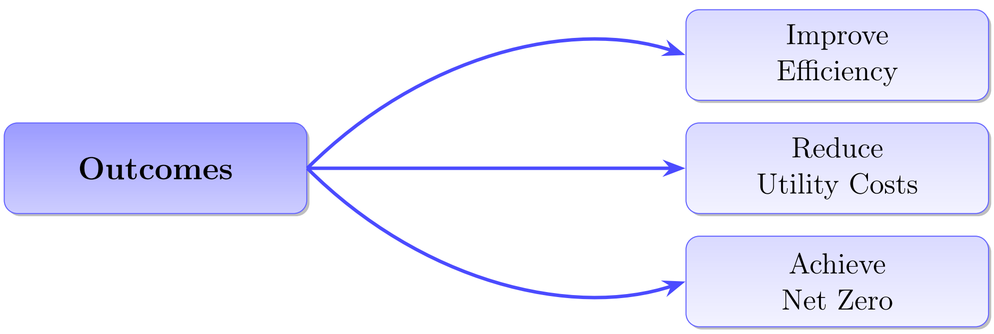

Figure 2.8: Key outcomes of Digital Twin applications in buildings

Architecture of Autodesk Tandem

Autodesk Tandem functions as a centralized hub where multiple data streams converge. Its architecture consists of the following layers:

1. **Data input**: BIM models (Revit, Civil 3D, InfraWorks), IoT sensors (temperature, vibration, passenger density), and legacy systems such as SCADA and maintenance logs.
2. **Data integration**: APIs and connectors unify real-time and historical data.
3. **Core Digital Twin model**: Cloud-hosted dynamic models linking physical and digital assets.

4. **Analytics and visualization**: Dashboards, KPIs, simulations, and predictive analytics.
5. **User interaction**: Web and mobile interfaces for engineers, operators, and decision-makers.

Traditional building management systems often rely on fragmented data workflows and manual coordination processes. In contrast, digital twin platforms such as Autodesk Tandem provide an integrated, data-centric environment. Table 2.2 presents a structured comparison between traditional systems and Autodesk Tandem.

Traditional Systems vs Autodesk Tandem

Traditional Systems	**Autodesk Tandem (Digital Twin)**
Data scattered across multiple tools	Centralized, integrated data environment
Manual coordination between teams	Cloud-based, real-time collaboration
Limited visibility of asset status	Continuous monitoring via sensors / IoT
Reactive maintenance	Predictive, data-driven maintenance
Decisions based on fragmented reports	Analytics-supported, data-driven decisions
Updates applied manually	Automatic synchronization with latest data

Table 2.2: Comparison between Traditional Systems and Autodesk Tandem (Digital Twin) [63]

Benefits of Using Autodesk Tandem in Metro

- **Holistic asset management**: Full visibility of stations, tunnels, and rolling stock.
- **Reduced lifecycle costs**: Predictive maintenance can reduce overall costs by approximately 15–20%.
- **Improved safety**: Faster emergency simulations and enhanced response planning.
- **Enhanced passenger experience**: Optimized crowd flow and reduced congestion.
- **Sustainability**: Continuous energy monitoring supports sustainability targets.

Challenges in Implementation

Despite its advantages, several challenges remain:

- Complexity in integrating legacy SCADA systems with modern IoT platforms.
- High initial investment costs.
- Skill gaps requiring training for engineers and operators.
- Cybersecurity risks associated with cloud-based systems.

2.4 Global Adoption of Digital Twin Technologies

Digital Twin technologies are increasingly being explored and adopted across metro systems and transportation infrastructure worldwide. Singapore MRT has implemented IoT-based monitoring to support predictive maintenance, while the London Underground uses digital models to optimize signalling upgrades and station refurbishments. Hong Kong MTR integrates AI-driven Digital Twins for real-time crowd management, and the Grand Paris Express leverages Digital Twin elements alongside BIM to coordinate large-scale construction activities [63].

Beyond metro systems, other transportation networks have also embraced Digital Twin technology. The Las Vegas Monorail, a high-speed system connecting major tourist attractions, introduced a digital twin in 2019 to monitor train speed and location in real time, enhancing operational efficiency and reducing passenger wait times. The Hong Kong–Zhuhai–Macao Bridge employs a digital twin to simulate events such as earthquakes, typhoons, and traffic accidents, enabling authorities to assess structural performance and mitigate risks. European systems such as the Paris Metro, London Underground, and Amsterdam's Schiphol Airport utilize predictive maintenance through sensor data and machine learning, reducing downtime and improving reliability [63, 62]. Collectively, these examples demonstrate the versatility and global adoption of Digital Twin technologies for improving operational efficiency, safety, and maintenance planning across diverse transportation systems.

In developing contexts, adoption remains uneven. Delhi Metro has begun integrating BIM-based tools with limited Digital Twin functionality, while Istanbul Metro authorities are exploring Digital Twin platforms to improve operational efficiency [19, 31, 15]. According to Autodesk [4] and Bentley [50], key drivers for adoption include rising passenger demand, increasing maintenance costs, sustainability targets, and smart city initiatives. Figure 2.9 shows the global adoption of Digital Twin technologies in metro projects.

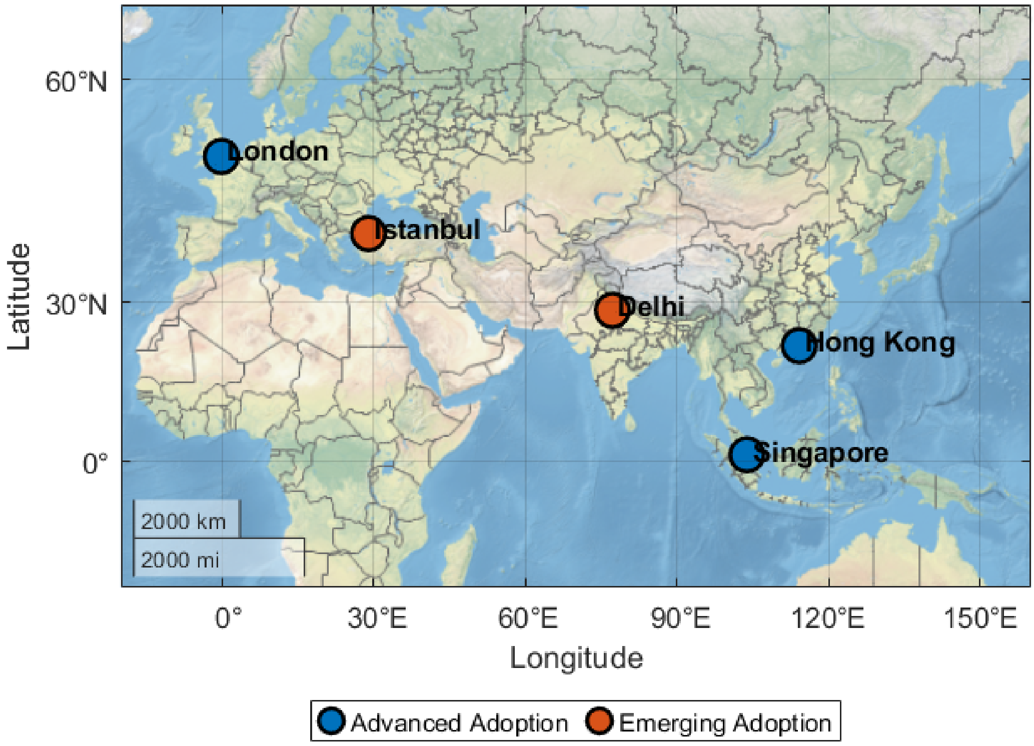

Figure 2.9: Global Adoption of Digital Twin Technologies in Metro Projects [63]

Research Gaps Identified

The literature review reveals several gaps:

- Digital Twin research in infrastructure is still emerging compared to BIM.
- Metro-specific Digital Twin studies are limited.
- Autodesk Tandem has received little academic attention.
- Comparative studies between developing and developed metro systems are rare.
- Operational and maintenance phases are often underexplored.
- Practical workflows linking BIM, IoT, and lifecycle data are insufficiently documented.

Addressing these gaps, this study focuses on the Delhi and Istanbul Metro systems and evaluates Autodesk Tandem as a Digital Twin platform [36, 11, 38, 50, 4].

2.5 Synthesis

The reviewed literature shows that BIM has enhanced coordination, visualization, and constructability analysis in metro projects but remains largely static and focused on design and construction phases [9, 47]. Digital Twins extend BIM by incorporating real-time IoT and sensor data, enabling continuous monitoring, predictive maintenance, and lifecycle decision-making [57, 25, 20]. However, metro-specific research and platform-focused case studies, particularly on Autodesk Tandem, remain limited [24, 10, 4]. These gaps justify the relevance of this research and highlight the need for empirical studies examining practical implementation in operational metro systems.

2.6 Summary

Digital Twins represent a fundamental shift in infrastructure management. With Autodesk Tandem, this approach is no longer theoretical but practically achievable. By providing a living digital representation of metro assets, Tandem supports safer operations, improved efficiency, and enhanced passenger satisfaction. This technological foundation prepares the ground for the case study analysis presented in the next chapter.

Digital Twins also represent a significant advancement by connecting design intent with real-world operations [57, 24]. While BIM laid the groundwork for 3D modeling and collaborative planning, platforms such as Autodesk Tandem are transforming how metro systems are planned, constructed, and maintained [4, 38]. Given the limited availability of detailed metro case studies, this research contributes valuable insights by examining practical applications in the Delhi and Istanbul Metro systems, addressing gaps in operational integration, platform evaluation, and lifecycle management.

Building on the insights from the literature, the next chapter outlines the methodology adopted in this study, including the integration of Digital Twin technologies and Autodesk Tandem in metro projects.

Chapter 3

Methodology

3.1 Research Framework and Approach

This research adopts an experimental and data-driven methodology integrating sensor-based environmental monitoring, Python-based data simulation, and Digital Twin (DT) implementation using Autodesk Tandem. The approach evaluates the integration of physical and synthetic data streams to support smart infrastructure management, specifically focusing on Indoor Environmental Quality (IEQ), scalability, and interoperability.

The methodology is structured into four distinct phases:

1. **Phase I: Sensor Monitoring and Data Acquisition**
   Establishment of the physical layer to capture real-time environmental metrics (e.g., temperature, VOC, humidity).

2. **Phase II: Data Simulation and Processing**
   Utilization of Python-based scripts to generate synthetic datasets, ensuring the model's robustness across various edge-case scenarios.

3. **Phase III: Digital Twin Integration and Data Exchange**
   Mapping of data parameters onto the Autodesk Tandem platform, focusing on schema alignment between physical sensors and digital assets.

4. **Phase IV: Visualization, Alerting, and Performance Evaluation**
   Analysis of the Shadow Object performance and the triggering of automated responses based on predefined threshold values.

This multi-stage framework ensures a continuous data flow from the physical environment to the digital model, enabling real-time analysis and informed decision-making.

Project Context: Infra.To Metro Line 2 (Turin)

The Infra.To Metro Line 2 project in Turin (Figure 3.1) serves as the primary case study for this research. The planned metro line extends approximately 27 km in a Y-shaped configuration and includes 32 stations, divided into a 16 km central section between Rebaudengo and Anselmetti (23 stations), a 6 km southern extension toward Orbassano (5 stations), and a 6 km northern branch reaching Pescarito/San Mauro (4 stations) [29]. Notably, Certosa station is located along the northern branch and serves as a key node connecting the surrounding urban area to the metro network. Within this research, Certosa is considered as part of the Digital Twin implementation, providing a representative segment for workflow validation [29].

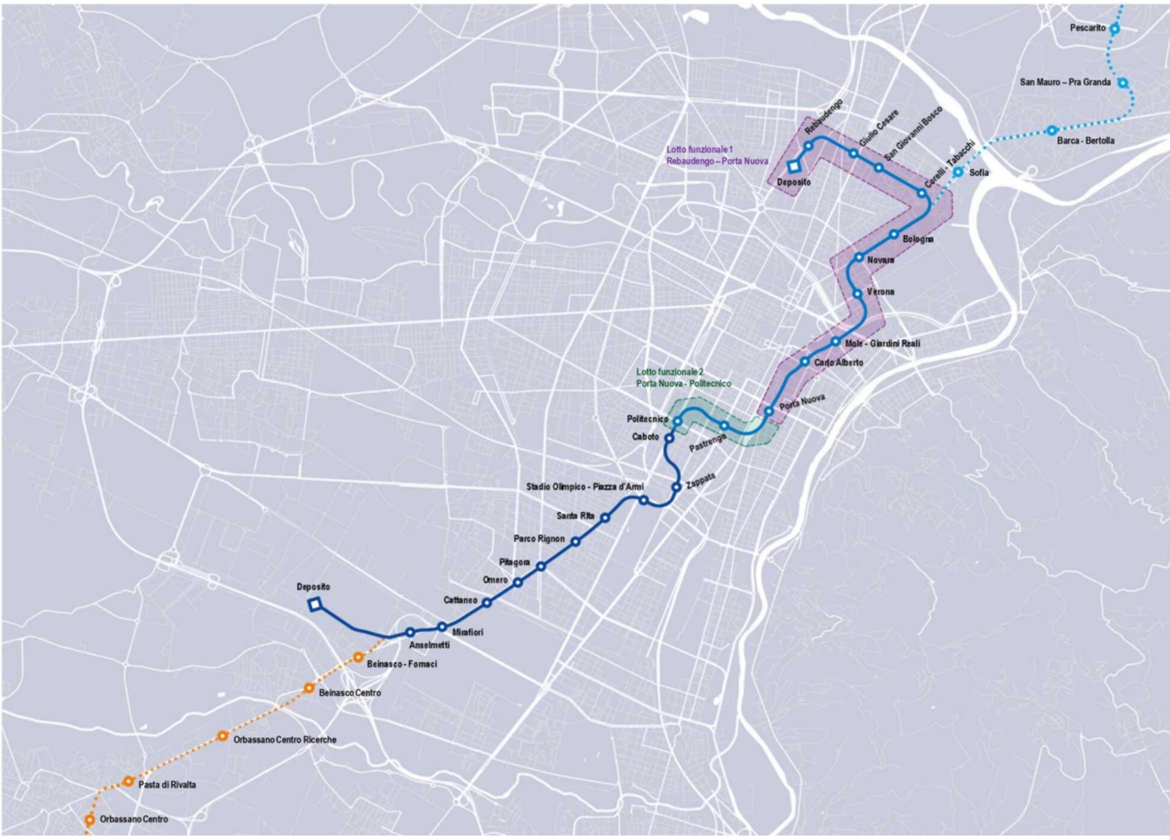

Figure 3.1: Map of Infra.To Metro Line 2 in Turin, showing central section, northern and southern branches, and key stations including Certosa [29]

The project improves connectivity to key urban areas and integrates with the existing public transport network through major interchange stations. Supporting infrastructure includes park-and-ride facilities, cycling infrastructure, and the redevelopment of a former railway corridor into a 67,000 m^2 green boulevard, contributing to sustainable urban mobility. Due to its scale and complexity, the Infra.To project provides a suitable environment for implementing and evaluating a Digital Twin using Autodesk Tandem. The integration of infrastructure and asset data within a digital platform supports visualization, management, and lifecycle analysis in a metro infrastructure context.

Comparison of Commercial Digital Twin Platforms

Several commercial platforms are available for implementing Digital Twins, with Autodesk Tandem and Bentley Systems being among the most widely used. Table 3.1 summarizes key features of both platforms relevant to metro and infrastructure projects.

Autodesk Tandem	Bentley Systems
User-friendly, intuitive interface	Complex interface, requires specialized training
Strong interoperability and seamless BIM workflows	Robust but steeper learning curve for BIM workflows
Cloud-based, multi-stakeholder collaboration	Primarily engineering-focused collaboration
Easy licensing access	Licensing can be restrictive and less accessible
Metro, buildings, general infrastructure projects	Infrastructure, transport, civil engineering projects

Table 3.1: Comparison of Autodesk Tandem and Bentley Systems for Digital Twin Implementation [1]

In this study, Autodesk Tandem was selected for its ease of use, cloud-based collaboration capabilities, and strong interoperability with BIM workflows. Based on previous experience with Bentley STAAD.Pro [1], Autodesk (via Revit workflows) provides a significantly easier and more efficient environment for metro infrastructure modeling, avoiding the steeper learning curves, limited compatibility, and restrictive licensing associated with Bentley products. The study focuses on the methodological workflow for Digital Twin development rather than software features.

3.2 Phase I: Sensor Monitoring and Data Acquisition

Sensor Principles Sensors monitor physical or environmental parameters by translating changes in physical states—such as temperature, humidity, or air quality—into electrical signals, typically voltage variations. Due to calibration limitations, environmental interference, and connectivity constraints, sensor measurements are inherently subject to inaccuracies.

Despite these limitations, sensors play a critical role in smart infrastructure systems. Their simulation is particularly valuable for:

- Generating synthetic datasets for machine learning and system testing
- Developing and validating Building Management Systems (BMS) under controlled conditions

Sensor Accuracy and Calibration:

- Temperature sensors: ±0.5°C
- Humidity sensors: ±3% RH
- VOC sensors: ±0.1 ppm

Sensors were calibrated according to manufacturer specifications prior to deployment.

Sensor Deployment Strategy Environmental monitoring was conducted in two stages:

1. Short-term deployment: 10 days in a residential environment
2. Long-term deployment: 1 month in an office environment [21]

Sensors were placed at four locations to capture spatial variability, considering room layout, proximity to heat/ventilation sources, and occupied zones.

Sensor Type / Quantity	Deployment Details / Connectivity
Temperature (3 sensors, °C / °F)	Various locations, including near heat sources
VOC (1 sensor, ppm)	General indoor area
Temperature (1 sensor, °C / °F)	Central location
Humidity (1 sensor, %)	Central location

Table 3.2: Deployed sensor details for environmental monitoring. *Note: All deployed sensors are battery-powered and connect via Hoboware software to read measurements.*

Figure 3.2: Wired (left) and wireless (right) sensors deployed for environmental monitoring [45]

In this study, the sensors were not connected to the Internet; data was collected via cable after 1 month. With current IoT sensors, real-time online collection can be performed directly.

Climatological and Air Quality Baseline of Turin Figure 3.3 shows the monthly climatological averages of maximum and minimum temperature and relative humidity in Turin, based on 30-year records. These data provide insight into seasonal trends and extremes in the local climate. The corresponding historical climate parameters and air quality baselines are summarized in Table 3.3, which highlights typical summer and winter conditions relevant for environmental analysis.

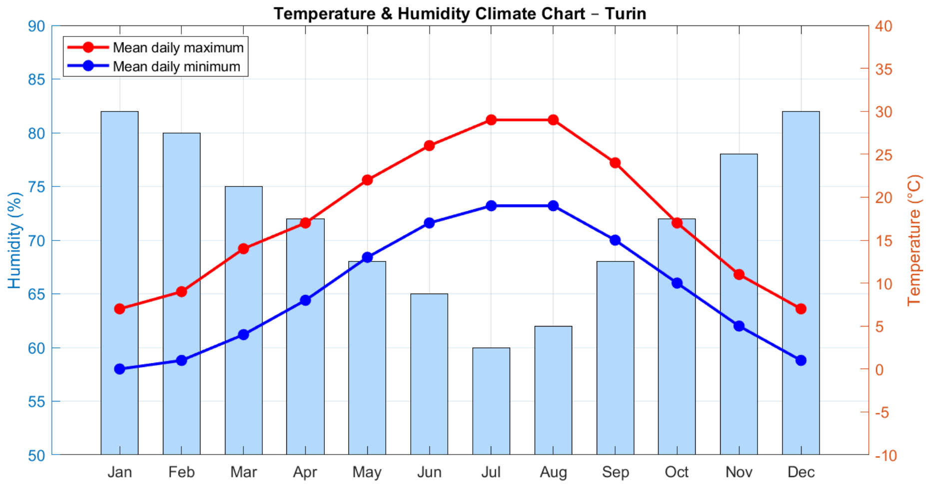

Figure 3.3: Monthly climatological averages of maximum and minimum temperature and relative humidity in Turin based on 30-year meteorological records [40]

🌡 Climate Parameter (Turin)	📈 Historical Range / Baseline Details
Summer Temperature (Jun–Aug, °C)	Typically 18 – 25.5; extreme heatwaves reach up to 30.
Winter Temperature (Dec–Feb, °C)	Averages around 0.5; extreme cold spells drop to -5.
Relative Humidity (Year-round, %)	Annual average of 72; peaks at 80+ in winter, 60–75 in summer.
Air Quality Index (AQI)	Generally Good (0–50); degrades to Unhealthy (101–150) in winter due to urban heating.

