Towards Planning Digital Twins for Urban Mobility

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***Abstract*—Urban and industrial areas increasingly face complex mobility challenges due to growing commuter demand, infrastructure constraints, and the need for sustainable transport solutions. However, there remains a lack of advanced digital tools to support long-term planning and scenario-based decision-making in such contexts. This paper addresses this gap by presenting BISTWIN, a Mobility Planning Digital Twin (MPDT) designed to support mobility planning in the Bissen industrial zone, Luxembourg. BISTWIN integrates historical traffic data with a high-performance simulation engine to evaluate the impact of mobility interventions. The key contributions include: (i) developing an MPDT tailored to the Bissen industrial zone, (ii) validating the model with publicly available traffic data, and (iii) demonstrating its decision support capabilities through two "what-if" scenarios. BISTWIN offers a scalable framework for sustainable transportation planning, providing valuable insights for future MPDT applications in industrial and urban settings.**

I. Introduction

In recent years, the concept of Digital Twins (DTs) has gained significant traction across multiple domains, including telecommunications, transportation, healthcare, agriculture, and smart cities [1, 2]. The fundamental premise of DTs is to create real-time digital replicas of physical entities, allowing for extensive simulations and "what-if" scenario testing in a controlled yet realistic environment before implementing changes in the real system. This capability enables data-driven decision-making, optimization of resources, and enhanced efficiency in complex systems.

In the transportation domain, the concept of Mobility Digital Twin (MDT) has emerged as a promising approach to enhance traffic safety, optimize mobility infrastructure, and improve transportation efficiency [3, 4, 5]. MDTs facilitate real-time traffic monitoring, predictive analytics, scenario-based evaluation, and decision support. Broadly speaking, MDTs can be classified into two categories: **operations** MDTs, which operate with real-time data to enable immediate feedback loops between digital models and the physical world, and **planning** MDTs, which leverage historical data and advanced analytics to anticipate future mobility patterns and support long-term decision making. Planning MDTs are sometimes referred to in the literature as digital siblings [6].

Despite these advancements, real-life implementations of MDTs remain scarce, and existing initiatives are often overly simplified, lacking comprehensive integration with predictive analytics and large-scale decision-support capabilities. The challenge lies in developing MDTs that can address real-world mobility issues while providing scalable and adaptable solutions to accommodate evolving transportation demands.

A. Motivation and Research Gap

The industrial zone of Bissen, Luxembourg, presents a compelling case for the deployment of a Mobility Planning Digital Twin (MPDT). Currently, this area is home to approximately 60 companies and 2500 employees, with daily commuting patterns that pose significant societal, economic, and environmental challenges. A study and survey conducted by Schroeder & Associates since May 2022 as part of a Mobility Management initiative by the municipality identified several critical mobility factors requiring urgent attention. These include enhancing public and shared transport utilization, encouraging soft mobility solutions, and preparing for electromobility adoption.

A conventional simulation approach alone is insufficient to address these challenges as it lacks dynamic adaptability and predictive power for long-term strategic mobility planning. Therefore, a more robust MPDT approach that integrates multiple digital tools and real data is necessary to provide enhanced mobility planning and decision-making capabilities.

B. Our Contribution

To bridge this gap, we propose BISTWIN, an MPDT designed for the industrial zone in Bissen, Luxembourg. The proposed MPDT aims to offer a comprehensive mobility management solution that facilitates traffic data processing, supporting strategic planning and operational decision-making. Our main contributions can be summarized as follows:

- We **develop an MPDT** tailored to the specific mobility challenges of the industrial zone in Bissen, addressing real-world transportation inefficiencies.
- We **validate the MPDT** using publicly available historical traffic data to ensure its reliability and accuracy.
- We **demonstrate the potential of the MPDT** by analyzing two "what-if" scenarios, showcasing its capability to support mobility planning, infrastructure optimization, and policy formulation.

