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Digital twin federation for urban mobility assessment: Definition, pillars, and a human-in-the-loop functional architecture

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ABSTRACT

Urban mobility systems face growing challenges. While various smart mobility solutions have been proposed, there is still a lack of comprehensive tools for assessing the impact of these solutions in a dynamic and iterative manner. Recent literature increasingly adopts the Digital Twin (DT) concept. However, DTs have conventionally been framed around automating solutions, which often conflict with the requirements of human-driven planning in socio-technical systems, leading to ambiguities in how DTs should be defined and operationalised for mobility planning. To fill this gap, this paper presents the concept of a Digital Twin Federation (FedDT) designed for comprehensive urban mobility assessments. Firstly, a definition of the FedDT concept is established based on four conceptual pillars, including physical & digital system exchange, system monitoring & planning, outcome evaluation & immersive experience, and human-in-the-loop control. Building on the concept and 5 stakeholder co-design sessions, we present a functional FedDT architecture that enables iterative, bidirectional data exchange between the physical and digital mobility systems, thereby supporting a data-driven decision-making process while ensuring the interests of stakeholders are continuously integrated. Finally, we demonstrate how the FedDT architecture can be instantiated through a proof-of-concept application framework. This framework serves as a research agenda that guides and links the development of separate modules to reduce private vehicle dependency in Amsterdam, the Netherlands. Overall, this work lays a conceptual and architectural foundation for FedDT, advancing the implementation of integrated digital twin solutions for sustainable mobility systems.

1. Introduction

As cities and urbanised areas continue to attract more residents, urban mobility systems face numerous challenges, such as congestion, transport emissions, and the lack of accessible spaces (Li et al., 2024b). In response, a wide range of interventions and service-oriented solutions have been proposed. However, understanding the extent to which combinations of these interventions can influence existing urban mobility systems remains a challenge. Conventionally, planners have relied on historical data analysis and traffic simulations to anticipate such impacts. Yet, new interventions can trigger dynamic transitions shaped by evolving travel

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behaviour, network interactions, and stakeholder decision-making (Belfadel et al., 2023; van Arem et al., 2022). Conventional tools remain largely static and fragmented, and are therefore becoming increasingly inadequate for such iterative, system-wide mobility assessments.

In response to these limitations, digital twins (DTs) have gathered increasing attention as a viable approach. In DTs' original concept, it is defined as *an integrated multi-physics, multilevel, probabilistic simulation of a system that uses the best available data and physical sensors to mirror the life of its corresponding [physical] twin* (Glaessgen and Stargel, 2012). However, this original concept was primarily developed for engineering systems (e.g. aerospace and manufacturing), where high-fidelity replication of automated monitoring is mostly a common design goal. Such requirements can be too rigid for socio-technical systems like urban mobility, which involve substantial human elements (Batty, 2018). Consequently, over the past decades, although relevant DT research for mobility systems is emerging, existing implementations typically focus on specific application contexts with varying levels of sophistication (Zomerdijk et al., 2024). Examples include DT related to 3D modelling of mobility infrastructures (White et al., 2021) or PT (Public Transit) supervision (Amrani et al., 2020). Yet, mobility systems are inherently multidisciplinary, involving interactions between travellers, land use, and mobility services. When deployed in isolation, such singular DT implementations are often inadequate for comprehensive evaluation of interventions and their impacts on the broader urban mobility system.

Rather than building a monolithic DT from scratch, van Arem et al. (2022) outlines the concept of Digital Twin Federation for urban mobility assessment (FedDT). Note that the concept of FedDT is not proposed as a wholly new requirement; rather, it is framed as a standardising approach that builds on **existing** data, methods, and DT instances by structuring them within a classic feedback-control loop (Wiener, 2019) linking the physical urban mobility system with its digital counterpart, facilitating model-based scenario development and intervention implementations for continuous and iterative analysis. However, for the broader adoption of the FedDT concept, two gaps remain: First, an exact definition and key features of FedDT remain unclear in the literature (Bao et al., 2021; Schnieder et al., 2024), which is essential for clarifying the differences between FedDT and existing tools. Second, a unified FedDT architecture is also lacking but would be immensely helpful for guiding separate module development, data transformation and module interaction (Wang et al., 2022a; Fan et al., 2022; Belfadel et al., 2023; Nwogu et al., 2022). The challenge associated with building such a FedDT architecture is that urban mobility is a socio-technical system in which problem formulation, intervention design, and evaluation criteria are shaped by multiple stakeholders and domains of expertise (Bruynseels et al., 2018). Accordingly, a FedDT architecture should not only orchestrate heterogeneous modules and structure their information flows, but also specify where and how expert knowledge and stakeholder input enter the federated workflow as meaningful human-in-the-loop control points.