Table 3.3: Historical climate and air quality baseline for the study area (Turin, Italy) [40, 59, 2]

Overview of IoT in Metro Infrastructure

The Internet of Things (IoT) connects everyday objects and industrial equipment to a network, transforming them into intelligent devices capable of collecting, transmitting, and managing data. This connectivity enhances operational efficiency, enables new services, and improves health, safety, and environmental performance.

In the context of Metro Line 2, IoT supports real-time monitoring of environmental parameters, infrastructure assets, and operational systems, forming a critical backbone for Digital Twin implementation. Figure 3.4 illustrates the evolution of traditional objects into IoT-enabled devices, showing how ordinary tools are transformed into smart, connected systems capable of monitoring, providing feedback, and supporting decision-making [47, 48]. Table 3.5 compares traditional metro components with their IoT-enabled functions, highlighting improvements in monitoring, maintenance, ticketing, and passenger services [63, 31].

Figure 3.4: Conceptual evolution of everyday objects into IoT-enabled devices [47, 48]

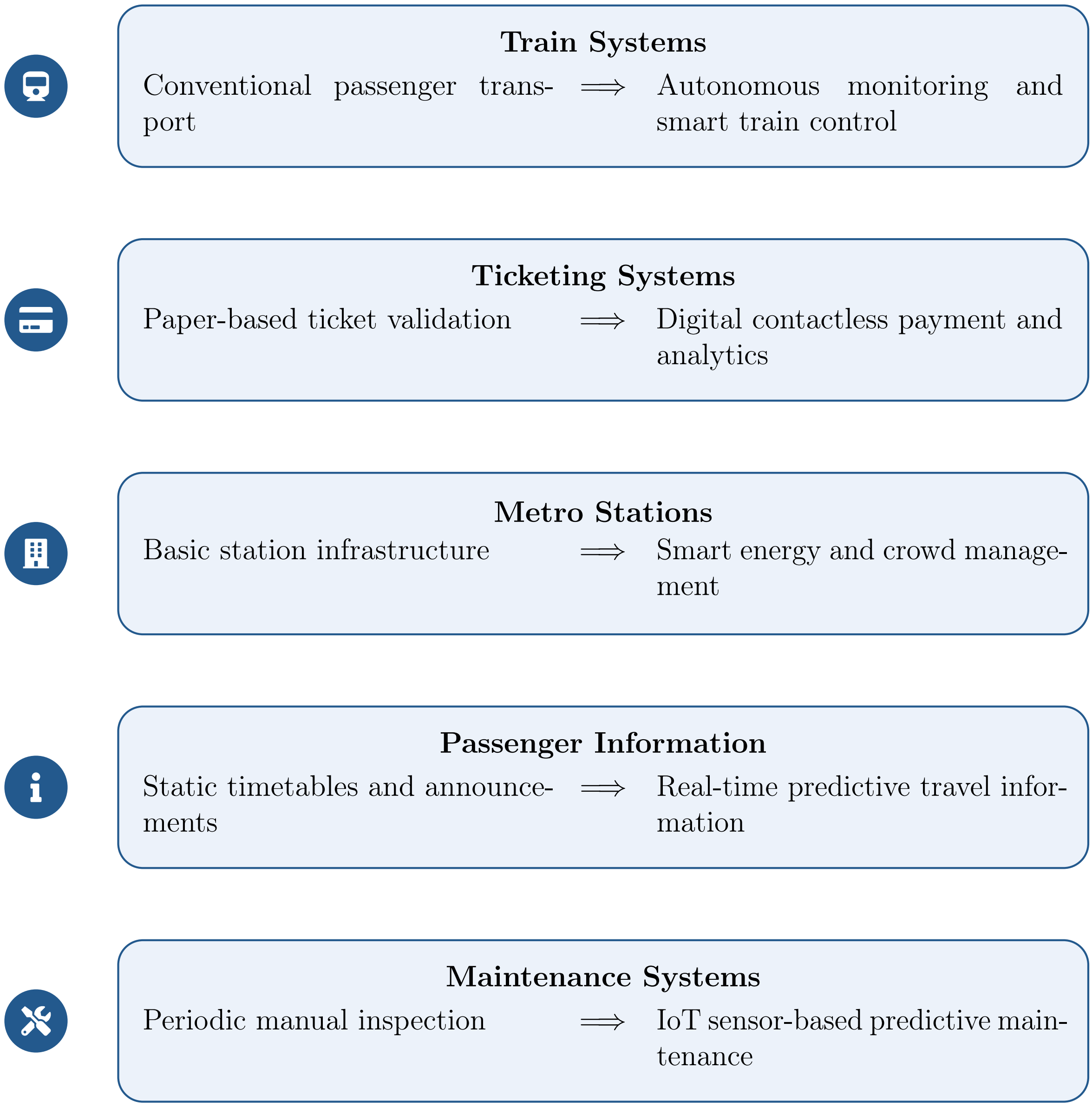

Figure 3.5: Transformation of metro infrastructure toward IoT-enabled smart systems [63, 31]

Data Communication Protocols

IoT devices use messaging protocols designed for real-time communication and networks with limited bandwidth:

- **HTTP:** Standard web-based communication for data requests and responses.
- **MQTT:** Lightweight publish/subscribe protocol optimized for low-bandwidth, real-time data transmission.
- **REST API:** Facilitates integration between sensors, third-party systems, and Autodesk Tandem, supporting bidirectional data exchange.

The design principles of REST APIs define how IoT sensors interact with the Autodesk Tandem system, ensuring standardized and efficient data communication.

REST API Integration

REST APIs (Representational State Transfer) allow standardized interaction with the metro IoT ecosystem. Key aspects include:

- **Resources:** Each sensor or asset is represented as a resource with a unique endpoint, e.g., `/api/sensors`.
- **HTTP Methods:**
  - GET: Retrieve data
  - POST: Create new records
  - PUT: Update existing records
  - DELETE: Remove records
- **Data Format:** JSON is used for lightweight and structured data exchange. Example:


```
{
  "sensorId": "123",
  "location": "Metro Station A - Platform 1",
  "type": "Temperature",
  "reading": 22.5,
  "status": "Active",
  "timestamp": "2024-11-07T14:30:00Z"
}
```

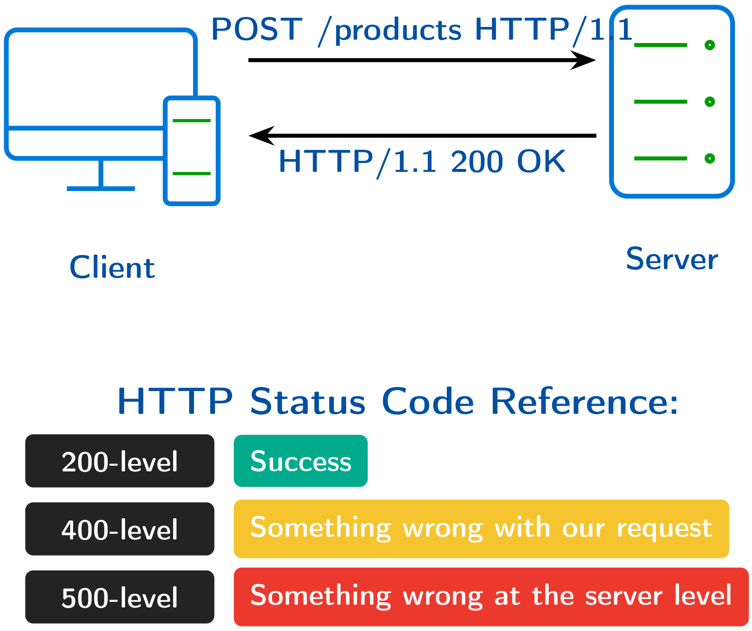

Figure 3.6: Client-server communication in the IoT system showing POST requests via HTTP, JSON data transfer, and HTTP status code responses for integration with Autodesk Tandem.

Tandem API Integration

While the main methodology employs REST API for sensor data integration, Autodesk Tandem also provides its own Tandem API. This API allows developers to:

- Push sensor data directly into the Tandem Digital Twin without an intermediate server.
- Map sensor readings to specific assets and metadata within the Twin.
- Access historical datasets and real-time dashboards programmatically.
- Manage thresholds, alerts, and asset relationships within Tandem.

Using the Tandem API can simplify the integration workflow and reduce potential points of failure, although the REST API approach remains fully compatible and flexible for multi-system architectures[7, 6].

Postman for API Testing

Postman was used to test, debug, and validate the REST API endpoints before integrating with Autodesk Tandem. Features utilized include:

- Sending GET/POST/PUT/DELETE requests
- Inspecting JSON responses
- Automating tests to validate data correctness

- Generating mock data to simulate real-time sensor feeds

Figure 3.7 illustrates the configuration of IoT devices, communication protocols, and integration with Autodesk Tandem. This system was tested using Postman to validate data flow and API responses, confirming that sensor readings were accurately transmitted and received in real time.

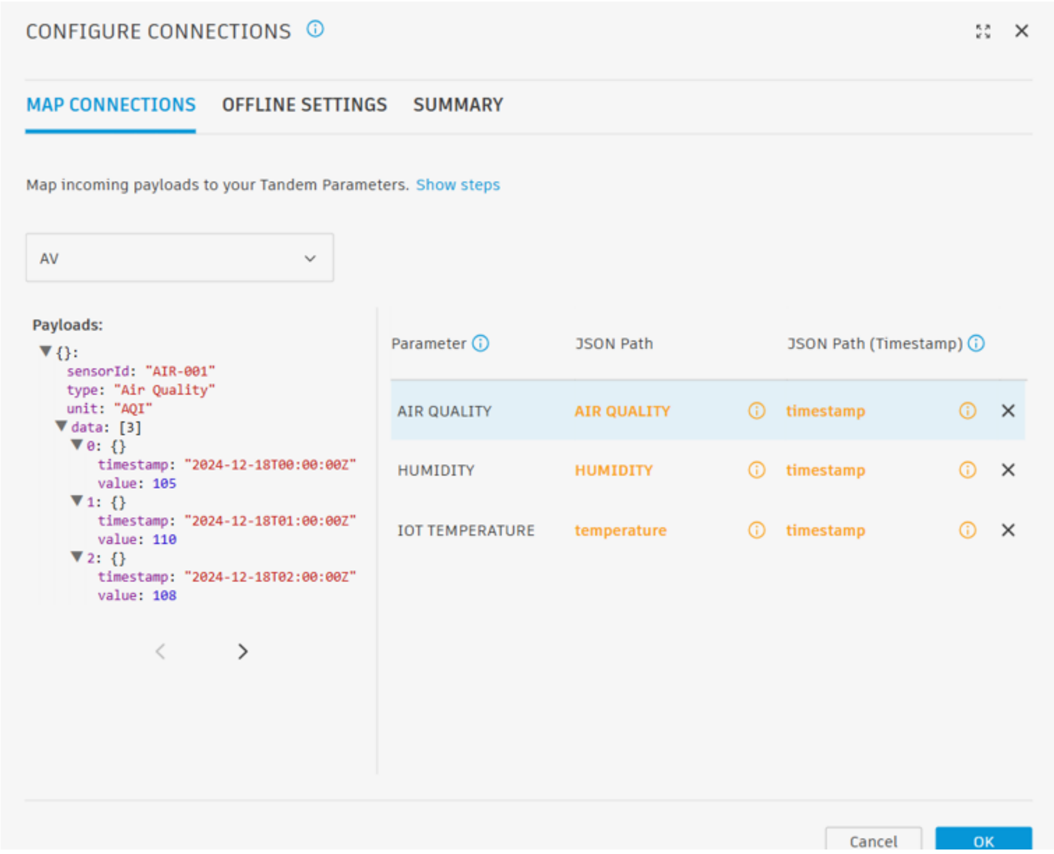

Figure 3.7: Configuration of IoT device connections for Metro Line 2, showing sensors, communication protocols, and integration with Autodesk Tandem.

Data Storage and Formats

Sensor data are initially stored in CSV(Comma-Separated Values) files, which offer a lightweight, structured, and easily accessible format for processing in Python:

- Each row represents a sensor reading
- Columns include: `sensorId`, `location`, `type`, `reading`, `status`, `timestamp`
- CSV files are compatible with Python scripts for simulation, aggregation, and Digital Twin integration

JSON and XML formats are also supported for API exchanges, with JSON preferred due to its simplicity and lightweight structure.

IoT Challenges

The deployment and integration of IoT systems face several challenges:

- **Timestamp Compatibility:** During integration with Autodesk Tandem, some sensors required timestamp reformatting to match Tandem's accepted time format, ensuring successful API communication and data synchronization.
- **Connectivity Issues:** Wired sensors can suffer from loose cables; wireless sensors require reinitialization.
- **Data Consistency:** Synchronizing real-time streams with historical datasets.
- **Scalability:** Handling large numbers of sensors and frequent updates.
- **Security:** Ensuring encrypted data transmission (HTTPS, MQTT) and secure API access.
- **Integration Complexity:** Mapping sensor metadata correctly to the Autodesk Tandem Digital Twin[48, 54, 51].

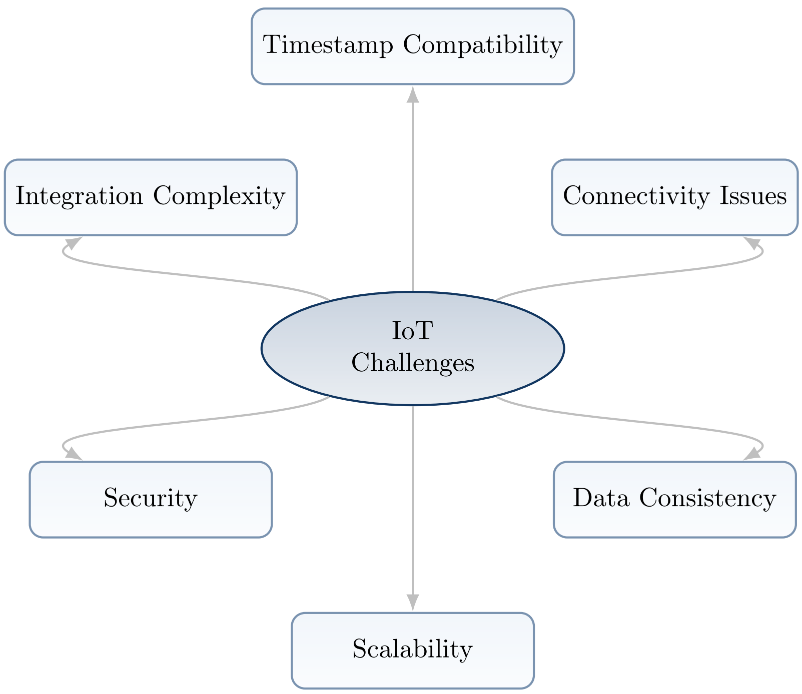

Figure 3.8: Key IoT Integration Challenges in Autodesk Tandem (Digital Twin)

Sensor Performance Evaluation

- Wired sensors: prone to connectivity disruptions due to loose cables
- Wireless sensors: stable, but required reinitialization after one month

Data Quality Measures:

- Logged at 1-minute intervals
- Missing or erroneous readings filtered via linear interpolation
- Dail calibration checks

Monitored Parameters

Monitored Parameter	Details / Notes
Temperature (4 sensors)	Measured in °C and °F; two near heat sources showed higher values
Humidity (1 sensor)	Measured in %; located centrally
VOC (1 sensor)	Measured in ppm (0–10); contributes to IEQ
Indoor Air Quality (AQI)	Monitored via AIRVISUAL app; AQI < 50; VOC included in analysis
Sampling Frequency	1-minute intervals for sufficient temporal resolution

Table 3.4: Monitored environmental parameters and data collection details

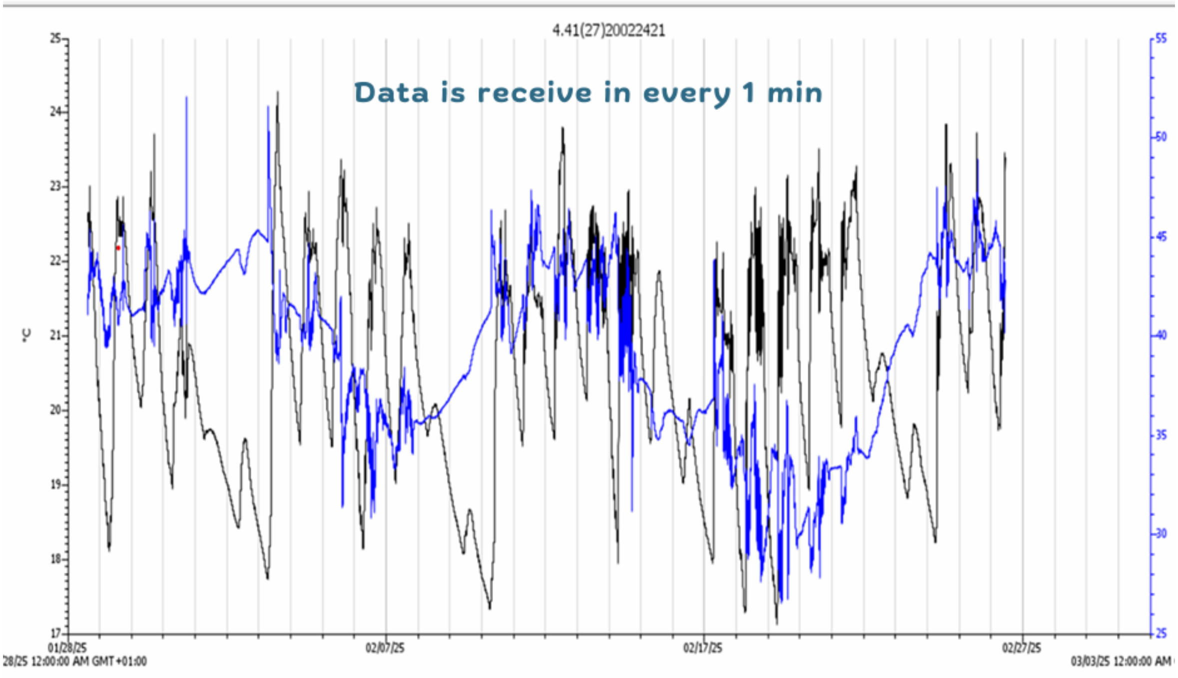

Figure 3.9: Real sensor data collected over 1 month of monitoring. Temperature (black) and relative humidity (blue) variations highlight real-time environmental fluctuations.

Sensor Data Analysis: The graph illustrates temperature and relative humidity variations over a one-month period, highlighting real-time fluctuations.