By advancing the state of MPDT implementations, BISTWIN represents a step forward in leveraging digital twins for sustainable and efficient urban mobility planning. The insights derived from this study can inform future MDT applications in similar industrial and urban settings, contributing to the broader adoption of planning DTs in transportation management.

II. Background and Related Work

A. Terminology

The definition of DTs has been widely debated in the literature. Some early definitions establish DTs as a mandatory

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combination of five dimensions: physical entities, virtual models, services, data, and connections [2, 7]. In its most common definition, a DT enables a real-time bidirectional connection between physical entities and their digital counterparts, facilitating both data flow and interactive control. Conversely, a Digital Shadow only provides a one-way data transfer from the physical to the digital world, primarily for long-term planning and optimization.

When considering large-scale MDT implementations, real-world deployments remain scarce to the best of our knowledge. Abdelrahman et al. [8] conducted an extensive review of over 15 000 scientific publications focused on DTs in the built environment, categorizing them into two major groups: High-Performance Real-Time (HPRT) DTs, closely aligned with the traditional DT definition, and Long-Term Decision Support (LTDS) DTs, which emphasize data representation, validation, and policy-driven decision-making. The latter category is particularly relevant for urban and city-scale DTs.

Given this distinction, we define our solution as an MPDT rather than a Digital Shadow or Sibling. Our approach aligns with the LTDS framework, as it integrates scenario evaluation and decision support for long-term mobility planning. Our MPDT incorporates historical data to enable proactive decision-making, making it a more suitable framework for addressing the mobility challenges in the industrial zone of Bissen.

B. *MDT state of the art*

Recent studies have extensively reviewed DT applications, architectures, and terminology in the transportation domain [6, 7, 9]. For example, Schwarz and Wang [7] review the existing literature discussing the role of DTs in the simulation and modeling of Connected and Automated Vehicles (CAVs). They describe three different methodologies for creating virtual testbeds, namely iterative-based, model-based, and DT-based. They also describe examples of DTs for CAVs and identify future opportunities and challenges. The role of DTs for CAVs is also discussed by Ali et al. [9], but with a particular focus on common issues in electric vehicle services.

Irfan et al. [6] provide a comprehensive overview of DT technology applications in the Intelligent Transportation System (ITS) domain. They also develop a hierarchical reference architecture for an MDT system with a focus on scalability, identify research challenges for each component of this system, and provide future research perspectives for the development and deployment of large-scale MDT systems for ITS.

Wang et al. [3] propose an MDT framework defined as an AI-based cloud-edge-device platform for mobility services. The proposed framework consists of three building blocks, namely *Human*, *Vehicle*, and *Traffic*, which are modeled in the digital space. The authors demonstrate the benefits of the proposed MDT by implementing several mobility microservices and a case study for personalized adaptive cruise control. Wang et al. [5] propose a smart MDT platform to provide cloud services to CAV users. In particular, they develop an MDT platform based on cloud and edge computing, and design a CAV navigation system that uses this MDT to navigate dynamic traffic events