This research addresses the aforementioned gaps through four key contributions.

- We review the state-of-the-art development of DTs, with a specific focus on urban mobility.
- Based on the literature, we identify four key pillars (and associated features) that distinguish a FedDT from conventional mobility planning tools and existing DT studies, and synthesise these into a domain-specific definition of FedDT for urban mobility assessment.
- Based on the definition and 5 co-design sessions with a consortium of mobility stakeholders and DT experts, we propose a functional FedDT architecture that specifies the information flows and interconnections among federated modules, including explicit human-in-the-loop control points.
- We demonstrate how the proposed FedDT architecture can be instantiated in a real-world context by presenting a proof-of-concept application framework, serving as a research agenda for regions transitioning towards reduced Private Vehicle (PV) dependency.

The remainder of this paper starts with the literature review in Section 2; Then, we describe four pillars (with their features) along with a definition of the FedDT in Section 3; Section 4 explains how different modules interact to form a unified functional FedDT architecture. Furthermore, in the same section, based on real-world data and tools, we present a proof-of-concept application framework of the proposed FedDT architecture as a research agenda for the deployment of FedDT in Amsterdam, the Netherlands. The paper finishes with a discussion and future works in Section 5 and a conclusion in Section 6.

2. Literature review

The concept of a DT originated in aerospace engineering by NASA during the 1960s (Glaessgen and Stargel, 2012), which defines three primary components of a DT: the physical world, virtual world and the exchange of information between the two systems. Recently, the DT concept has been expanded to various domains with different terminologies and applications, such as manufacturing, healthcare, automotive, construction and power systems (TAO et al., 2024). As DT becomes more domain-specific, DT architectures tailored to specific fields are usually necessary to identify commonalities across applications and ensure consistency across separate DT modules (Nwogu et al., 2022). For instance, the ISO 23,247 standard proposes a reference architecture for digital twins in manufacturing (Ferko et al., 2023). In power systems, Zomerdijk et al. (2024) introduces a standard DT ecosystem architecture that provides services beyond real-time updates and seamlessly integrates with existing transmission and distribution processes. Yet, these architectures are often either too generic or too specific, making it difficult to transfer them from one domain to another (Belfadel et al., 2023).

Transportation is a fundamental part of cities, enabling the movement of people and goods. Despite the DT concept having been effectively adopted in many fields, in transportation, it is currently applied to a limited range of scenarios. One of the most common DT applications in transport is in infrastructure design and inspection, including railways, highways, bridges and tunnels (Gao et al., 2021). While DTs have been applied to relatively static infrastructure objects in transportation systems, their potential extends further. Urban mobility systems, characterised by more complex and dynamic interactions between human behaviours, multimodal transport networks, and diverse stakeholders, can also benefit from DT applications for real-time monitoring, simulation, visualisation and analysis (van Arem et al., 2022). Recently, a growing body of research has adopted the DT concept to study one or more components of urban mobility systems. For instance, some studies (White et al., 2021; Campolo et al., 2020) focus on developing DTs that provide 3D reproductions of physical entities within urban mobility networks, where planners and citizens can interactively view the changes in buildings, networks, and land uses. However, due to the lack of analytical capability, these DTs fail to capture the connection between physical mobility patterns and the underlying factors influencing them (Caprari et al., 2022).