Data-Driven Maintenance: Trend analysis in temperature and humidity enables predictive maintenance, preventing system failures and enhancing operational efficiency.

3.3 Phase II:Data Simulation and Processing

Evaluation of Simulation Tools

EnergyPlus and Python were evaluated for environmental and energy simulation. EnergyPlus is effective for static, predefined building energy simulations but lacks flexibility for real-time data integration. Python was selected due to:

- Processing of real-time and historical sensor data
- Full control over simulation logic
- Compatibility with AI/ML models
- Seamless integration with Autodesk Tandem

EnergyPlus	**Python**
Requires IDF and weather files	Works directly on CSV sensor data
Designed for static energy simulations	Supports dynamic, real-time simulation and sensor integration
Limited AI/ML and Digital Twin integration	Fully compatible with AI/ML and Autodesk Tandem
Difficult for real-time updates	Flexible and programmable, full control over simulation
Suitable for predefined scenarios	Suitable for scenario testing, anomaly detection, and scalable datasets

Table 3.5: Comparison of EnergyPlus and Python for sensor-driven environmental simulation

Sensor Data Simulation Workflow

1. Convert sensor data into CSV format
2. Simulate 12 days of sensor behavior using Python
3. Apply mean $\pm$ standard deviation to generate realistic fluctuations
4. Run 20 simulations per sensor type

Simulated Dataset Structure

The simulated outputs for Temperature (4 sensors), Humidity (1 sensor), and VOC (1 sensor) were merged to form a unified dataset named *EnviroSense*, consisting of 20 CSV files resampled to hourly intervals for consistency. CSV files provide a straightforward way to store large datasets in plain text.

Sensor Type	Quantity / Simulations
Temperature(°C / °F)	4 sensors, included in 20 simulated datasets
Humidity (%)	1 sensor, included in 20 simulated datasets
VOC(ppm)	1 sensor, included in 20 simulated datasets

Table 3.6: Sensor types and number of simulations included in the EnviroSense dataset

3.4 Phase III: Digital Twin Integration and Data Exchange

Environmental Parameter Definition

These parameters were selected to capture key aspects of indoor air quality and passenger comfort. Thresholds were established based on historical data trends and internationally accepted standards, ensuring that deviations are detected before impacting safety or comfort. Furthermore, these parameters were identified as critical through extensive literature review, confirming their relevance for environmental monitoring in metro infrastructure and smart buildings

Data Exchange and Integration Workflow

EnviroSense datasets were transmitted to Autodesk Tandem using a continuous Python-based workflow designed for reliability and efficiency. The workflow performs the following functions:

- **Automated data transmission:** Sensor readings are collected at regular intervals and automatically pushed to the Digital Twin, minimizing manual intervention.
- **Historical data preservation:** All incoming datasets are archived in a structured database, enabling long-term trend analysis and model validation.
- **Real-time monitoring:** Continuous updates allow operators to visualize current environmental conditions across all floors and respond promptly to anomalies or threshold violations.

The workflow incorporates data validation, error handling, and secure transmission protocols to ensure the integrity and reliability of the datasets. This automated and continuous data exchange forms the backbone of the Digital Twin, enabling both real-time monitoring and data-driven decision-making for environmental management.

Sensor Representation in the Digital Twin

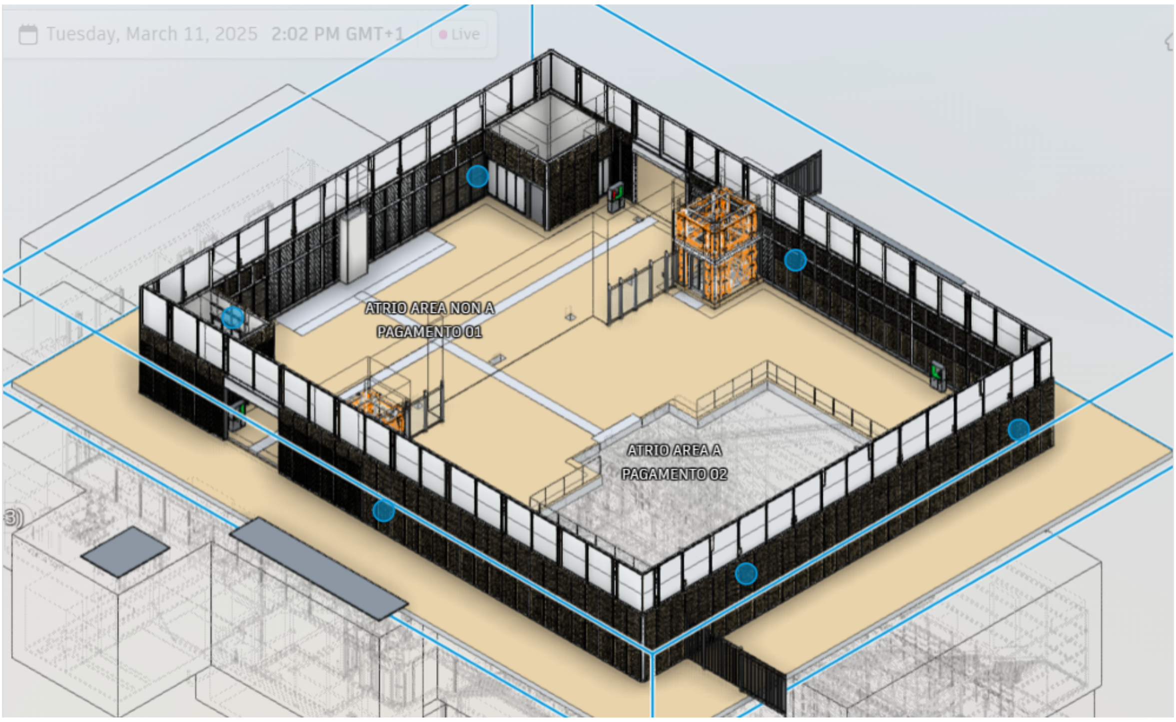

Figure 3.10: Sensor placement on Ground Floor (0).

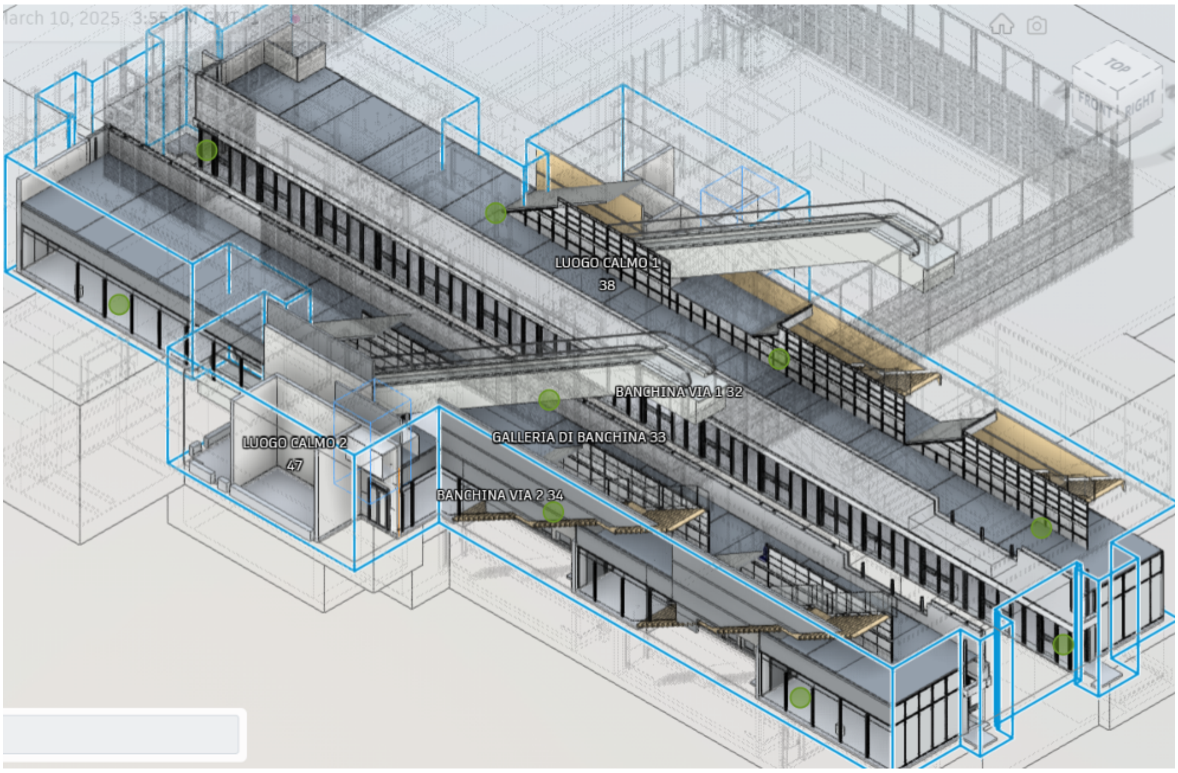

Figure 3.11: Sensor placement on Floor -2.

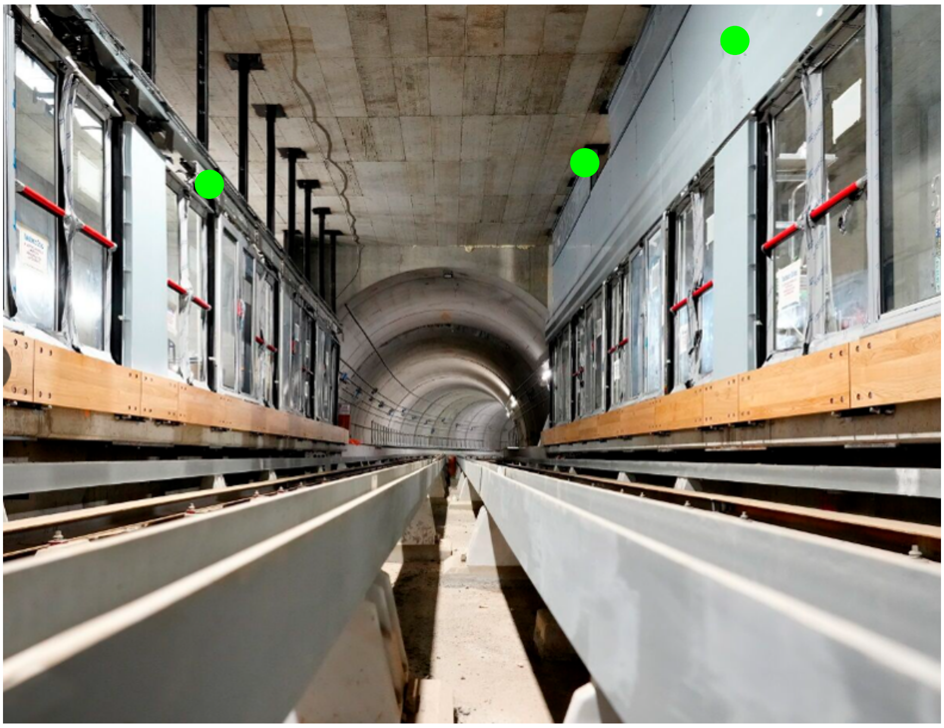

Figure 3.12: Metro line schematic showing sensor positions (green dots)[29]

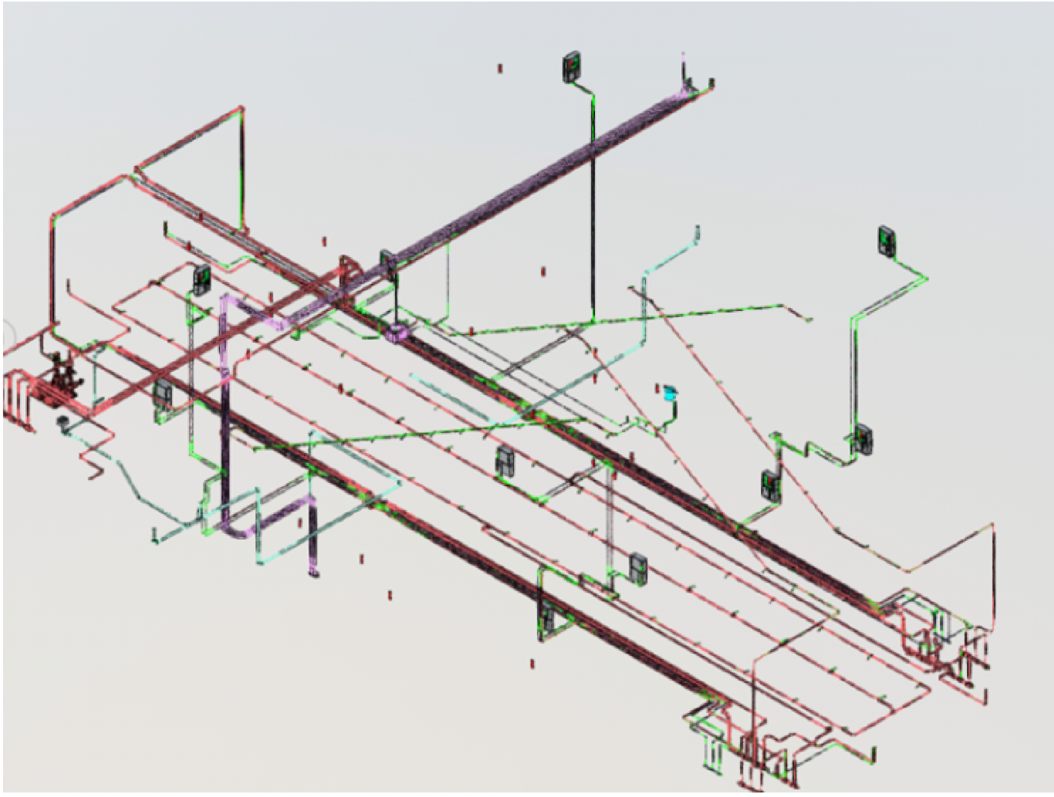

Figure 3.13: MEP layout showing HVAC infrastructure and environmental sensor integration.

Representing each sensor as a 3D object within the Digital Twin allows accurate spatial visualization, evaluation of coverage, and correlation of readings with specific zones. This approach also enables simulation-based testing to optimize sensor placement and ensure reliable environmental monitoring

Floor	Number of Sensors	Approx. Coverage (m^2)
Ground Floor (0)	6	50–200
Floor -1	3	50–200
Floor -2	9	50–200
Floor -3	2	50–200

Table 3.7: Summary of sensor distribution across metro station floors

Placement Guidelines:

- Approx. 170 cm above floor level
- At least 1 m from doors, windows, and ventilation
- Minimum 50 cm from other electronics

Optimal Sensor Placement Considerations The sensors in this study were deployed based on practical considerations, such as room layout, proximity to heat or ventilation sources, and occupied zones. However, formal approaches for optimal sensor placement exist, aiming to maximize spatial coverage, reduce measurement uncertainty, or improve data representativeness [34, 23, 62]. Techniques such as simulation-based optimization, spatial interpolation, or information-theoretic methods could be applied in future work to further enhance the accuracy and efficiency of environmental monitoring.

Outcome of Phase III

- Simulated environmental data fully synchronized with Autodesk Tandem
- Real-time visualization enabled
- Historical datasets retained for trend analysis
- Threshold-based alerts allow proactive monitoring

These outcomes provide a validated and synchronized dataset that forms the basis for advanced analysis and optimization in Phase IV. Following the integration and validation of sensor data in Phase III, Phase IV focuses on visualization, real-time monitoring, and optimization using the Digital Twin platform

3.5 Phase IV: Visualization, Monitoring, and Optimization

In this phase, Autodesk Tandem's time navigation and analytical tools were employed to explore both historical and real-time environmental data. The following techniques were implemented:

- **Heatmaps:** Spatial representations of temperature, humidity, and VOC levels across all floors were generated to quickly identify areas of concern or unusual environmental behavior.
- **Stream analysis:** Continuous sensor data streams were monitored to track dynamic changes over time and detect correlations between parameters, such as temperature and humidity fluctuations.
- **Time-based dashboards:** Interactive dashboards allowed operators to monitor key performance indicators (KPIs), view temporal trends, and receive automated alerts when thresholds were exceeded.

By combining these techniques, the methodology enables:

- Proactive environmental management through early detection of anomalies.
- Optimization of HVAC and ventilation strategies to maintain comfort while reducing energy use.
- Historical trend analysis to inform maintenance planning and infrastructure upgrades.

3.6 Summary

The methodology presented in this study integrates physical sensor monitoring, Python-based data simulation, and Digital Twin implementation to enable comprehensive environmental analysis in metro infrastructure and smart buildings. By combining real-time sensor measurements with synthetic datasets, the framework ensures both accuracy and robustness across a range of operational scenarios. The phased approach—from data acquisition and preprocessing to Digital Twin integration and visualization—supports continuous monitoring, historical trend analysis, and proactive decision-making.

Through careful sensor deployment, rigorous data validation, and automated data exchange with Autodesk Tandem, the methodology provides a scalable and interoperable system capable of optimizing indoor environmental quality, enhancing operational efficiency, and facilitating predictive maintenance. Heatmaps, time-based dashboards, and stream analysis further enable proactive environmental management and informed operational strategies.

Overall, this integrated approach establishes a strong, validated foundation for subsequent analyses, simulations, and optimization strategies, directly supporting the research objectives of assessing environmental performance, improving comfort, and guiding decision-making in smart infrastructure systems.

The next chapter presents the results of the study, including environmental data visualization, Digital Twin system performance, and insights from the integration of Autodesk Tandem in metro projects.

Chapter 4

Results

This chapter presents and discusses the results obtained from integrating environmental sensor data into the Autodesk Tandem Digital Twin platform. The evaluation focuses on environmental data visualization, asset and data management capabilities, system connectivity, and predictive monitoring potential. The results demonstrate how Digital Twin technologies enhance environmental awareness, operational transparency, and facility intelligence within complex infrastructures.

4.1 Environmental Data Visualization

4.1.1 Individual Sensor Visualization

Visualization of individual sensor streams provides detailed insight into localized environmental behavior within the monitored facility. Figure 4.1 presents time-series plots of humidity, temperature, and volatile organic compound (VOC) measurements acquired from selected EnviroSense sensors and visualized in Autodesk Tandem.

The results indicate stable environmental conditions throughout the monitored period. Humidity values fluctuate within acceptable indoor comfort ranges (%RH), while temperature measurements remain consistent and well regulated. VOC concentrations exhibit only minor deviations, suggesting effective ventilation and air quality control strategies. These observations confirm the reliability of individual sensor data streams and the capability of the Digital Twin environment to represent real-time environmental conditions accurately.

The integration of threshold indicators enables rapid identification of abnormal conditions at the individual sensor level. In the analyzed dataset, no persistent threshold violations were detected, confirming operational stability. This level of granularity supports early fault detection and localized diagnostics, which are essential for large-scale facilities where environmental conditions may vary spatially.