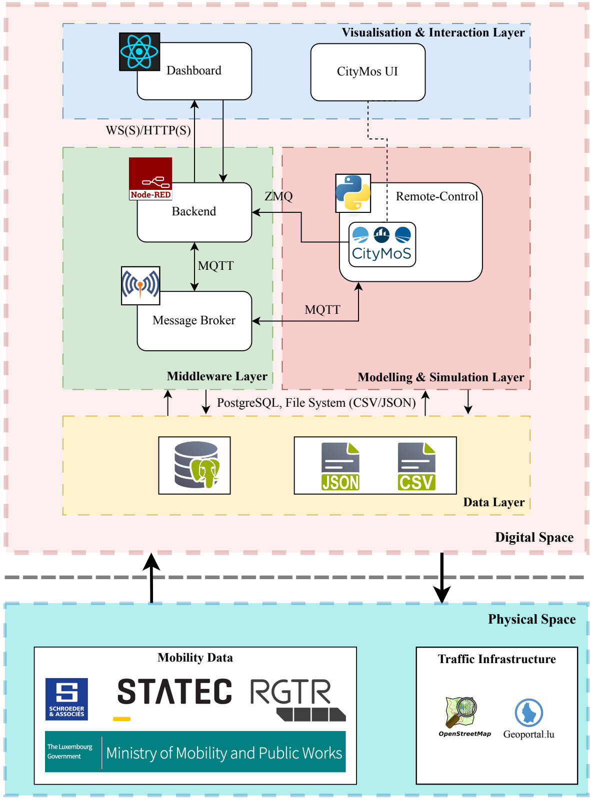

Figure 1. BISTWIN system architecture.

and improve overall traffic safety and efficiency. Yeon et al. [4] propose DTUMOS, a DT designed for urban mobility operating systems. This is a first attempt to build an MDT capable of covering large-scale urban mobility systems. At the heart of DTUMOS is a novel architecture that combines an AI-driven estimated time of arrival model and a vehicle router algorithm to achieve high speed without compromising accuracy.

While prior work has made valuable contributions to MDT research, several limitations remain. Some studies focus on vehicle-level simulations or real-time control of CAVs, with limited attention to large-scale, long-term mobility planning [7, 9]. Others propose conceptual frameworks without demonstrating their applicability in real-world settings [3, 5] or lack integration of public transportation [4].

BISTWIN advances the state-of-the-art in several ways: (i) it provides a validated, high-resolution model of a real industrial zone; (ii) it includes private vehicles, public bus services, and Electric Vehicle (EV) infrastructure, supporting future multi-modal modeling; (iii) and it is designed explicitly for long-term scenario evaluation rather than short-term control. By bridging these gaps, BISTWIN offers a scalable and extensible MPDT framework to support data-driven infrastructure planning and sustainable mobility strategies.

III. BISTWIN SYSTEM ARCHITECTURE

A. *High-Level Architecture*

The BISTWIN MPDT architecture, illustrated in Figure 1, is structured around multiple layers, each playing a crucial role in ensuring seamless data integration, processing, and decision support. The *Physical Layer* serves as the foundation, representing real-world infrastructure, mobility data, and historical datasets that feed into the system. Since this architecture is designed for long-term planning rather than real-time operations, the Physical Layer does not establish continuous feedback loops with real-world entities but instead relies on validated historical records to inform its models.

Above the Physical Layer, the *Data Layer* acts as the central repository, housing structured datasets in PostgreSQL databases and file-based formats like CSV and JSON. This layer serves as the intermediary between raw data ingestion and higher-level processing, ensuring consistency, accessibility, and efficient querying of information.

The *Middleware Layer* acts as an intermediary between the simulation and visualization. It facilitates seamless communication between those components using MQTT and ZMQ message brokers, and aggregates raw simulation data in real-time ensuring smooth and efficient visualization of key metrics. The *Modeling & Simulation Layer* processes the mobility data, creates the MPDT models, and runs scenario-based simulations to evaluate urban planning strategies, such as public transport optimization and electrification trends. Finally, the *Visualization & Interaction Layer* provides a user-friendly interface, allowing stakeholders to interact with the simulation results and assess different planning scenarios.

B. Physical Layer

The input data provided by the Physical Layer is described in Table I. Traffic infrastructure information is sourced from OpenStreetMap and Geoportal, Luxembourg's official platform for governmental geodata and services. These sources provide a detailed representation of the road network, including intersections, road classifications, and public transport stops. Additionally, mobility within the industrial zone is analyzed using traffic counting data obtained from the "Administration des Ponts et Chaussées" portal[1]. We identified five traffic counters strategically placed on motorways and national roads surrounding the industrial zone of Bissen, as detailed in Table I. Further refining the model, local traffic surveys conducted between March 15-21, 2023, by Schroeder & Associates and the municipality of Bissen contribute granular insights into movement patterns within the industrial zone.

To accurately represent vehicle composition, statistical data from STATEC[2], Luxembourg's official statistics service, is utilized. We extracted a dataset covering January to October 2023 that details vehicle registrations by type, including private cars, heavy-duty vehicles, and the proportion of internal combustion versus electric vehicles.

Public transport infrastructure and usage are integral to the Physical Layer. Data from the regional public transport operator, RGTR-Network, provides a comprehensive overview of available bus routes and schedules, allowing for an assessment of public transport integration within the broader mobility system.

[1]https://travaux.public.lu/fr/infos-trafic/comptage.html

[2]https://statistiques.public.lu/en.html

Table I
INPUT DATA DESCRIPTION.

Data Type	Description	Provenance
Traffic infrastructure	Road network, buildings, car parking, bus stops, traffic lights, rivers, and woods within the geographical area of the industrial zone in Bissen.	OpenStreetMap, Geoportal
National traffic counters	Counting of road traffic data from five counters installed around the Bissen industrial zone on motorways and national roads: 495, 501, 511, 705, 710.	APC Portal
Bissen traffic counters	Counting of road traffic data from two counters installed inside the Bissen industrial zone between March 15-21, 2023.	Schroeder & Associates
Vehicle types	Number of new registered vehicles in Luxembourg per vehicle and motor type between January 2023 – October 2023.	STATEC
Bus timetable	Bus timetable and itineraries for the following lines: 119, 936, 937, 941.	Régime général des transports routiers (RGTR)

C. Data Layer

The Data Layer ensures the compatibility of Physical Layer data with the Simulation Layer, acting as an intermediary between the two. It consists of two main components: **data preprocessing** and **simulation output management**. The first component processes incoming data through three key steps:

- **Data Wrangling** – Raw data from various sources, such as Excel sheets, web data, PDFs, and GPX files, is converted into structured formats like CSV and JSON to ensure consistency and usability.
- **Data Filtering** – Only the relevant data required for the simulation of the industrial zone in Bissen is extracted, removing unnecessary or redundant information.
- **Data Mapping** – Each data point from the Physical Layer is mapped to its corresponding virtual representation, ensuring accurate alignment with the Simulation Layer.

The second component manages the output data from CityMoS, the mobility simulation platform. It maintains a 24-hour rolling record of key mobility metrics – such as parking occupancy, average vehicle speed, and traffic density – within the industrial zone. This data is securely stored in a PostgreSQL database, enabling efficient querying, analysis, and long-term mobility insights.

D. Modeling & Simulation Layer

This layer is responsible for generating and instantiating the MPDT models, executing "what-if" simulation scenarios, and producing relevant output data. At its core, BISTWIN relies on the City Mobility Simulator (CityMos) engine [10], a high-performance, multi-core, agent-based, microscopic mobility simulator and DT solution. CityMos was chosen over other popular simulators (e.g., SUMO, MATSim, Aimsun) due to its unique combination of features: it supports multi-agent simulation at full microscopic scale, handles city-wide networks with high spatial and temporal resolution, and natively integrates heterogeneous transport modes, including private vehicles, logistics fleets, and public transportation. Unlike many existing tools, CityMos is natively multi-core and optimized for parallel execution, enabling efficient simulation of large-scale, high-fidelity scenarios. Moreover, it provides flexible APIs for integration with external models, and a modular architecture that aligns with the layered structure of our MPDT. These features make CityMos particularly well suited for planning-oriented DT implementations such as BISTWIN, where scalability, detail, and extensibility are essential.

The BISTWIN simulated scenario spans approximately 60 km^2, with the 20 km^2 industrial zone positioned centrally within the modeled area. The models simulate mobility patterns over a 24 h period, representing a typical working day. CityMos processes structured data from the Data Layer to instantiate three key MPDT model categories: **Infrastructure models**, which include representations of the road network, buildings, car parks, EV charging stations, and traffic lights; **Mobility models**, which define zonal demands, traffic itineraries, vehicles, and driver behaviors; and **Public transportation models**, which encompass bus stops, depots, terminus stations, schedules, and individual bus agents.