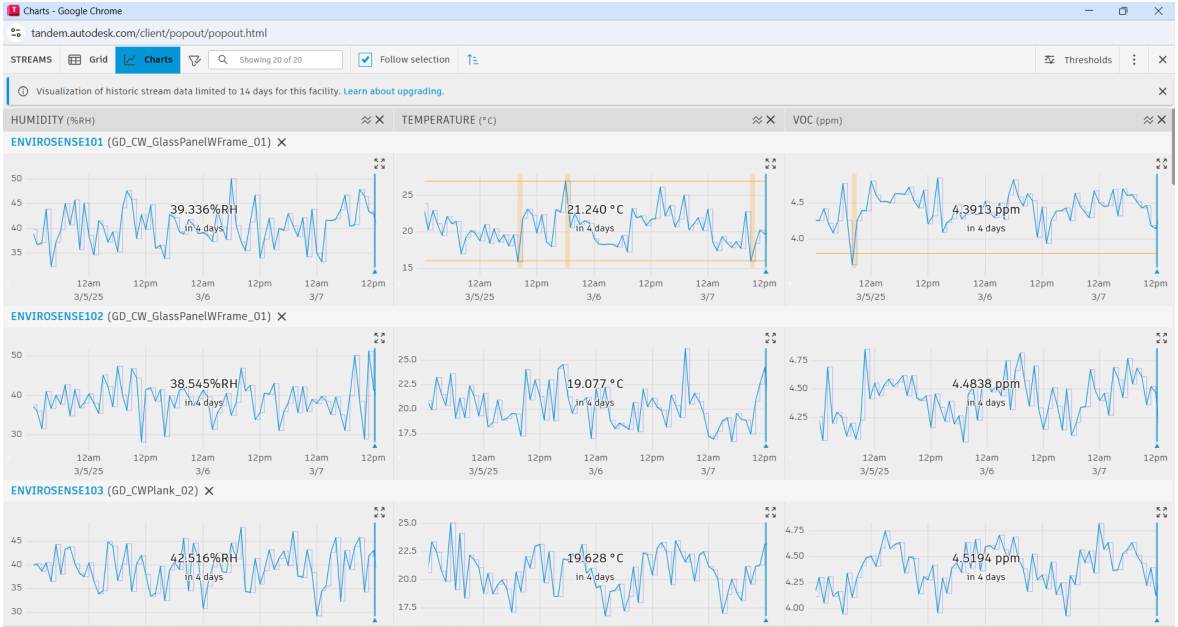

Figure 4.1: Individual visualization of humidity, temperature, and VOC sensor data in Autodesk Tandem.

Note: Each line represents a single sensor parameter over time. Fluctuations remain within expected ranges, indicating stable environmental control.

4.1.2 Threshold Stream Visualization

Threshold stream visualization overlays operational limits on environmental data, enabling immediate identification of excursions and near-critical conditions. Figure 4.2 shows the Autodesk Tandem Stream Value interface for the ENVIROSENSE system, presenting synchronized VOC (ppm), humidity (%RH), and temperature (°C) data over the monitored period together with defined warning and alert thresholds.

The threshold levels applied in this study are summarized in Table 4.1. These limits were defined based on indoor comfort guidelines, sensor manufacturer specifications, and operational best practices, ensuring that the monitoring framework aligns with recognized environmental standards.

Parameter	Warning (Low / High)	Alert (Low / High)
Humidity (%RH)	≤25 / ≥65	≤20 / ≥70
Temperature (°C)	≤14 / ≥27	≤13 / ≥29
VOC (ppm)	≤3.8 / ≥5	≤3.5 / ≥5.5

Table 4.1: Threshold levels for environmental parameters, including warning and alert limits.

The visualization highlights periods during which environmental parameters approach predefined warning or alert thresholds. In the analyzed dataset, all parameters remain within acceptable limits, indicating stable environmental performance. The integration of thresholds with historical data enables the foundation for predictive monitoring, allowing operators to identify trends that may precede future threshold violations.

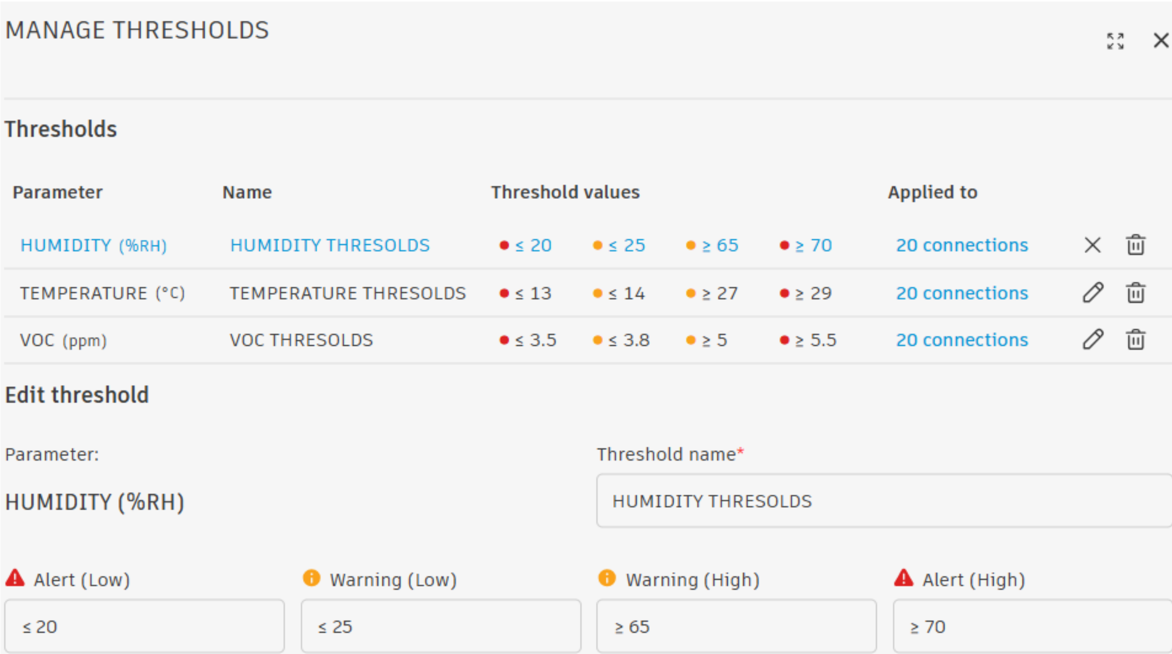

Figure 4.2: Autodesk Tandem Stream Value interface for ENVIROSENSE, showing synchronized VOC (ppm), humidity (%RH), and temperature (°C) data with threshold indicators.

Note: Warning and alert limits are represented using red lines. Lighter red lines denote warning levels, while darker red lines indicate alert limits. Observed peaks are temporary and remain within acceptable ranges.

4.1.3 Merged Multi-Sensor Visualization

Merged visualization integrates multiple sensor streams into a unified representation, enabling system-wide analysis of environmental conditions. Figure 4.3 presents synchronized trends across multiple sensors, highlighting spatial consistency and temporal correlations.

Minor variations between sensors reflect localized influences such as occupancy patterns, airflow distribution, or proximity to ventilation elements. Periodic oscillations observed in the data likely correspond to daily operational cycles. The ability to visualize multiple streams simultaneously demonstrates the scalability of the Digital Twin platform and its suitability for managing high-density sensor networks typical of large infrastructures such as metro stations.

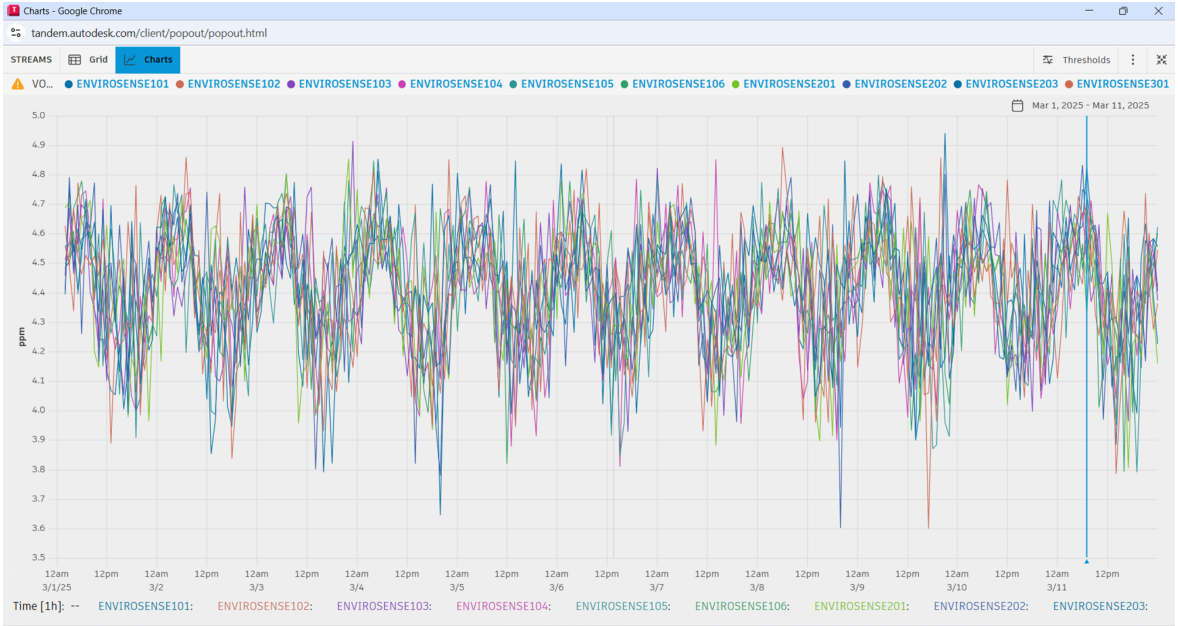

Figure 4.3: Merged visualization of multiple environmental sensor streams showing synchronized trends for humidity (%RH), temperature (°C), and VOC (ppm).

Note: Multiple sensors are displayed simultaneously to illustrate spatial consistency. Small variations indicate localized effects, while overall trends confirm uniform environmental regulation. Humidity is displayed in red, temperature in green, and VOC in blue. Solid and dashed lines represent warning and alert thresholds, respectively.

4.1.4 Heatmap Analysis of Environmental Parameters

Heatmaps provide an intuitive spatial representation of environmental conditions across the monitored facility. Figures 4.4–4.6 present static heatmap snapshots for humidity, temperature, and VOC measurements recorded by ENVIROSENSE302 sensors.

The humidity heatmap incorporates embedded metadata, including sensor identification, system classification, real-time readings, and network relationships. Temperature and VOC heatmaps highlight spatial variations and operational performance across the facility. Although only static visualizations are presented, temporal inspection indicates that regions of higher intensity are generally short-lived and remain within acceptable thresholds, confirming effective environmental regulation.

Heatmaps condense complex datasets into easily interpretable spatial patterns, supporting anomaly detection, performance assessment, and operational decision-making. Compared to traditional time-series representations, heatmaps enable spatial reasoning, which is particularly valuable in large facilities where localized issues may otherwise remain undetected.

Figure 4.4: Humidity heatmap recorded by ENVIROSENSE302, showing spatial variations of relative humidity along with embedded metadata.

Includes general metadata, system class, real-time parameters, and system relationships. Darker shades indicate higher humidity (%RH).

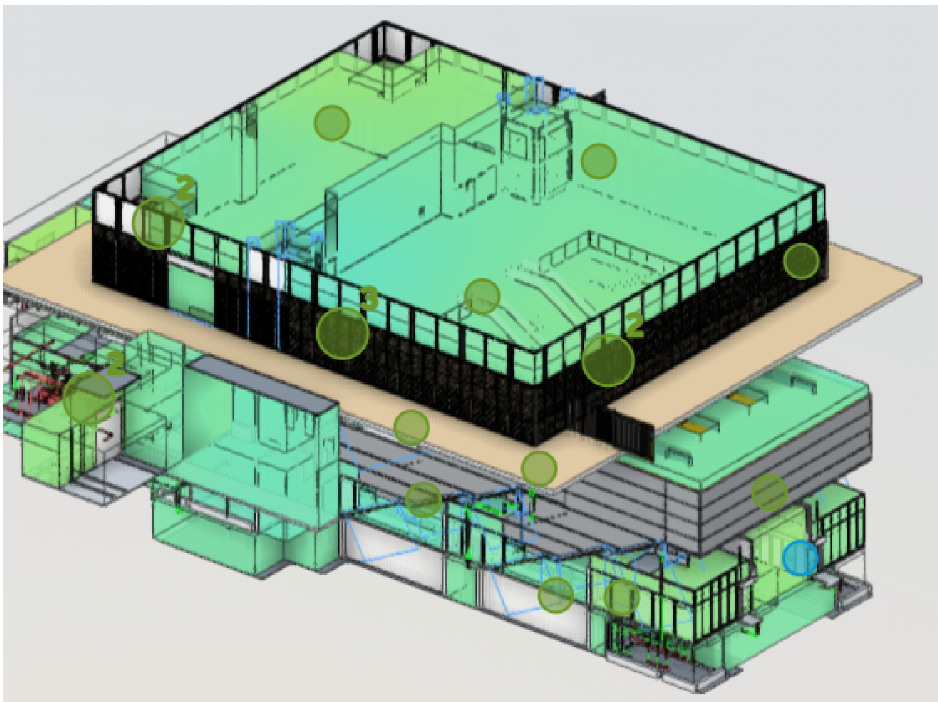

Figure 4.5: Temperature heatmap across sensors.

Darker shades indicate higher temperature (°C).

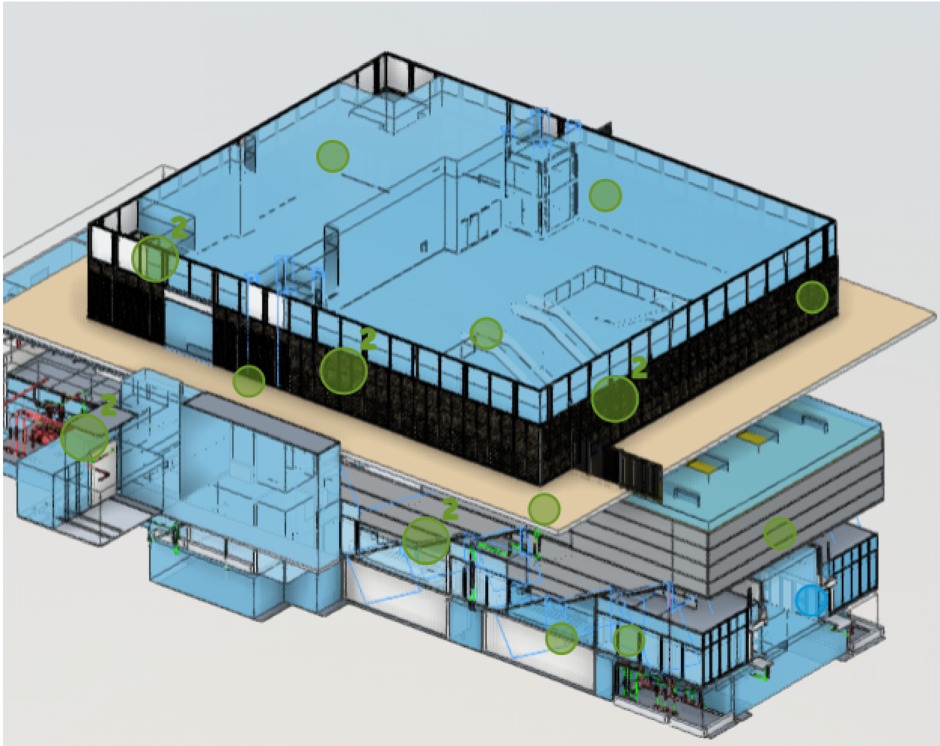

Figure 4.6: VOC heatmap across sensors.
Darker shades indicate higher VOC concentration (ppm).

4.2 Digital Twin Data Management and System Capabilities

Parameter Standardization

The Parameters module ensures data consistency by restricting asset and space parameters to predefined value sets. This standardization minimizes input errors, improves data reliability, and establishes a robust foundation for Digital Twin analytics. Consistent parameter structures also support interoperability and scalable system integration across complex infrastructures.

Filtering and Navigation Efficiency

Advanced filtering tools enable users to organize Digital Twin components by floors, spaces, classifications, and categories. Multi-layer filtering enhances information accessibility and reduces management complexity in large facilities. Efficient navigation accelerates troubleshooting, improves situational awareness, and supports rapid operational decision-making.

Asset Tracking and Inventory Management: Pump Stations

The Inventory panel provides structured asset tracking for critical components such as pump stations, HVAC units, and other mechanical equipment. Using standardized classification systems and spreadsheet-style organization, each asset is uniquely identified, categorized, and linked to relevant documentation and system hierarchies.

Real-time monitoring of pump stations enables early detection of performance degradation, such as abnormal flow rates, pressure losses, or energy inefficiencies. When an issue is detected, maintenance interventions can be targeted at the affected component rather than requiring shutdown or replacement of the entire station. This targeted maintenance strategy reduces downtime, minimizes operational disruption, and lowers lifecycle costs.

Integrated document and system management further enhances collaboration and data governance by linking assets to manuals, specifications, and historical maintenance records. This ensures that technical and administrative stakeholders access consistent, up-to-date information, supporting informed decision-making throughout the asset lifecycle.

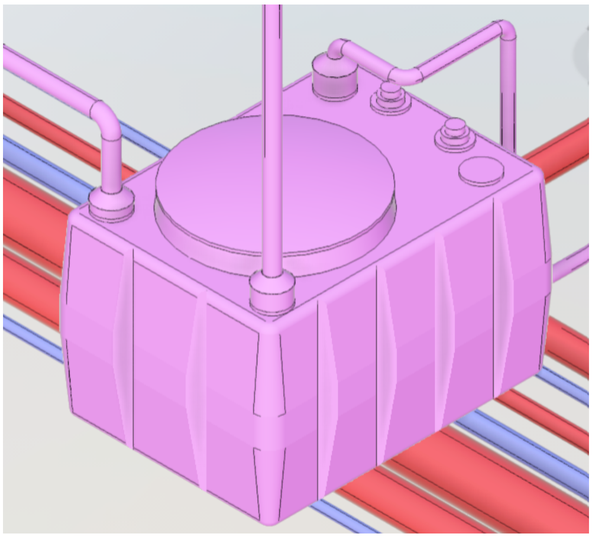

Figure 4.7: Inventory panel view for a pump station in Autodesk Tandem, showing asset classification, real-time monitoring, and targeted maintenance capabilities.

Note: Performance issues can be detected at the component level, allowing maintenance actions to be limited to affected assets.

System Connectivity and Relationship Mapping

The Connections module visualizes relationships between assets, systems, and spatial locations, creating a digital representation of facility topology. Mapping host systems and classifications improves system diagnostics, resilience planning, and impact analysis. Understanding these relationships allows facility managers to evaluate cascading effects during failures and optimize operational strategies within the Digital Twin environment.

4.3 Visualization Tools and Predictive Maintenance

Effective visualization tools are essential for monitoring environmental parameters and managing assets in complex facilities. By transforming large volumes of sensor data into intuitive graphical representations, these tools support trend identification, anomaly detection, and predictive maintenance readiness. This section discusses the visualization capabilities of Autodesk Tandem, including dashboards and automated reporting.

Automatic Reporting and Dashboard Analytics

The Autodesk Tandem dashboard provides a real-time interface for monitoring environmental parameters and asset performance. It consolidates key indicators, threshold alerts, and asset statuses into a unified view, enabling operators to identify deviations from normal operation and respond promptly.

Dashboard analytics support predictive maintenance by visualizing trends, highlighting threshold proximity, and enabling correlation across multiple assets and systems. While the current implementation does not perform autonomous predictive analytics, it establishes the data foundation required for future AI-driven maintenance models.

In addition to dashboards, Autodesk Tandem enables automatic generation of structured data reports for analysis, documentation, and compliance purposes. Figures 4.8–4.11 present representative examples of these reports.

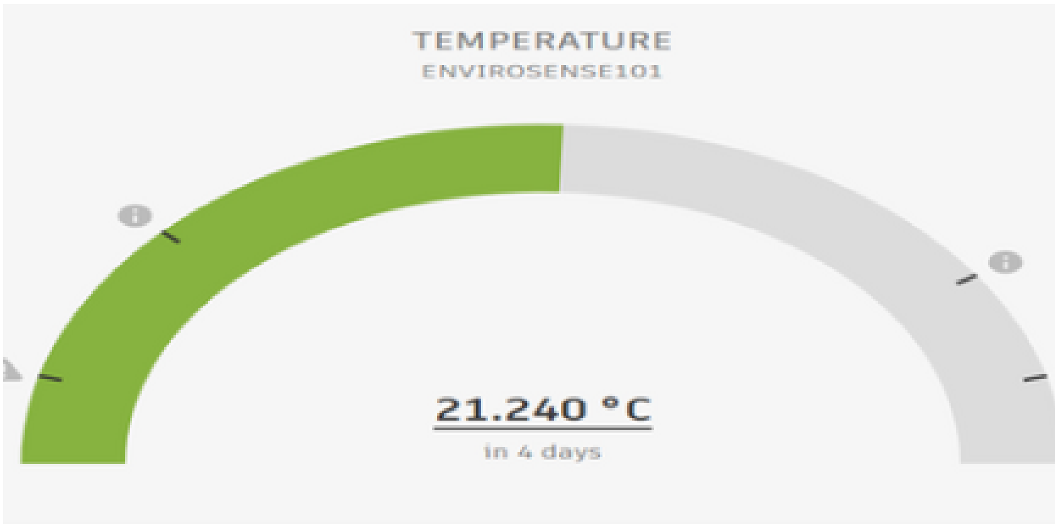

Figure 4.8: Real-time temperature status gauge for ENVIROSENSE, indicating current thermal performance relative to thresholds.

System Class	✓	⊖	%	Total
Exhaust Air	54	33	62%	87
Other	54	33	62%	87
Other Air	54	33	62%	87
Return Air	54	33	62%	87
Supply Air	54	33	62%	87
Vent	54	33	62%	87

Figure 4.9: Automatic connectivity report showing data synchronization percentages aggregated by HVAC system class.

Stream Parameters by Classification ×

Name	✓	⊖	%	Total
11.ME Mechanical Equipment				
HUMIDITY	20	13	61%	33
TEMPERATURE	20	13	61%	33
VOC	20	13	61%	33

Figure 4.10: Operational status of stream parameters categorized by mechanical equipment classification.

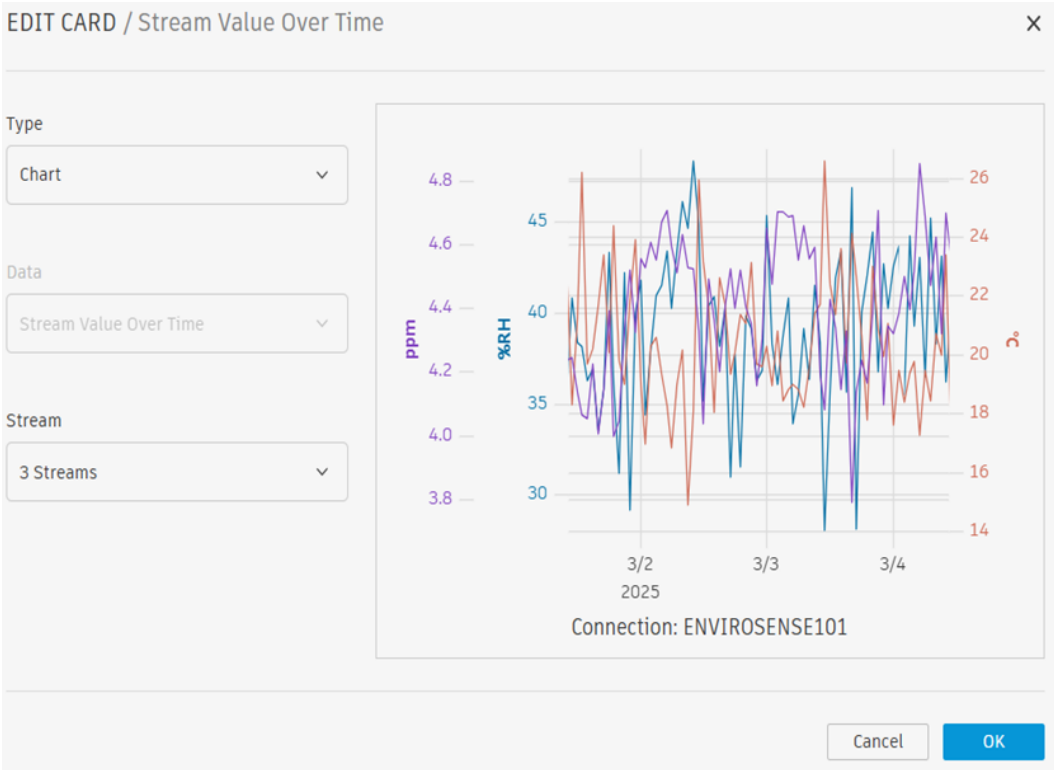

Figure 4.11: Multi-axis time-series visualization showing synchronized VOC, humidity, and temperature trends.

4.4 Overall System Performance Discussion

The presented results demonstrate that Autodesk Tandem provides a comprehensive Digital Twin environment capable of integrating environmental monitoring with asset intelligence. Individual and merged visualizations confirm stable environmental performance, while heatmap analytics enhance spatial awareness and anomaly detection.

Asset management and system connectivity features enable structured data governance, operational transparency, and targeted maintenance strategies. Dashboard-driven analytics transform heterogeneous sensor and asset data into actionable insights, supporting informed decision-making and predictive maintenance readiness.

Overall, the Digital Twin framework establishes a scalable architecture for smart infrastructure management. The results validate the effectiveness of Autodesk Tandem as a platform for integrating BIM, sensor data, and operational intelligence, forming a solid foundation for future AI-driven optimization and adaptive facility management.

Recommended Sensor Enhancements The analysis of environmental behavior in relation to the MEP infrastructure revealed that airflow dynamics and air quality indicators significantly influence indoor environmental performance. While the current sensor network effectively captures temperature, humidity, and VOC levels, the integration of airflow sensors within HVAC ducts is recommended to enhance system observability and ventilation diagnostics. Additionally, CO_2 sensors would provide valuable insight into occupancy patterns and ventilation efficiency, supporting energy optimization and indoor air quality management. Differential pressure sensors could further improve predictive maintenance by enabling early detection of airflow imbalances or filter degradation. Together, these enhancements would strengthen Digital Twin simulations, improve anomaly detection, and support more efficient environmental control strategies.

Table 4.2 summarizes the proposed sensor enhancements and their expected contributions to Digital Twin performance.

Proposed Sensor	**Primary Function**	**Benefit to Digital Twin**
Airflow (Flow) Sensor	Measure HVAC airflow rate	Improves ventilation diagnostics and simulation accuracy
CO_2 Sensor	Monitor occupancy and air quality	Supports energy optimization and indoor comfort control
Differential Pressure Sensor	Detect airflow imbalance and filter degradation	Enhances predictive maintenance and fault detection

Table 4.2: Recommended additional sensors to enhance Digital Twin monitoring capabilities

Additionally, multi-parameter sensors (e.g., AirCare 2.0) can be deployed in occupied spaces to monitor a wide range of environmental parameters, with the option to add targeted sensors for any additional measurements as needed.

Building on the findings presented in this chapter, the next chapter illustrates the application of Digital Twin technologies in metro and transport projects through detailed case studies, including the Istanbul Metro, Delhi Metro, and Denver International Airport.

Chapter 5

Case Study: Application in Metro and Transport Projects (Istanbul Metro, Delhi Metro, and Denver International Airport)

Introduction

Digital Twin technologies are also applied in large-scale transportation infrastructure beyond metro systems. At Denver International Airport, Autodesk Tandem has been used for real-time monitoring, predictive maintenance, and operational optimization of terminals, runways, and airport utilities. Case studies provide valuable insight into the practical application of Digital Twin technologies in large-scale urban infrastructure projects. By examining real-world scenarios, it becomes possible to evaluate not only the technical feasibility of Autodesk Tandem but also its operational and socio-economic impacts.

This chapter analyses two major metro systems: the Istanbul Metro in Turkey and the Delhi Metro in India. These systems represent different geographical, economic, and operational contexts. The comparison helps illustrate how Digital Twin integration has supported, or could support, metro project development, operation, and long-term maintenance.

5.1 Istanbul Metro: Digital Twin Integration

Background

Istanbul is one of the fastest-growing megacities in the world and uniquely spans two continents, Europe and Asia. The Istanbul Metro is among the largest and most ambitious rail transit systems globally[31].

Currently, the network consists of over 241 km of operational metro lines[31], with plans to expand by an additional 300 km by 2030. Due to complex geological conditions—including high seismic risk, groundwater presence, and dense urban development—metro construction and operation in Istanbul require advanced technological solutions for safety and efficiency[4].

Use of Digital Twins

The Istanbul Metropolitan Municipality has collaborated with international engineering and software firms to implement Digital Twin solutions within metro projects. Key applications include[4]:

- **Design and construction simulation**: Integrated BIM models and Autodesk Tandem were used to visualize geological layers, assess water intrusion risks, and simulate tunnel boring operations under seismic zones.
- **Operations monitoring**: IoT-enabled sensors monitor vibration levels, energy consumption, and passenger density in real time. This data is fed into centralized Digital Twin dashboards, allowing operators to identify trends and detect potential equipment failures before they occur.
- **Emergency management**: Earthquake and fire scenarios were simulated within the Digital Twin environment. These simulations supported the redesign of evacuation routes and the optimized placement of safety equipment.

The practical application of Digital Twin technology in the Istanbul Metro project is demonstrated through an integrated system of hardware and software. The Autodesk Tandem interface (Figure 5.1) provides a centralized 3D visualization hub that maps real-time metadata onto station and tunnel geometry. This interface is supported by a robust data architecture, as outlined in the sensors flow chart (Figure 5.4), which manages the pipeline from raw signal acquisition to cloud-based processing. The physical layer of this network includes flow sensors (Figure 5.2) deployed within tunnels to monitor airflow and passenger movement for safety and ventilation management. Complementing these vibration sensors (Figure 5.3) are installed in mechanical systems, such as elevators, to enable predictive maintenance and ensure structural health monitoring. Together, these components transform static BIM data into a dynamic operational tool that enhances safety and maintenance efficiency across the transit network[31, 4].

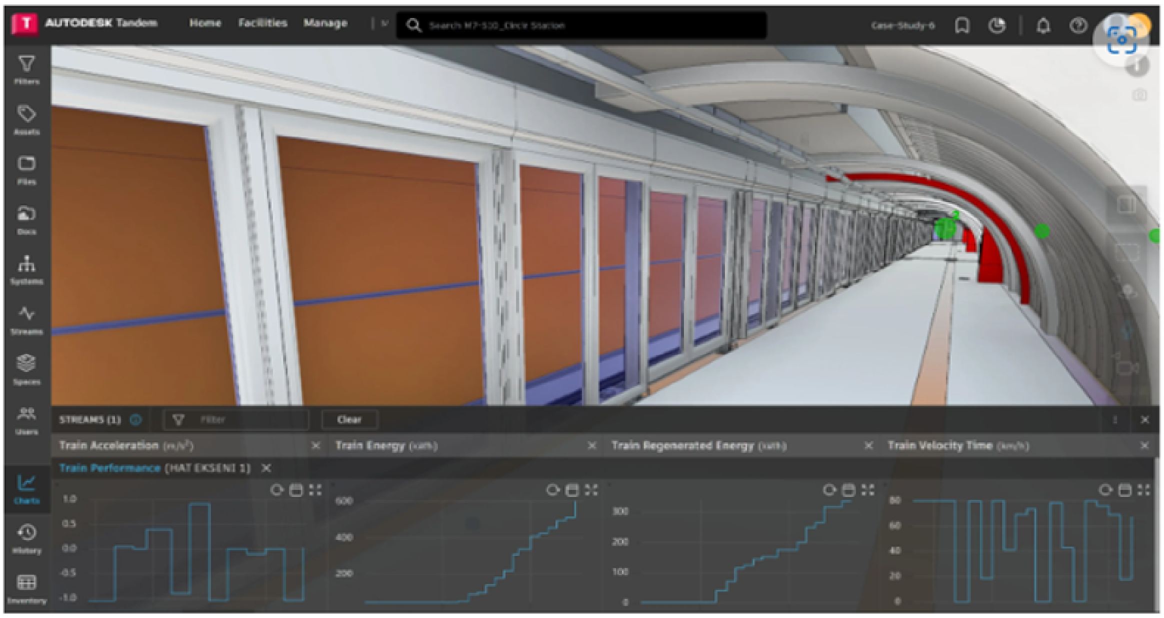

Figure 5.1: Autodesk Tandem interface for the Istanbul Metro project[31, 4]

.

Figure 5.2: Deployment of flow sensors in tunnels for passenger movement and airflow monitoring[31, 4]

.

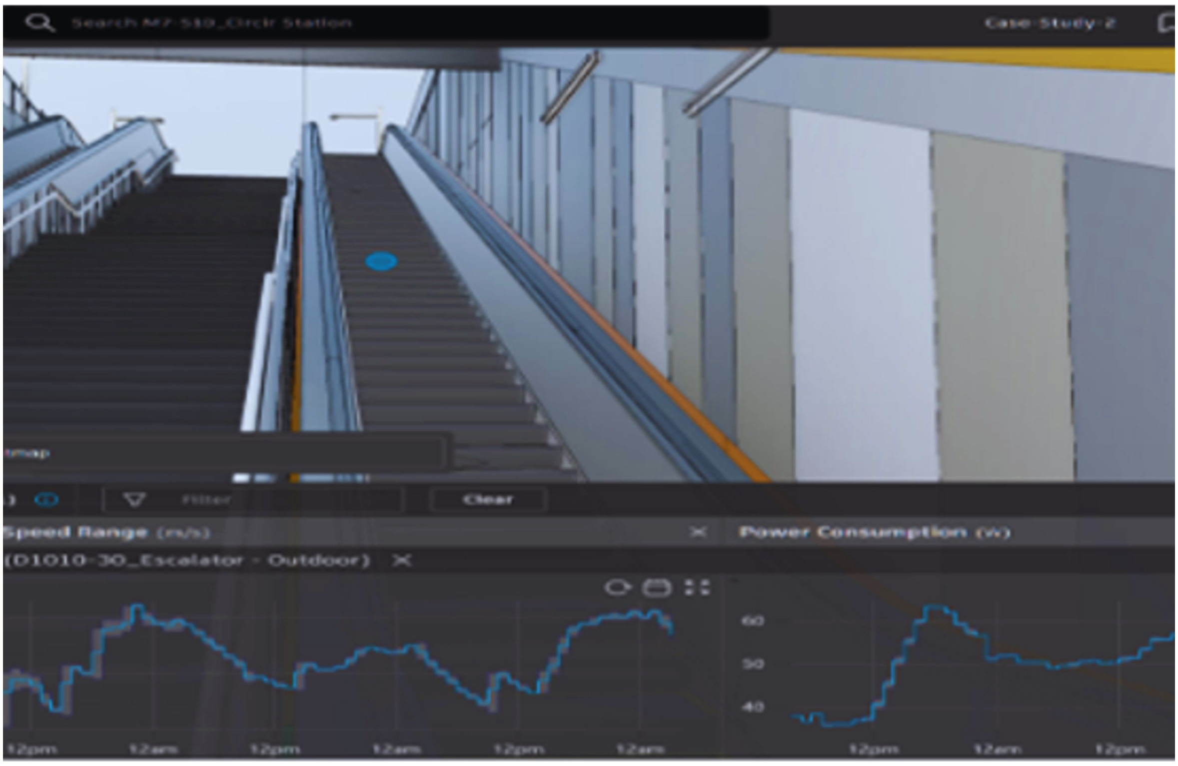

Figure 5.3: Vibration sensors installed on elevator systems for structural health monitoring[31, 4]

.

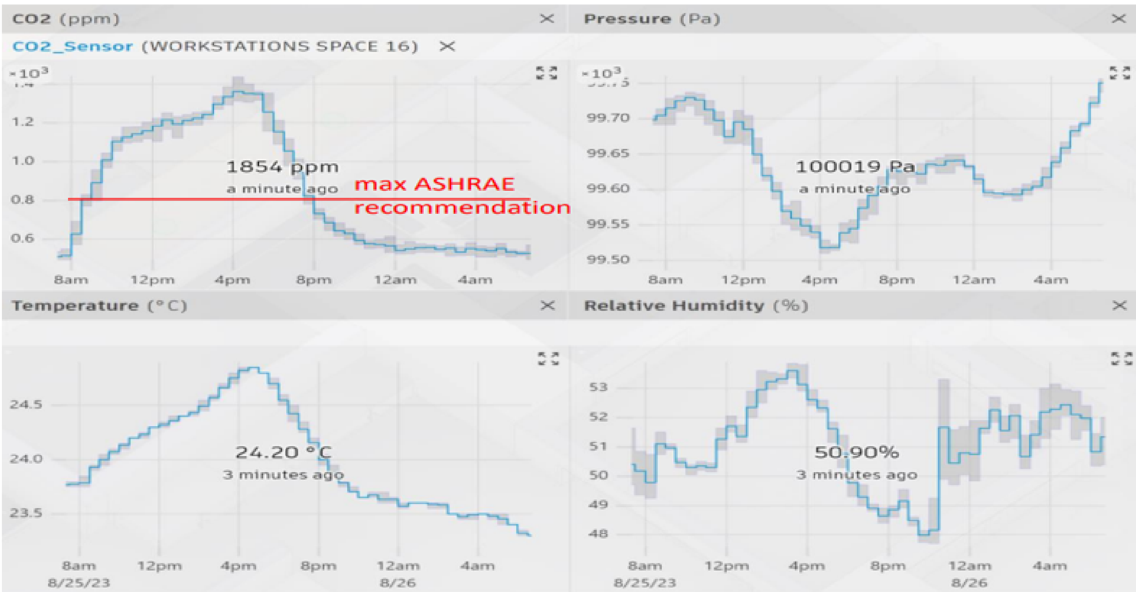

Figure 5.4: Istanbul Metro sensors data flow and processing architecture[31, 4]

.

Key Benefits Observed

The application of Digital Twin technology in the Istanbul Metro has resulted in several measurable benefits

- **Cost savings**: An estimated reduction of 15–20% in project delays.
- **Predictive maintenance**: Significant reductions in downtime of escalators and rolling stock.
- **Passenger safety**: Improved safety through real-time risk assessment and monitoring.
- **Scalability**: Easy integration of Digital Twins for network expansions and new metro lines. [31, 4]

5.2 Delhi Metro: Towards Smart Operations

Background

The Delhi Metro Rail Corporation (DMRC) is one of the most successful metro systems in the developing world and the largest in India[19]. It has significantly transformed public transportation in Delhi and the surrounding National Capital Region (NCR).

At present, the network extends over 390 km and continues to grow with new phases under development. DMRC is widely recognized for its strict adherence to project timelines and cost control. The system is known for its safety, cleanliness, and reliability, making it a preferred mode of transport for millions of daily passengers[19, 66, 12, 53, 35].