To improve the accuracy of the traffic representation, a calibration process was conducted by defining 35 virtual zones. Of these, 14 zones subdivide the industrial area, allowing for a granular representation of traffic dynamics, while the remaining 21 zones represent external areas that interact with the industrial zone. This calibration process involved the construction of an Origin-Destination (O/D) matrix for the traffic flow, ensuring that the simulated traffic flows are consistent with the real data collected from Bissen and national traffic counters, as referenced in Table I.

E. Middleware Layer

This layer serves as a critical intermediary between the simulation and visualization layers. It provides an API to static reference data, such as street network, car parks, or bus stations. It also aggregates real-time simulation events received via ZMQ and historical simulation events stored in PostgreSQL. This enables replay and visualization of past or pre-simulated scenarios, allowing for comparison of different simulation outcomes. Moreover, built on Node-RED, the layer provides a low-code environment that simplifies future extensions, allowing for an easy implementation of additional data aggregation flows to support new metrics. This ensures flexibility and scalability as the system evolves.

F. Visualization & Interaction Layer

The BISTWIN architecture includes a web-based Visualization & Interaction Layer, developed using React on a Node-RED server, combining modular UI components with dual-mode functionality. The framework supports real-time analysis via HTTP/WebSocket protocols for live simulator data (e.g., vehicle positions, dynamic graphs) and historical replay via HTTP-based database queries, ensuring efficient resource utilization. Performance optimizations include caching mechanisms and Redux state management to maintain consistent data rendering across modes.

(a) Dashboard capture

(b) CityMos UI capture

Figure 2. The two components of the Visualization & Interaction Layer.

The implementation uses color-coded zones (dynamically scaled gradients) and ChartJS plots to display aggregated metrics, while a unified Node-RED API fetches GeoJSON, vehicle data, and time-framed statistics for processing via Redux (see Figure 2a). Key features include interactive exploration via zone filtering and time-based data handling, scalability via adaptive color gradients for variable zone counts, and business-focused tools for highlighting efficiency metrics. This dual-mode architecture (live simulation or historical analysis) provides an intuitive, scalable platform for analyzing urban mobility patterns and improving decision-making by bridging real-time and retrospective insights.

Finally, this layer includes the CityMoS UI, a high-performance graphical user interface that enables real-time visualization of the simulation state within a dynamic 3D environment (see Figure 2b). The 3D frontend allows users to analyze traffic on both macroscopic and microscopic levels, leveraging built-in tools to assess overall flow while also observing individual vehicle movements and driver behavior in detail. Beyond traffic visualization, CityMoS enhances realism by incorporating visual representations of active and passive infrastructure elements, including parking facilities, buildings, bus stops, depots, and rail stations.

IV. SCENARIO EVALUATION AND VALIDATION

A. MPDT Validation

To validate the MPDT models, we use the five national traffic counters and two counters inside the industrial zone, as described in Table I, considering traffic flow in both directions. This results in a total of 14 measurement points. At each location, we compare the synthetically generated traffic flow

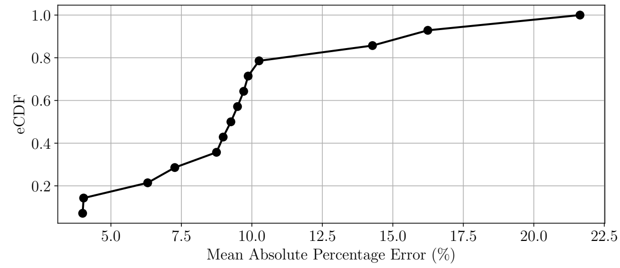

Figure 3. eCDF of MAPE values comparing simulated and real traffic data.