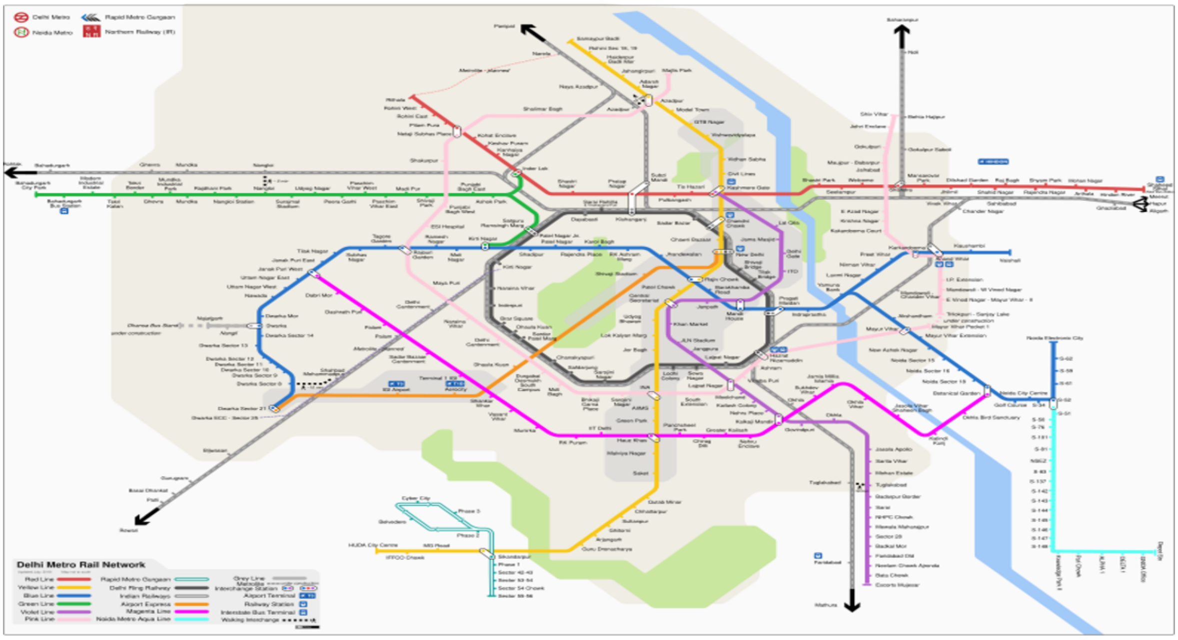

Figure 5.5: Delhi metro map showcasing the interconnectivity of the National Capital Region (NCR)[66]

.

Potential Application of Digital Twins with Autodesk Tandem

While BIM has been widely used by DMRC during design and construction, Digital Twin implementation remains limited. Autodesk Tandem offers several opportunities to enhance metro operations and maintenance:

1. **Asset lifecycle management**: Autodesk Tandem can create virtual replicas of stations, tunnels, and rolling stock, enabling condition monitoring and optimized maintenance planning.

2. **Energy optimization**: Digital Twins can analyse electricity consumption patterns, evaluate regenerative braking strategies, optimize train schedules, and assess the use of renewable energy sources.

3. **Passenger flow analysis**: IoT sensors integrated with Tandem can visualize passenger movement during peak hours, supporting station redesign, platform management, and train frequency optimization.

4. **Disaster preparedness**: Given Delhi's seismic vulnerability, Digital Twin simulations can help assess tunnel and station behaviour during earthquakes or fire incidents, improving emergency response planning[4].

Comparison of Istanbul and Delhi Metro

Comparison Metric	Istanbul Metro	Delhi Metro
Digital Twin Maturity	Deeply integrated into the design and operational lifecycle.	Emerging adoption with high scalability potential.
Structural Constraints	High seismic risk, complex hilly terrain, and heritage preservation.	Extreme passenger density and large-scale energy management.
Strategic Focus	Safety-first, predictive maintenance, and system scalability.	Operational energy efficiency and real-time crowd mitigation.
Operational Impact	Optimized maintenance costs and reduced downtime.	Early-stage resilience building and long-term sustainability.

Table 5.1: Strategic Comparison: Istanbul vs. Delhi Metro Infrastructure Framework[31, 4, 19, 66, 12, 53, 35]

.

As summarized in Table 5.1, both metro systems utilize different strategies based on their unique regional challenges. Istanbul's framework is heavily influenced by geological safety (seismic risk), whereas the Delhi Metro's priorities are centered on managing massive ridership and energy consumption.

Future Prospects

The potential of Digital Twin adoption in Delhi Metro is significant. Future metro phases could integrate Digital Twins from the early design stage, reducing costs and improving efficiency[4]. Linking Digital Twin systems with India's National Smart Cities Mission could further enhance coordination across urban infrastructure networks.

Autodesk Tandem's cloud-based platform can centralize data from multiple metro lines, enabling faster decision-making, improved monitoring, and long-term sustainability planning[60].

Lessons Learned

The analysis of both metro systems highlights several important lessons:

- Early integration of Digital Twins significantly enhances operation and maintenance efficiency.
- Digital Twin models must be customized to local conditions and network-specific challenges.
- Real-time data and simulation tools improve passenger safety and emergency preparedness.
- Delhi Metro shows strong potential for Digital Twin adoption to support sustainability and energy optimization.

5.3 Denver International Airport: Advancing Smart Operations

Denver International Airport (DIA) is one of the largest and most complex airports in the United States, with extensive terminals, runways, and supporting infrastructure[5]. To manage such a large-scale facility efficiently, Digital Twin technologies have been implemented to monitor operations in real time, optimize resource allocation, and support predictive maintenance. Autodesk Tandem provides a centralized platform to integrate data from sensors, systems, and assets, enabling smarter operational decision-making and improved passenger experience[5].

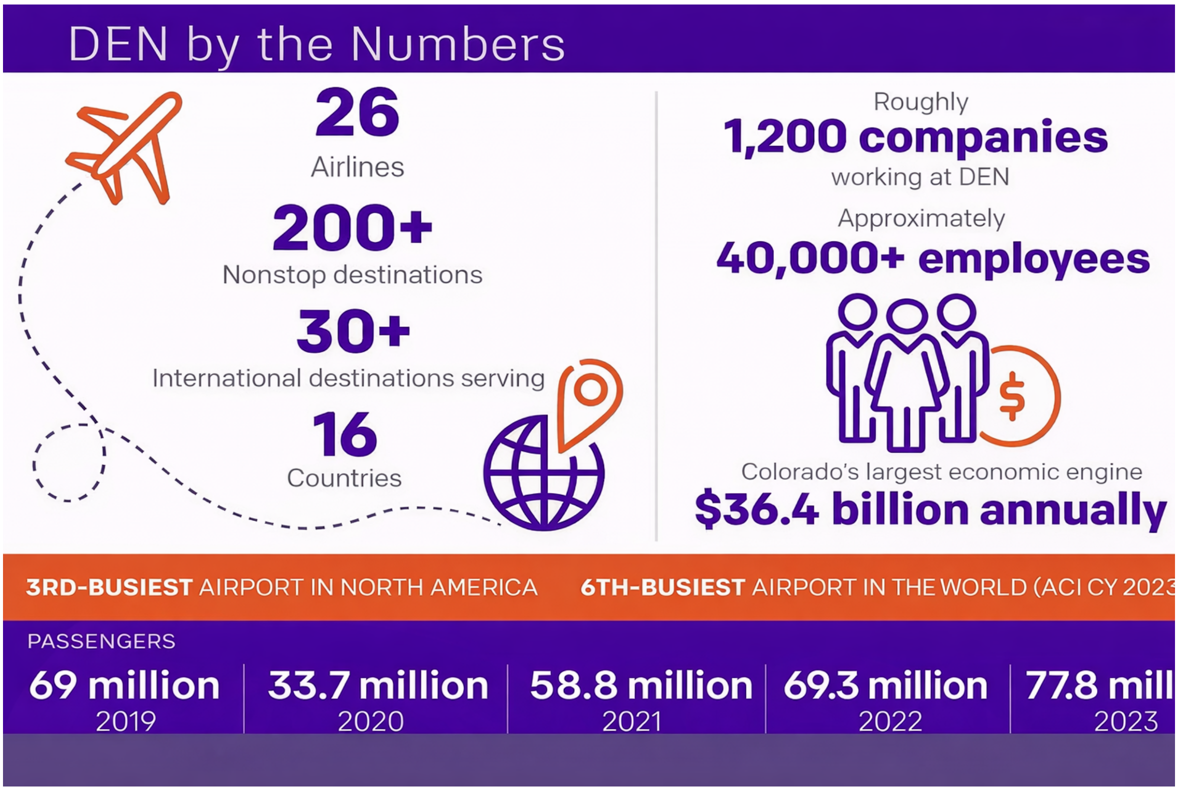

Figure 5.6: Overview of Denver International Airport terminal infrastructure[5]

Figure 5.7: Digital Twin and asset management infrastructure for Denver International Airport[5]

5.4 Summary

The Istanbul Metro, Delhi Metro, and Denver International Airport case studies demonstrate the transformative potential of Autodesk Tandem in metro infrastructure projects. Istanbul illustrates the advantages of early and comprehensive Digital Twin integration, while Delhi highlights the opportunities available in rapidly expanding urban systems. These examples confirm that Digital Twins are not merely futuristic concepts but practical tools capable of improving safety, efficiency, and sustainability in modern urban transport systems[4].

The following chapter discusses the benefits, challenges, and governance considerations of implementing Digital Twin technologies and Autodesk Tandem in metro projects, drawing lessons from the presented case studies.

Chapter 6

Discussion: Benefits, Challenges and Governance

Introduction

The integration of Digital Twin systems through platforms such as Autodesk Tandem has the potential to significantly transform the way metro projects are planned, delivered, and managed. These technologies offer substantial benefits across the entire project lifecycle, from early design to long-term operation and maintenance. At the same time, their implementation presents several challenges, including technical, financial, organizational, and human resource constraints.

Beyond technical functionality, Digital Twins also influence decision-making processes, risk management strategies, and long-term asset performance. Their ability to integrate real-time data, predictive analytics, and lifecycle information creates new opportunities for improving efficiency, safety, sustainability, and service quality in metro systems. However, these advantages can only be realized when appropriate governance frameworks, clear data ownership structures, cybersecurity measures, and stakeholder coordination mechanisms are in place.

Moreover, the adoption of Digital Twin technologies requires cultural transformation within organizations. Project teams, operators, and public authorities must develop new digital competencies and adapt to data-driven management approaches. Without adequate training, institutional support, and long-term strategic planning, the full potential of these systems may remain underutilized.

This chapter examines the key benefits of using Digital Twins in metro projects and highlights the major challenges and governance considerations that must be addressed to ensure successful and sustainable adoption.

6.1 Benefits of Using Digital Twins with Autodesk Tandem

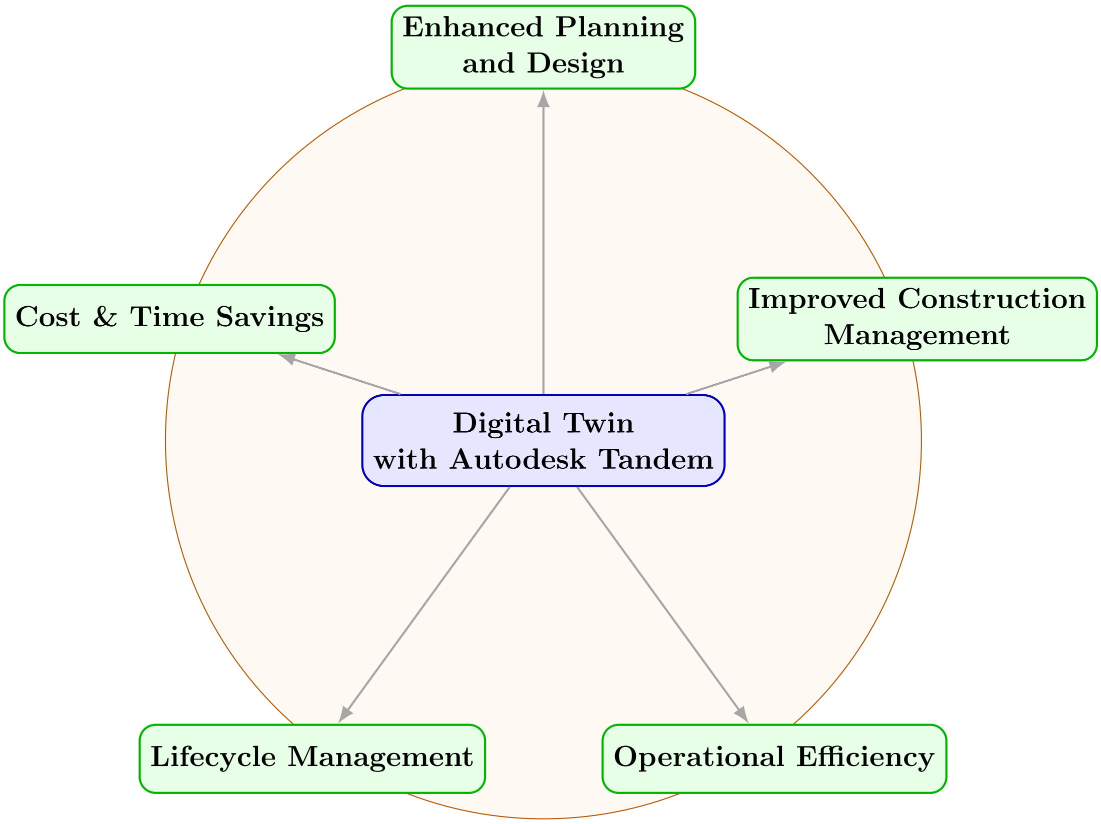

Figure 6.1: Key Benefits of Implementing Digital Twins using Autodesk Tandem in Metro Projects

Enhanced Planning and Design

Digital Twins improve planning and design by providing advanced visualization and simulation capabilities before construction begins [63, 18]. The main benefits include:

- **Improved visualization**: Engineers and architects can explore detailed three-dimensional models of metro lines, stations, and tunnels, enabling early detection of design conflicts.
- **Scenario simulation**: Multiple design alternatives can be tested virtually, including station layouts, tunnel alignments, and track configurations, reducing uncertainty during construction.
- **Stakeholder collaboration**: Designers, contractors, and decision-makers work within a shared digital environment, minimizing miscommunication and improving coordination.

Example: In Delhi Metro Phase 4, Digital Twin simulations can be used to model tunnel-boring activities and identify high-risk zones before construction begins [18].

Improved Construction Management

During construction, Digital Twins enable closer control and better decision-making through real-time monitoring [63, 42].

- **Real-time monitoring**: IoT-enabled devices provide live data on construction activities such as concreting, track installation, and equipment operation, allowing progress to be tracked accurately.
- **Resource optimization**: Digital Twins support efficient allocation of materials, labour, and machinery, reducing waste and improving productivity.
- **Risk identification**: Early warning alerts help identify safety hazards or equipment failures before they escalate into serious issues.

Example: In the Istanbul Metro, Digital Twin tools have been applied in complex underground excavation zones to reduce delays and avoid cost overruns [42].

Operational Efficiency

Once metro systems become operational, Digital Twins support efficient day-to-day management [63, 5].

- **Predictive maintenance**: Sensors embedded in trains, tracks, escalators, and HVAC systems help identify early signs of wear, preventing unexpected breakdowns.
- **Energy management**: Digital Twins analyse energy consumption patterns and recommend optimization strategies for traction power, station lighting, and ventilation systems.
- **Passenger flow management**: Real-time data allows operators to monitor crowd movement during peak hours, improving safety and comfort.

Example: At busy interchange stations, Digital Twins can support crowd control strategies during peak-hour operations.

Lifecycle Management

Autodesk Tandem enables continuity of information throughout the asset lifecycle [7].

- **Single source of truth**: All design, construction, and operational data are stored in one centralized system.
- **Digital handover**: Facility operators inherit a fully populated Digital Twin after construction, simplifying maintenance planning.
- **Sustainability support**: Lifecycle monitoring helps reduce material waste, energy consumption, and environmental impact.

Cost and Time Savings

Digital Twin adoption contributes to both short-term and long-term cost efficiency [7, 63, 70].

- **Error reduction**: Early identification of design and construction issues prevents costly rework.
- **Predictive maintenance**: Preventing failures reduces service disruptions and maintenance costs.
- **Faster project delivery**: Shared data environments improve collaboration and reduce project timelines.

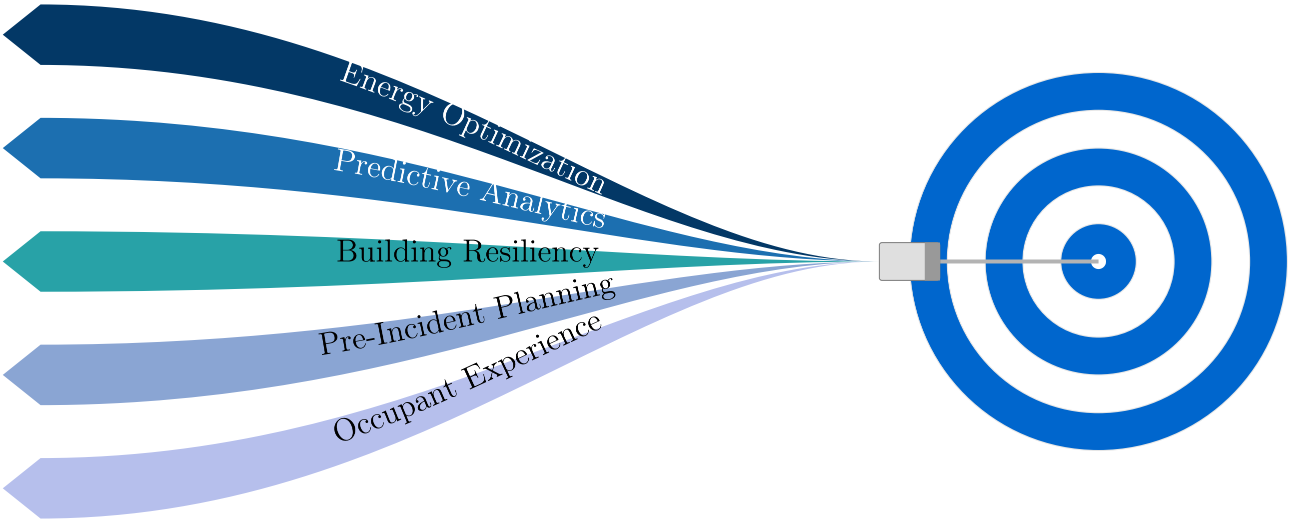

Figure 6.2: Five Real-World Applications of Digital Twin Technology [7]

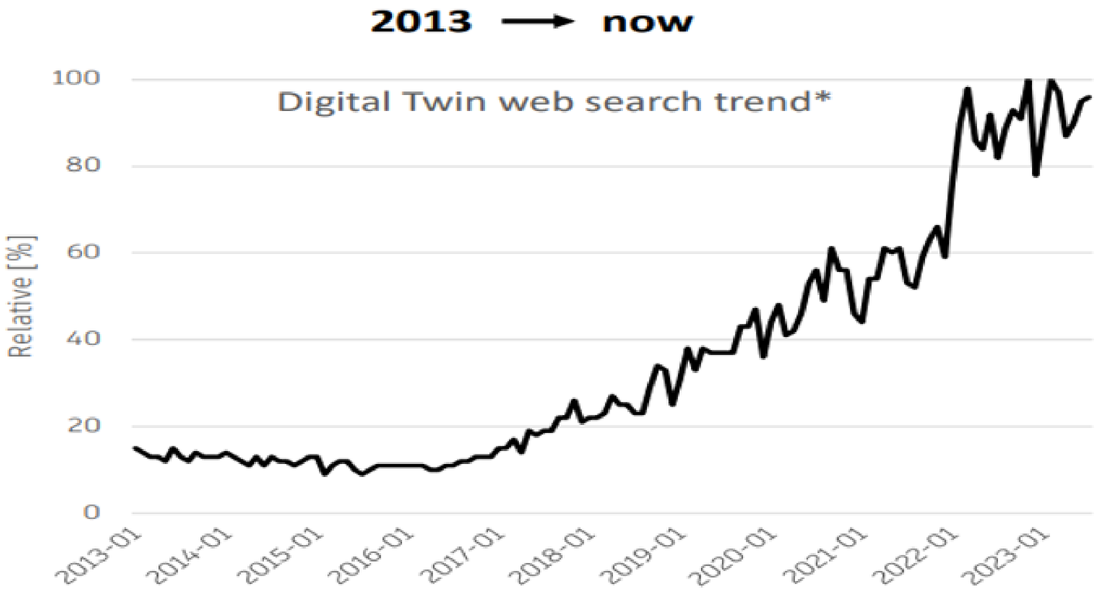

Figure 6.3: Digital Twin adoption trend from 2013 to present [60].