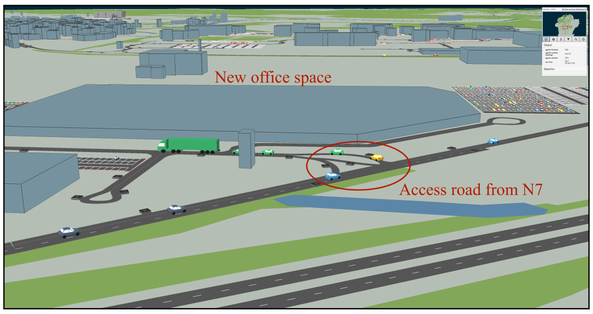

Figure 4. New planned office space with only access from national road N7.

(veh/h) obtained from our calibrated MPDT models over a 24 h period ($T = 24\,\text{h}$) against real-world observations. Let s_t^i represent the simulated traffic flow and r_t^i the real traffic flow at measurement point i and time t. The Mean Absolute Percentage Error (MAPE) is then computed as follows:

$$\text{MAPE} = \frac{1}{T}\sum_{t=1}^{T}\left|\frac{s_t^i - r_t^i}{r_t^i}\right| * 100 \quad (1)$$

Figure 3 presents the empirical Cumulative Distribution Function (eCDF) of the MAPE values for all 14 data points. As observed, 70 % of the measurement points have an error of less than 10 %, with a maximum error of 21.64 %. These results confirm the accuracy of our calibrated MPDT model.

Notably, the four highest errors exceeding 10 % correspond to the two counters within the industrial zone. This suggests that incorporating additional measurement points within the industrial zone could further refine the model's accuracy by capturing more localized traffic dynamics.

B. Scenario 1: Infrastructure Planing

This scenario evaluates the impact of future infrastructure expansions by analyzing the addition of new office spaces and corresponding parking facilities in the industrial zone. The planned development features a single entry/exit point connected to the national road N7 (see Figure 4). The MPDT infrastructure models were updated based on actual development plans provided by the municipality of Bissen to reflect the anticipated changes.

To assess the effects on traffic flow around the entry/exit point of N7, we modified the original O/D matrix to account for the additional commuting demand. The newly introduced traffic follows a normal distribution for both arrival and departure times, with morning inflows between 07:00 and 09:00, centered at 08:00, and evening outflows between 16:00 and 18:00, centered at 17:00.

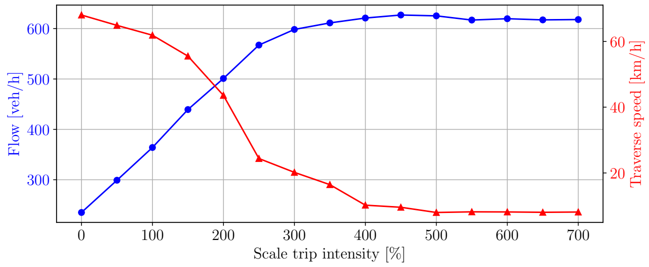

Figure 5. Average flow and speed vs scale trip intensity.

Figure 5 presents the measured traffic flow and average traverse speed on the lane entering the new development from the northeast side, under varying levels of trip intensity. In this scenario, a 0 % trip intensity represents the baseline condition with no additional traffic. The results indicate that for trip intensities between 0–200 %, vehicles maintain free-flow speed. However, when trip intensity exceeds 400 %, the area experiences full congestion. These findings provide insight into the capacity limits of the planned infrastructure and its potential impact on traffic conditions along N7, helping stakeholders refine urban mobility strategies accordingly.

C. Scenario 2: New Electromobility Services

This scenario showcases BISTWIN's capability to support the design and evaluation of new electromobility services. In collaboration with Emile Weber, a Luxembourg-based bus company, we identified public transportation gaps within the industrial zone. To enhance accessibility and encourage public transport use, we simulate a new electric shuttle bus service, connecting the Mersch train station (south of the industrial zone) to key areas within the zone.

The electric shuttle service is synchronized with the regional train from Luxembourg City to Mersch, operating from 05:00 to 22:30 with 30-minute intervals and 23 stops per round trip. Each bus in the model is a 14-seat electric vehicle, accurately reflecting an actual bus from Emile Weber's fleet, including size, passenger capacity, battery specifications, and charging behavior. A new bus is deployed only when the existing fleet cannot meet the schedule, allowing us to analyze both battery consumption over time and the number of buses required to sustain operations efficiently.

Figure 6 illustrates the State of Charge (SOC) over time for each deployed bus. Initially, two buses operate in the morning. However, by midday, an additional bus is required to maintain the schedule. Later in the evening, around 21:00, a fourth bus is deployed as the SOC of the earlier buses becomes insufficient to complete the day. These findings suggest that fleet deployment could be optimized by strategically charging buses during low-demand periods, even before the battery is fully depleted. Such an approach could sustain operations with only three buses instead of four, improving energy efficiency and resource utilization.

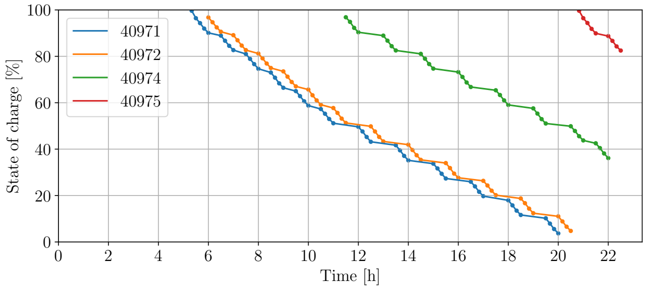

Figure 6. SOC of electric bus batteries over travel time. Each line represents an individual deployed bus.

V. Limitations of the Proposed MPDT

While the BISTWIN MPDT provides a robust framework for mobility simulation and decision-making, its current implementation is primarily focused on transportation planning within the Bissen industrial zone. To evolve into a multi-purpose DT, several key aspects require enhancement.

First, interoperability is essential to integrate diverse data sources and domains such as energy management, environmental monitoring, and socio-economic analysis [11, 12, 13]. Standardized data exchange protocols and semantic frameworks could facilitate cross-domain interactions, enabling the MPDT to support broader urban planning efforts [14].

Second, real-time data integration remains a challenge, as the current system relies on historical data for simulations [15, 16]. Incorporating IoT sensors, satellite imagery, and AI-driven analytics would enable real-time monitoring and dynamic decision support, enhancing the adaptability of the MPDT to evolving urban conditions.

Lastly, achieving interconnected DT networks is crucial for scalability and collaboration. By linking the BISTWIN MPDT with regional and national DTs, the system could support multi-modal transport coordination, smart grid management, and climate adaptation strategies. Aligning with initiatives such as Local Digital Twins (LDTs) from the European Commission would further enhance interoperability and broaden the impact of DT-driven urban development.

VI. Conclusion

In this paper, we presented BISTWIN, a Mobility Planning Digital Twin (MPDT) designed to address the mobility challenges in the industrial zone of Bissen, Luxembourg. Our work demonstrated how MPDTs can be used to support long-term mobility planning with data-driven insights and scenario-based evaluations. We developed a robust MPDT architecture that integrates historical traffic data, mobility modeling, and high-resolution microscopic simulations, providing a scalable and adaptable framework for urban mobility management.

The validation process showed that our calibrated MPDT models achieve high accuracy, with 70 % of the measurement points exhibiting an error of less than 10 %, confirming its reliability for decision-making. Furthermore, the infrastructure planning scenario illustrated the potential impact of new developments on existing road networks, identifying capacity thresholds and congestion risks. The new electromobility services scenario demonstrated how our MPDT can support the introduction of electric shuttle services, optimizing fleet deployment and energy efficiency.

Future work will focus on expanding our MPDT capabilities by integrating real-time data sources and dynamic traffic control strategies to further improve planning accuracy and operational effectiveness.

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