The increasing fascination with digital twins, coupled with fast-evolving supporting technologies, is expected to drive digital twin investments to surpass 48 billion dollars by 2026.

6.2 Challenges of Using Digital Twins with Autodesk Tandem

Despite the numerous benefits, several challenges must be addressed before widespread adoption of Digital Twins in metro projects [7, 63, 47, 9, 14, 60].

High Initial Investment

The implementation of Digital Twin systems requires significant upfront investment in software platforms, IoT sensors, cloud infrastructure, and skilled personnel. For developing countries, these costs can be a major barrier despite long-term savings.

Example: Smaller metro projects in Tier-2 cities may hesitate to adopt Digital Twin technology due to budget constraints.

Complexity of Data Integration

Metro systems generate vast volumes of data from signalling, energy systems, rolling stock, and stations. Integrating this data into a unified Digital Twin is technically complex. Lack of standardized data formats among contractors and operators can further create interoperability issues.

Skill and Training Gaps

Digital Twin platforms such as Autodesk Tandem require expertise in BIM, data analytics, and IoT systems. Many metro authorities face shortages of trained professionals and must invest heavily in staff training and capacity building.

Cybersecurity Concerns

Digital Twins depend on real-time data exchange through cloud-connected systems, making them vulnerable to cyber-attacks. Security breaches could disrupt metro operations and pose serious risks to passenger safety and infrastructure reliability.

Organizational Resistance

Resistance to change remains a significant challenge. Stakeholders accustomed to traditional workflows may be reluctant to adopt transparent, data-driven systems. Contractors and consultants may also resist the increased accountability associated with Digital Twins.

Technical Limitations

Reliable internet connectivity and advanced computing infrastructure are essential for real-time Digital Twin operation. In regions with limited digital infrastructure, maintaining continuous data updates and managing large-scale 3D models can be challenging.

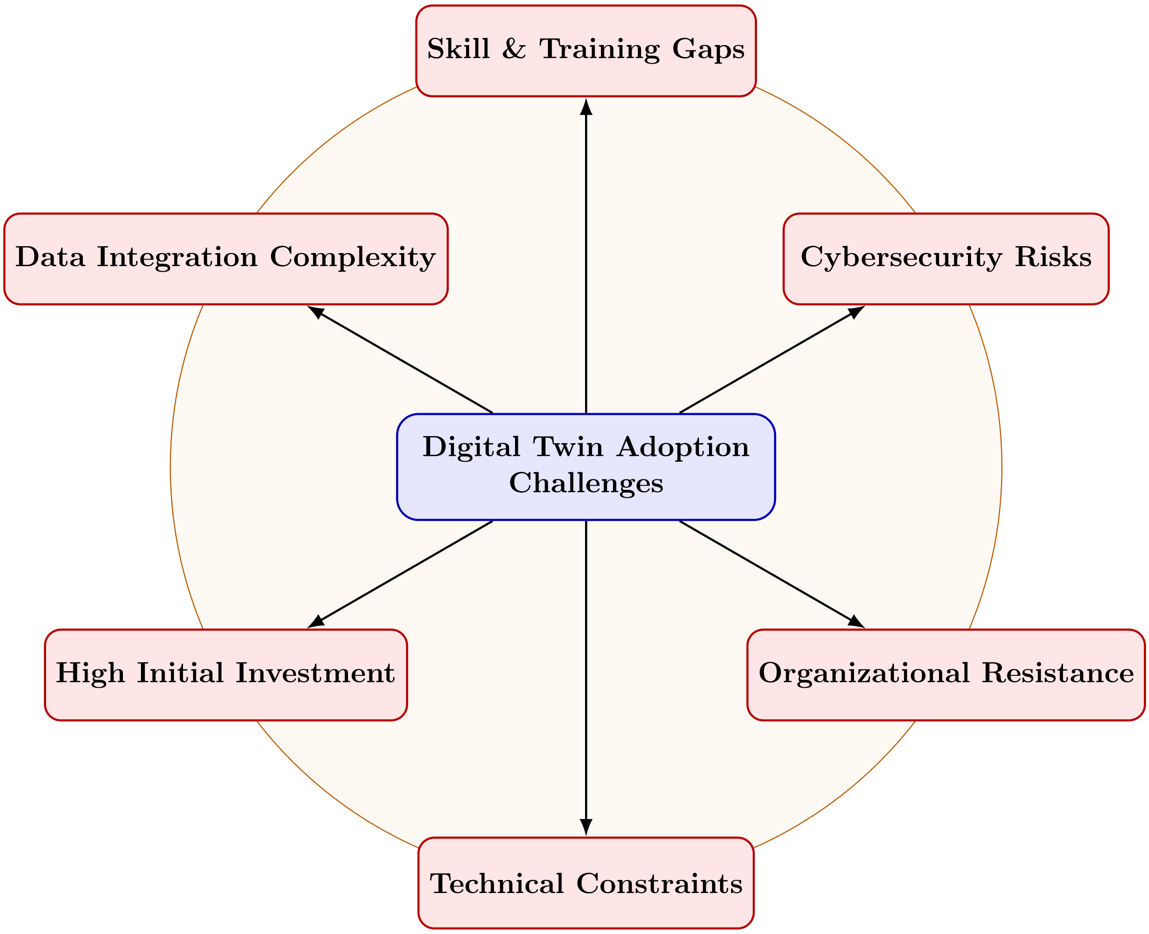

Figure 6.4: Key Challenges in Implementing Digital Twins using Autodesk Tandem in Metro Projects

Balancing Benefits and Challenges

Successful implementation of Digital Twins in metro projects requires a balanced approach [7, 63, 9, 14, 60, 31, 19, 5]:

- **Strategic investment**: High initial costs can be justified by long-term operational and maintenance benefits.
- **Capacity building**: Structured training programs and collaboration with technology providers can address skill gaps.
- **Standardization**: Industry-wide data standards improve interoperability and collaboration among stakeholders.

- **Cybersecurity frameworks**: Robust security policies are essential to protect data integrity and system reliability.

If these challenges are addressed through strategic planning and institutional support, metro systems such as Delhi and Istanbul have the potential to become global benchmarks for smart, resilient, and future-ready urban transportation infrastructure.

6.3 Policy, Governance, and Ethical Frameworks for Digital Twin Adoption in Metro Systems

Policy, Governance, and Ethical Frameworks for Digital Twin Adoption in Metro Systems. Digital Twin technology represents a large-scale and capital-intensive digital infrastructure system. Its adoption in metro projects should not be viewed solely as a technological transition; it is equally a matter of governance, regulation, institutional readiness, and political will for sustainable long-term growth. Metro projects are public infrastructure initiatives, often involving massive investments, international contractors, and long-term maintenance obligations. Governments, regulatory agencies, and urban development authorities must create policies that support the integration of tools like Autodesk Tandem across planning, execution, and operations, considering long-term national benefits [32]. Digital Twin adoption also raises important questions about ethics, data protection, and fairness. Beyond technical implementation, these systems affect millions of people daily and must adhere to rules of accountability [56]. This section examines the institutional, regulatory, and ethical frameworks required to ensure responsible technological advancement while maintaining public trust and long-term infrastructure resilience, with special reference to India (Delhi Metro) and Turkey (Istanbul Metro) [16, 30].

6.3.1 Policy Frameworks

Metro systems operate under multiple layers of policy:

National Policies

- **National Urban Transport Policy (NUTP), India:** Directs the development of sustainable metro systems and promotes safety, passenger comfort, and resource efficiency aligned with Digital Twin adoption [43].
- **National AI Strategy, Turkey (2021–2025):** Supports AI adoption in transport, facilitating Digital Twin implementation [52].

Smart City Missions and Digital Infrastructure

- Cities like Delhi, Istanbul, and Singapore use Digital Twins as part of smart city plans [58].
- Governments must support funding, standardized data systems, and safe trial zones for new technologies.

- Policies around IoT, 5G, and AI create ecosystems and incentivize private investment.

Sustainability and Green Policies

- Digital Twins enable energy optimization, predictive maintenance, and lifecycle carbon accounting to achieve Net Zero Carbon goals [17].

International Standards

- ISO 19650: Standardizes BIM information management [8].
- IFC (Industry Foundation Classes): Ensures interoperability across platforms.
- EU BIM Task Group Guidelines: Supports Digital Twin adoption in transport.
- UK Centre for Digital Built Britain (CDBB): Provides frameworks for Digital Twin use in public infrastructure.
- EU Data Governance Act: Guides secure and private management of project data.

6.3.2 Governance and Institutional Frameworks

Governance is the backbone of large-scale infrastructure management. Digital Twin adoption requires coordination across:

- Government ministries like Transport, Urban Development, Environment, and IT.
- Metro corporations, e.g., DMRC in Delhi and Metro Istanbul [16, 30].
- Technology providers (Autodesk, Siemens, Bentley, etc.).
- Regulatory authorities for safety, data protection, and cybersecurity.
- Public stakeholders including citizens, commuters, and civil society for feedback.

Institutional Frameworks: India – Delhi Metro

The Delhi Metro Rail Corporation (DMRC) demonstrates strong institutional readiness for advanced technology adoption:

- **Central & State Government Support:** Joint ownership ensures policy alignment and mitigates initial cost barriers [16].
- **BIM Mandates:** Government policies promote Building Information Modeling for accurate and efficient asset management [8].
- **Environmental and Urban Policy Integration:** DMRC aligns with the National Urban Transport Policy (NUTP) for sustainable, technology-enabled urban mobility [43].
- **Digital India Initiative:** Encourages cloud-based tools and smart infrastructure technologies, supporting Autodesk Tandem implementation.

Institutional Frameworks: Turkey – Istanbul Metro

Metro Istanbul, under the Istanbul Metropolitan Municipality (IMM), leverages several frameworks:

- **National AI Strategy:** Supports AI adoption in transport, facilitating Digital Twin implementation [52].
- **EU Standards Alignment:** Compliance with EU and ISO standards enables interoperable Digital Twin systems [8].
- **City Governance:** Integrates metro lines within Istanbul's smart city vision, using real-time digital insights for operations [30].
- **Public–Private Partnerships (PPPs):** Collaboration with global firms like Autodesk brings international expertise and technology.

Public-Private Partnerships (PPPs)

- Metro systems rely on multiple partners including software vendors and IoT providers.
- Policies must ensure clear contracts, shared accountability, and regulatory compliance [56].

6.3.3 Ethical Considerations

Data Privacy

- Data from CCTV, IoT devices, and ticketing systems must be anonymized and securely handled [56].
- GDPR-like safeguards and access limitations should be implemented [32].

Equity and Accessibility

- Digital Twins should support inclusive decisions, such as train schedules and platform design, benefiting all passenger groups [58].

Cybersecurity Risks

- Real-time connected systems are vulnerable to attacks.
- Regular risk assessments and mitigation strategies are essential [56].

Environmental Ethics

- Digital Twins can track energy use and minimize waste [17].
- Metro authorities have a responsibility to ethically use insights to achieve sustainability goals [58].

Challenges

- Lack of skilled personnel for efficient Digital Twin usage [58].
- Data security and privacy concerns [32].
- Siloed departmental operations leading to poor coordination.
- High funding requirements for Digital Twin projects [8].
- Legal and regulatory gaps (e.g., liability, data sovereignty, cross-border data issues) [56].

Recommendations

- Develop national roadmaps for metro Digital Twin adoption, similar to the UK's National Digital Twin Programme.
- Implement training programs across metro agencies, universities, and technology partners [58].
- Strengthen PPP models for collaboration with global technology providers [8].
- Offer incentives such as tax benefits or funding support for Digital Twin implementation.
- Adopt global standards (ISO, IEEE) to ensure uniformity and data protection [8].
- Establish Data Ethics Committees to oversee proper use of metro data [56].
- Maintain transparency through open dashboards on efficiency and sustainability [58].
- Clearly define data ownership and responsibilities for errors or breaches [32].

Case Reflections

- **Delhi Metro:** Strengthen data protection and public trust policies alongside BIM and IoT adoption [16, 8].
- **Istanbul Metro:** Align with EU privacy and ethical standards to safeguard passenger and operational data [30, 32].

6.4 Summary

The integration of Digital Twins through Autodesk Tandem offers significant advantages for metro projects, including improved efficiency, cost savings, sustainability, and enhanced passenger experience. However, challenges such as high initial investment, complex data management, skill shortages, and cybersecurity risks must be carefully managed. Digital Twin systems thrive under strong governance, clear policies, and ethical compliance. When managed effectively, these technologies make metro projects smarter, cleaner, and future-ready. Issues like data privacy, skill gaps, coordination, funding, and legal frameworks must be addressed to realize the full potential of Digital Twins in public transport systems [58, 32, 8]. If these challenges are addressed through strategic planning and institutional support, metro systems such as Delhi and Istanbul have the potential to become global benchmarks for smart, resilient, and future-ready urban transportation infrastructure.

The final chapter outlines the future prospects of Digital Twin technologies in metro projects, provides recommendations for effective implementation, and presents the overall conclusions of this study.

Chapter 7

Future Prospects, Strategic Recommendations, and Conclusion

Introduction

Digital Twin technology has already transformed sectors such as aviation, energy, and manufacturing. In the context of metro systems, the integration of Autodesk Tandem into planning, construction, and operational phases represents only the beginning of a broader digital transformation. This chapter explores the future prospects of Digital Twin technology in metro projects, highlighting emerging trends, global opportunities, and strategic recommendations for metro authorities, governments, and key stakeholders. It also summarizes the main conclusions of this study.

7.1 Future Prospects of Digital Twins in Metro Projects

Full Lifecycle Digitalization

In the near future, Digital Twins are expected to enable complete lifecycle digitalization of metro systems, from conceptual design to decommissioning. Autodesk Tandem's capability to preserve data integrity across all project phases ensures that decisions made during early stages remain accessible and valuable throughout the asset's operational life[63].

- **Design Stage:** A unified digital model enables seamless collaboration among architects, engineers, and planners.
- **Construction Stage:** Real-time progress tracking, resource optimization, and quality assurance become possible through integrated data environments.
- **Operation Stage:** Predictive analytics support maintenance planning, passenger flow optimization, and energy management.
- **Decommissioning Stage:** Digital Twins facilitate safe dismantling, material traceability, and recycling strategies.

Integration with Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) are expected to play a central role in enhancing Digital Twin capabilities. By leveraging real-time and historical data within Autodesk Tandem, metro systems can move toward self-optimizing operations[63, 14].

- AI algorithms can predict passenger demand surges during peak periods, festivals, or emergency situations, enabling proactive mitigation strategies.
- ML models can recommend cost-efficient maintenance schedules by analyzing long-term performance data of assets.

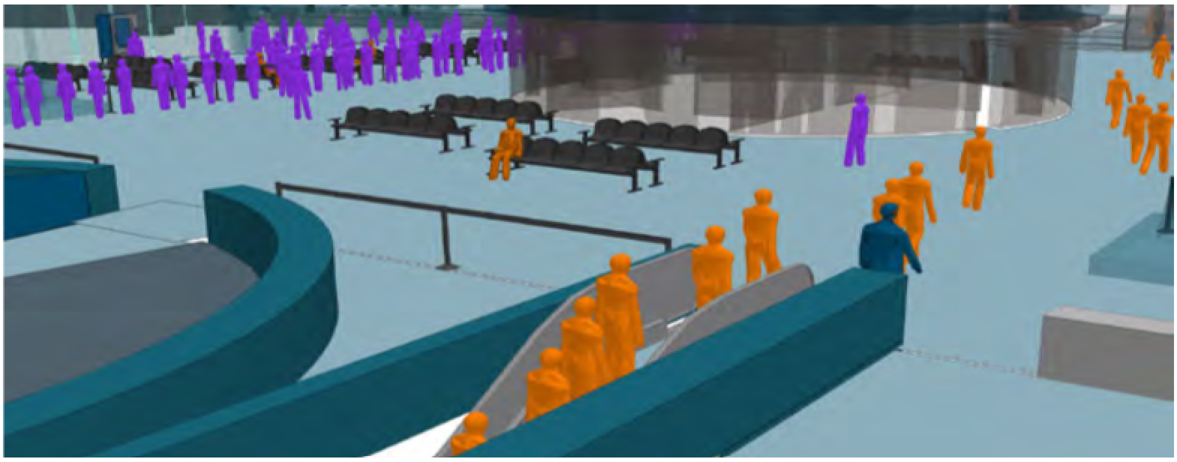

Figure 7.1: Example of real-time crowd capture and simulation with MassMotion Live [63]. This demonstrates potential applications for metro system monitoring and predictive passenger management.

Smart Cities and Intermodal Integration

Future metro systems will increasingly operate as integral components of smart city ecosystems rather than isolated transport networks. Digital Twins of metro systems can be interconnected with citywide Digital Twins covering roads, airports, utilities, and residential infrastructure[63, 5].

- **Passenger-Centric Benefits:** Real-time multimodal travel guidance enhances journey efficiency and convenience.
- **Urban Planning Advantages:** Simulation-based forecasting allows assessment of metro expansions on traffic flow, emissions, and land use.
- **Policy Support:** Data-driven insights support informed decision-making to reduce congestion and environmental impact.

Sustainability and Green Transition

Sustainability objectives and climate commitments are driving metro authorities toward low-carbon and energy-efficient operations. Digital Twins can significantly contribute to these goals by enabling continuous monitoring and optimization of environmental performance[63, 64].

- Optimization of energy consumption across trains, stations, and auxiliary systems.
- Support for circular economy practices, including reuse and recycling of construction materials.
- Transparent reporting of energy and resource usage to support green certifications and regulatory compliance.

Extended Reality and Passenger Experience

The integration of Digital Twins with Extended Reality (XR) technologies—such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—is expected to redefine both workforce training and passenger experience[63, 48, 61].

- **AR-enabled Maintenance:** Maintenance personnel can receive real-time, overlaid repair instructions directly on physical components.
- **Immersive Passenger Guidance:** AR-based navigation systems can improve accessibility for visually impaired and first-time users.
- **VR-based Training:** Immersive simulations enable safe and effective emergency training for metro staff.

Global Adoption and Standardization

As Digital Twin adoption increases worldwide, the development of international standards will become essential to ensure interoperability and data exchange across metro systems.

- Knowledge sharing between metro systems in cities such as Delhi, Istanbul, and London can accelerate best practices.
- Government mandates for BIM- and Digital Twin-based submissions in large infrastructure projects are likely to increase.

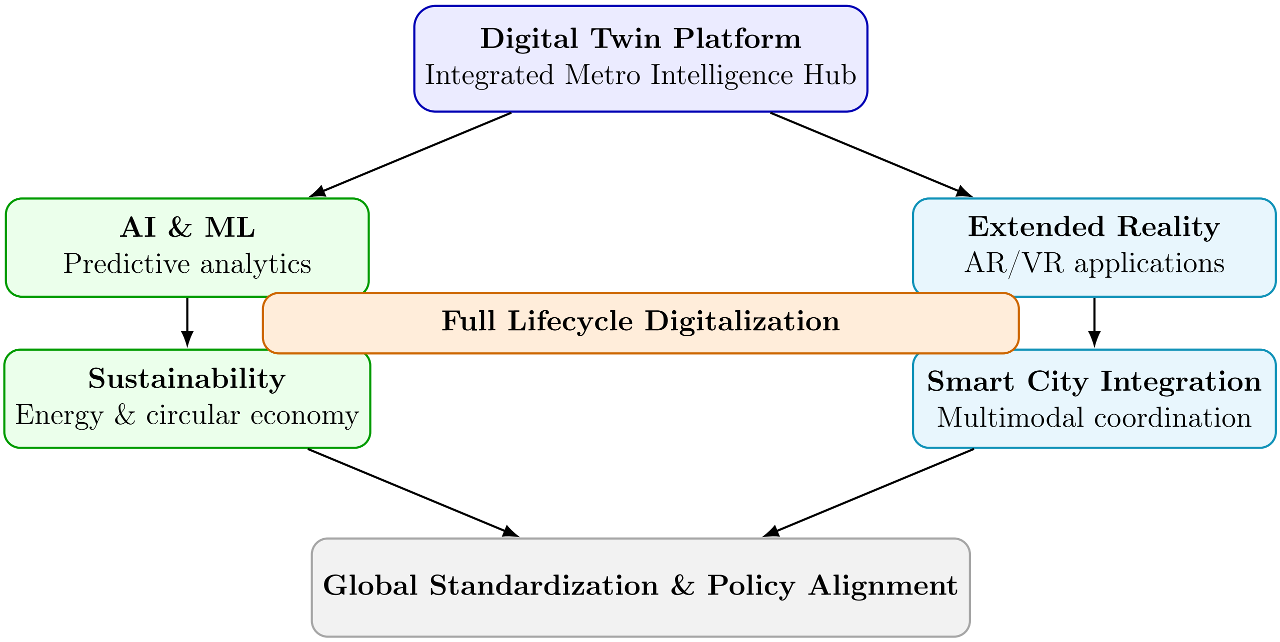

Figure 7.2: Future Strategic Framework of Digital Twin-enabled Metro Systems with Full Lifecycle Digitalization[63]

7.2 Recommendations for Effective Implementation

The following discussion is based on [63, 42, 9]

Institutional Commitment

Metro authorities should adopt a Digital Twin-first strategy from the earliest planning stages. Government support through policy frameworks, funding mechanisms, and capacity-building initiatives is essential to promote large-scale adoption.

Workforce Training and Capacity Building

Continuous training programs are required to equip engineers, planners, and operators with skills in Autodesk Tandem, BIM, data analytics, and IoT technologies. Establishing specialized Digital Twin laboratories within universities and metro organizations can further support innovation and skill development.

Data Governance and Security

Robust data governance frameworks must be established to address data ownership, access control, and cybersecurity risks. Open data standards should be adopted while ensuring the protection of sensitive operational and passenger information.

Collaborative Ecosystem

Strong collaboration between technology providers, metro authorities, government agencies, and academic institutions is crucial. Pilot projects should be encouraged to validate feasibility and performance before large-scale implementation.

Long-Term Cost–Benefit Perspective

Investment decisions should consider lifecycle cost savings rather than focusing solely on upfront implementation costs. Public–Private Partnership (PPP) models can provide effective financing mechanisms for Digital Twin integration.

Challenges That Must Be Addressed

Despite promising prospects, several challenges require immediate attention. These include high initial investment costs, resistance to organizational change, increased cybersecurity vulnerabilities, and the need for industry-wide data standardization.

7.3 Conclusion

Digital Twins, empowered by Autodesk Tandem, represent a paradigm shift in the planning, construction, and operation of metro systems. Their future application promises safer, smarter, greener, and more passenger-centric urban transport networks. With strategic planning, institutional commitment, and collaboration between public and private stakeholders, Digital Twins can transition from an emerging innovation to a mainstream practice in global urban transportation. The case studies of the Delhi Metro and Istanbul Metro clearly demonstrate this potential and highlight the path forward for sustainable and resilient metro infrastructure. This study set out to understand how Digital Twin technology, supported by Autodesk Tandem, reshapes the planning, construction, and operation of metro systems. Through a close look at both the Delhi and Istanbul Metro projects, it has become clear that Digital Twins are not just digital models but living reflections of physical infrastructure, bridging design and real-time intelligence.

The findings show that Autodesk Tandem helps weave together BIM, IoT, and analytics into a single, evolving model of the metro network. It improves asset lifecycle management, enables predictive maintenance, enhances energy efficiency, and supports decision-making through real-time insights.

The potential observed in both cases—Delhi and Istanbul—includes lower operational costs, safer systems, and better alignment with sustainability goals. However, challenges such as high initial costs, interoperability concerns, data security issues, and limited technical expertise remain. Yet, when weighed against the long-term advantages, these barriers appear more like stepping stones than roadblocks.

By connecting live data to digital models, Digital Twins have evolved from futuristic concepts into essential components of modern infrastructure, allowing metro systems to grow, learn, and adapt in transforming urban mobility.

Key Findings

- **Lifecycle Integration:** Autodesk Tandem ensures continuity of data from design to operation, minimizing information loss and ensuring consistent efficiency.
- **Operational Excellence:** Predictive maintenance and analytics reduce downtime, improving reliability and passenger satisfaction.
- **Sustainability:** Real-time monitoring supports energy optimization and reduces carbon footprints.
- **Passenger-Centric Design:** Simulations of passenger flows improve comfort, accessibility, and safety.
- **Governance Role:** Strong policies and institutional collaboration are vital for responsible, secure, and ethical implementation.

Future Roadmap

The roadmap to unlock the full potential of Digital Twins technology in metro infrastructure is structured as follows:

Early-Stage Integration

- Begin using Digital Twin systems in planning from the design stages.
- Introduce Autodesk Tandem or similar platforms during tender and procurement stages to guide project execution from the beginning.

Data Infrastructure and IoT Expansion

- Deploy IoT networks across stations, tunnels, and rolling stock to collect richer real-time data.
- Strengthen interoperability between legacy systems and emerging digital ecosystems to maintain consistency and accuracy of insights.

Capacity Building

- Establish continuous training programs for engineers, planners, and operators in Digital Twin technologies and data analytics.
- Create dedicated Centers of Excellence within metro corporations and academic institutions.

Policy and Governance Alignment Governments should integrate Digital Twin strategies into national infrastructure policies and Smart City missions to ensure long-term alignment between technology, sustainability goals, and regulatory frameworks.

Bibliography

[1] M. M. Ansari, M. T. Khan, F. Sami, Farhan, and S. K. Parmar. Design of g+10 storey residential building using staad.pro. *International Research Journal of Engineering and Technology (IRJET)*, 2021.

[2] AQI India. Aqi: Real-time air quality index | air pollution level. `https://www.aqi.in/`, 2026. Accessed: 12 February 2026.

[3] Autodesk. Metro istanbul: Building a better transit system with bim. Autodesk Customer Stories, 2022.

[4] Autodesk. Autodesk tandem for metro projects. `https://www.autodesk.com/tandem`, 2024. Accessed: Jan 2026.

[5] Autodesk. Taking off with digital twins – autodesk tandem webinar. `https://intandem.autodesk.com/resource/webinar-2025-february/`, 2025. Accessed: February 2026.

[6] Autodesk Revit. Revit api developer guide. Official Documentation, 2026. Accessed: 2026-02-17.

[7] Autodesk Tandem. Tandem api documentation. Official Documentation, 2026. Accessed: 2026-02-17.

[8] Murat Aydın. A data-driven bim framework for digital twin integration with iso 23247-compliant automation in construction. *DergiPark*, 2023.

[9] S. Azhar. Building information modeling (bim): Trends, benefits, risks, and challenges. *Leadership and Management in Engineering*, 11(3):241–252, 2011.

[10] B. R. Barricelli, E. Casiraghi, and D. Fogli. A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE Access*, 7:167653–167671, 2019.

[11] M. Batty. Digital twins for urban simulation and planning. *Environment and Planning B: Urban Analytics and City Science*, 45(6):1095–1111, 2018.

[12] Bentley Systems, Incorporated. Delhi metro rail corporation: Railway track alignment design using openrail designer. Case study, Bentley Systems, Incorporated, Exton, PA, USA, 2018. CS20207.

[13] C. Boje, A. Guerriero, S. Kubicki, and Y. Rezgui. Towards a semantic construction digital twin: Directions for future research. *Automation in Construction*, 114:103179, 2020.

[14] A. S. Borkowski. Low-cost internet of things solution for building information modeling level 3b—monitoring, analysis and management. *Journal of Sensors and Actuator Networks*, 2024.

[15] Delhi Capital. Delhi metro phase 4 – what's coming and when, 2024.

[16] Delhi Metro Rail Corporation. Digital twin aided sustainability and vulnerability audit for subway stations. *Sustainability*, 12(19):7873, 2020.

[17] Delhi Metro Rail Corporation. Digital twin aided sustainability and vulnerability audit for subway stations. *Sustainability*, 12(19):7873, 2020.

[18] Delhi Metro Rail Corporation. Predictive maintenance and digital twin implementation in delhi metro. `https://www.delhimetrorail.com`, 2023. Accessed: February 2026.

[19] Delhi Metro Rail Corporation. Delhi metro official website, 2024.

[20] X. Deng, R. Zhong, and X. Xu. Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robotics and Computer-Integrated Manufacturing*, 67:102080, 2021.

[21] Drawing to the Future Lab, Politecnico di Torino. Drawing to the future – research and teaching laboratory. `https://www.diseg.polito.it/dipartimento/strutture_interne/centri_e_laboratori/drawing_to_the_future`, 2026. Thesis laboratory support, Accessed: 2026-02-17.

[22] C. Eastman, P. Teicholz, R. Sacks, and K. Liston. *BIM Handbook: A Guide to Building Information Modeling*. Wiley, 3rd edition, 2018.

[23] Anthony D. Fontanini, Umesh Vaidya, and Baskar Ganapathysubramanian. A methodology for optimal placement of sensors in enclosed environments: A dynamical systems approach. *Building and Environment*, 100:145–161, 2016.

[24] A. Fuller, Z. Fan, C. Day, and C. Barlow. Digital twin: Enabling technologies, challenges and open research. *IEEE Access*, 8:108952–108971, 2020.

[25] M. Grieves. Digital twin: Manufacturing excellence through virtual factory replication. Florida Institute of Technology, 2014.

[26] Kerem Halicioglu, Esra Erten, and Cristian Rossi. Monitoring deformations of istanbul metro line stations through sentinel-1 and levelling observations. *Environmental Earth Sciences*, 80(361):1–17, 2021.

[27] Li Hu. Research on the application of digital twin in smart cities. In *Proceedings of the 7th International Conference on Economic Management and Green Development*, Edinburgh, UK, 2023. Corresponding author: NifferL@outlook.com.

[28] B. Huston, S. Spangler, and B. Brucker. Building information modeling (bim) roadmap: Supplement 2 - bim implementation plan for military construction projects. Bentley Systems, 2011. Available at: Bentley Systems or ResearchGate.

[29] InfraTo. Infrastructure technology services. `https://infrato.it/`. Accessed: 16-Feb-2026.

[30] Metro Istanbul. Metro istanbul annual reports. Technical report, Istanbul Metropolitan Municipality, 2021.

[31] Metro Istanbul. Digital twin implementation in metro projects. `https://www.metro.istanbul`, 2024. Accessed: Jan 2026.

[32] Bo Nørregaard Jørgensen and Zheng Grace Ma. Digital twins under eu law: A unified compliance framework across smart cities, industry, transportation, and energy systems. *Electronics*, 14(24):4881, 2025.

[33] S. Kaewunruen and J. M. Sussman. Digital twin and smart railway: Opportunities and challenges. *Journal of Rail and Rapid Transit*, 233(5):525–541, 2019.

[34] Hrvoje Kalinić, Leon Ćatipović, and Frano Matić. Optimal sensor placement using learning models—a mediterranean case study. *Remote Sensing*, 14(13):2989, 2022.

[35] Tushar Khattar. Customer satisfaction research on delhi metro services. Research proposal, Dr. B. R. Ambedkar University, Delhi, September 2023.

[36] Werner Kritzinger, Matthias Karner, Georg Traar, Jan Henjes, and Wilfried Sihn. Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 51-11:1016–1022, 2018. Proceedings of the 16th IFAC Symposium on Information Control Problems in Manufacturing, Bergamo, Italy, June 11–13, 2018.

[37] Jian Li, Yifan Wang, and Rui Chen. Digital twin-based resilience analysis and emergency maintenance with generative ai of smart urban metro systems. *Reliability Engineering & System Safety*, 238:111537, 2026.

[38] Q. Lu and Y. Zhang. Digital twin-driven smart urban transportation management. *Automation in Construction*, 112:103091, 2020.

[39] A. M. Madni, C. C. Madni, and S. D. Lucero. Leveraging digital twin technology in systems engineering. *Systems*, 7(1):7, 2019.

[40] meteoblue. Weather Archive and Climate Data for Turin, Italy. `https://www.meteoblue.com/en/weather/historyclimate/weatherarchive/turin_italy_9033541`, 2025. Accessed: 2026-02-11.

[41] Mayank Mishra, Paulo B. Lourenço, and G.V. Ramana. Structural health monitoring of civil engineering structures by using the internet of things: A review. *Journal of Building Engineering*, 48:103954, 2022.

[42] Istanbul Metropolitan Municipality. Digital twin applications in istanbul metro operations. `https://www.istanbul-ulasim.com.tr`, 2022. Accessed: February 2026.

[43] Ministry of Housing and India Urban Affairs. National urban transport policy (nutp). Technical report, Ministry of Housing and Urban Affairs, India, 2014.

[44] Hossein Omrany, Karam M. Al-Obaidi, Amreen Husain, and Amirhosein Ghaffarianhoseini. Digital twins in the construction industry: A comprehensive review of current implementations, enabling technologies, and future directions. *Sustainability*, 15:14109, 2023. Correspondence: hossein.omrany@adelaide.edu.au; Published: July 2023.

[45] Onset Computer Corporation. Hobo data loggers and environmental monitoring solutions. `https://www.onsetcomp.com/`, 2026. Accessed: 12 February 2026.

[46] A. Osello. *Il futuro del disegno con il BIM per ingegneri e architetti (The Future of Drawing with BIM for Engineers and Architects)*. Dario Flaccovio Editore, 2012.

[47] A. Osello. Parametric modelling and digital twins in built heritage projects. *Journal of Cultural Heritage Management and Sustainable Development*, 15(2):150–168, 2025.

[48] Anna Osello. Conoscenza del patrimonio costruito nell'epoca dei cambiamenti climatici / knowledge of the built heritage in the era of climate changes. Master of Science course, Ingegneria Edile, Politecnico di Torino, 2025. Accessed: 01-Feb-2026.

[49] Anna Osello. Parametric and algorithmic modeling b. Bachelor of Science course, Architettura per la Sostenibilità, Politecnico di Torino, 2025. Accessed: 01-Feb-2026.

[50] R.M. Pavón, M.G. Alberti, J.J. Cepa, and T.L. Ripa Alonso. Bim-based digital twin for the management of a railway station. *Journal of Civil Engineering and Management*, 2025.

[51] Charith Perera, Arkady Zaslavsky, Peter Christen, and Dimitrios Georgakopoulos. Context aware computing for the internet of things: A survey. *arXiv:1305.0982*, 2013. Preprint.

[52] Digital Transformation Office Republic of Turkey. National ai strategy 2021–2025. Technical report, Republic of Turkey, Digital Transformation Office, 2021.

[53] Rashmi Sadana. On the delhi metro: An ethnographic view. *Special Article*, November 2010.

[54] Sabrina Sicari, Alessandra Rizzardi, Luigi Alfredo Grieco, and Alberto Coen-Porisini. Security, privacy and trust in internet of things: The road ahead. *Computer Networks*, 76:146–164, 2015.

[55] Siemens. Digital twin for rail infrastructure. Siemens White Paper, 2020.

[56] Springer. *Rights and Responsibilities: Legal and Ethical Considerations in Adopting Local Digital Twin Technology*. Springer, 2024.

[57] F. Tao, Q. Qi, A. Liu, and A. Kusiak. Digital twin driven smart manufacturing. *Journal of Manufacturing Systems*, 50:121–131, 2019.

[58] Lucy Temple et al. Unravelling the use of digital twins to assist decision- and policy-making in smart cities. *arXiv preprint arXiv:2405.20916*, 2024.

[59] Time and Date AS. Climate & weather averages in turin, italy. `https://www.timeanddate.com/weather/italy/turin/climate`, 2026. Accessed: 12 February 2026.

[60] Autodesk University. Digital twins with autodesk tandem: From setup to data-driven analysis. Autodesk University, 2023.

[61] et al. Wang. Digital twin in transportation infrastructure management: a systematic review. *Intelligent Transportation Infrastructure*, 2024.

[62] Siyi Wang, Xiangwei Zhang, Jiaying Wang, Tao Tao, Kunlun Xin, Hexiang Yan, and Shuping Li. Optimal sensor placement for the routine monitoring of urban drainage systems: A re-clustering method. *Journal of Environmental Management*, 335:117579, 2023.

[63] Wenjuan Wang, Qasim Zaheer, Shi Qiu, Weidong Wang, Chengbo Ai, Jin Wang, Sicheng Wang, and Wenbo Hu. *Digital Twin Technologies in Transportation Infrastructure Management*. Springer Nature Singapore Pte Ltd., Singapore, 2024. Book; Capital University of Economics and Business, Beijing, China; Central South University, Changsha, Hunan, China; University of Massachusetts Amherst, Amherst, MA, USA.

[64] X. Wang, H. Song, W. Zha, J. Li, and H. Dong. Digital twin based validation platform for smart metro scenarios. In *IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI)*, 2021.

[65] Yixing Wang, Qingrui Yue, Xinzheng Lu, Donglian Gu, Zhen Xu, Yuan Tian, and Shen Zhang. Digital twin approach for enhancing urban resilience: A cycle between virtual space and the real world. *Resilient Cities and Structures*, 3:34–45, 2024. Affiliations: Institute of Engineering Mechanics, China Earthquake Administration; University of Science and Technology Beijing; Tsinghua University; Central South Architectural Design Institute Co., Ltd.

[66] Wikipedia. Delhi metro, 2024.

[67] D. Wu et al. Digital twin technology in transportation infrastructure: A comprehensive survey, 2025. A recent review of digital twin technology applications in transport infrastructure over the full lifecycle, including metro systems.

[68] W. Wu, Y. Zhang, and Q. Yue. Digital twin technology in transportation infrastructure: A comprehensive survey. *Applied Sciences*, 15(4):1911, 2025.

[69] et al. Zhang. A webgis-based digital twin platform for intelligent operation and maintenance of rail transit infrastructure. *Expert Systems With Applications*, 2026.

[70] Z. Zhang, Z. Wei, S. Court, L. Yang, S. Wang, A. Thirunavukarasu, and Y. Zhao. A review of digital twin technologies for enhanced sustainability in the construction industry. *Buildings*, 14(4):1113, 2024.

[71] Y. Zhao, Y. Liu, and E. Mu. A review of intelligent subway tunnels based on digital twin technology. *Buildings*, 2024.

[72] Cheng Zhou, Wenbo Qin, Hanbin Luo, Qunzhou Yu, Bin Fan, and Qi Zheng. Digital twin for smart metro service platform: Evaluating long-term tunnel structural performance. *Automation in Construction*, 167:105713, 2024. Digital twin application for metro tunnel maintenance and O&M management, emphasizing structural performance evaluation.