To support the long-term planning of urban mobility systems, several studies have shifted towards enhancing DTs' analytical capabilities (Yeon et al., 2023; Lv et al., 2022). These approaches employ mathematical models to analyse the underlying interactions between mobility infrastructure and users, thereby providing deeper insights into dynamic mobility patterns and facilitating more informed decision-making. At the same time, the distinction between DT-based research and conventional urban mobility simulations remains ambiguous (Li et al., 2021). This boundary is further blurred with the recent developments of several integrated, multi-model platforms for mobility planning, where coupling traffic simulation with other domains (e.g., energy, land-use) and scales (e.g., micro and macroscopic) is increasingly common to deliver more comprehensive evaluations of the mobility system. For example, BEAM CORE (Laarabi et al., 2023) and POLARIS(Auld et al., 2016) couple activity-based travel demand with agent-based network dynamics for the interaction between transport demand and supply. In addition, their detailed transport outputs can further inform (and vice versa) freight operations and energy-related assessments. Other examples include SimMobility (Adnan et al., 2015) and PILATES (Needell et al., 2024), which support coupled land-use and mobility modelling, thereby enabling long-term what-if analysis of urban and transport system evolution. Nevertheless, the implementation of both single- and multi-modal simulation platforms remains a relatively static process: modellers generate data inputs based on historical data over a long period. After models are calibrated and validated, they remain largely unchanged over time, even after several applications. The static nature of existing transport simulation presents challenges to adapting to state-of-the-art changes in mobility systems or responding to unexpected shifts in mobility behaviours (van Arem et al., 2022). In addition, decision-making in transport simulations primarily relies on the simulation output and engineering expertise, where qualitative factors such as opinions from stakeholders with diverse interests are mostly not explicitly represented. In general, we conclude that transport simulations are the foundation of DT, whereas DT is regarded as the final goal of transport simulation (Bao et al., 2021; Ambra and MacHaris, 2020). Still, how to incorporate transport simulation into DTs with a dynamic feedback loop between physical and digital systems for urban mobility systems remains unclear in the literature (Abouelrous et al., 2023).

Some recent research has advanced more complicated DT implementations by integrating analytical capability, visualisation, and bi-directional information exchange between physical and digital systems into one DT application. For instance, studies have developed DTs for the control and management of intelligent vehicular systems (Ali et al., 2023; Sharafian et al., 2025; Yasir Naeem et al., 2022; Naeem et al., 2024). Wang et al. (2022b) proposes a DT framework for investigating the warning system for connected vehicles between vehicles and pedestrians; whereas Amrani et al. (2020) demonstrates a Public Transport (PT) DT supervision system for a bus lane within a district in Paris. However, it should be noted that these studies primarily concentrate on sub-modules within the urban mobility systems in constrained areas. Thus, they are not capable of offering a comprehensive assessment of the system-wide impacts of mobility interventions.

Urban mobility systems worldwide are confronted with numerous challenges, such as congestion and transport emissions (Li et al., 2024b). Given that several algorithms and DT instances are already available, rather than building everything from scratch, it is more feasible to integrate existing components into a comprehensive framework as a digital twin federation. Nevertheless, unlike other sectors such as manufacturing (Ferko et al., 2023), power systems (Zomerdijk et al., 2024) and urban logistics (Belfadel et al., 2023) - where the essential features of a DT have already been defined and demonstrated in specific contexts, an exact definition of a FedDT for urban mobility assessment is still far from being established (Ketzler et al., 2020). Based on the definitions, developing a unified FedDT architecture for urban mobility assessment would help establish a standardised framework to address the multifaceted challenges of urban mobility. Ultimately, compared to the existing toolkits in urban mobility planning, such a FedDT architecture would offer a more advanced, comprehensive and effective alternative for assessing the impacts of various interventions towards more sustainable and efficient mobility systems.

3. Digital twin federation for urban mobility assessments: 4 pillars & definition

To establish a definition of FedDTs for urban mobility assessments, it is essential to first identify and understand the core features of such a complex system. More recent work has refined the concept of the original DT definition towards a five-dimensional design that covers data collection in the physical world, data representation, data analysis, connectivity and data visualisation and interaction (Grübel et al., 2022). Another key aspect that recent research on DTs has highlighted is the need for separate representations of the physical-to-digital (sensors) and digital-to-physical (actuators) links to fully automate workflows (Thelen et al., 2022). However, the five-dimensional design originates in technical systems, where end-to-end control can mostly be done automatically. In contrast, urban mobility is a socio-technical system shaped by continuous interaction between mobility infrastructure and a diverse range of stakeholders, where meaningful human involvement is indispensable (Yigitbas et al., 2021).

For augmenting typical automated components of DT with human interventions, we extend the generic DT concept into a six-dimensional dual-loop FedDT design in Fig. 1. The right of Fig. 1 illustrates FedDT's concept: the physical mobility system provides data for updating the digital replicas, which, in turn, generate predictive analyses of proposed actuation interventions. We also distinguish different stages of this process between the automated process and human control. Notably, the decision-making by FedDT contains 2 loops: the principal system loop for the bidirectional data exchange between the physical mobility system and its

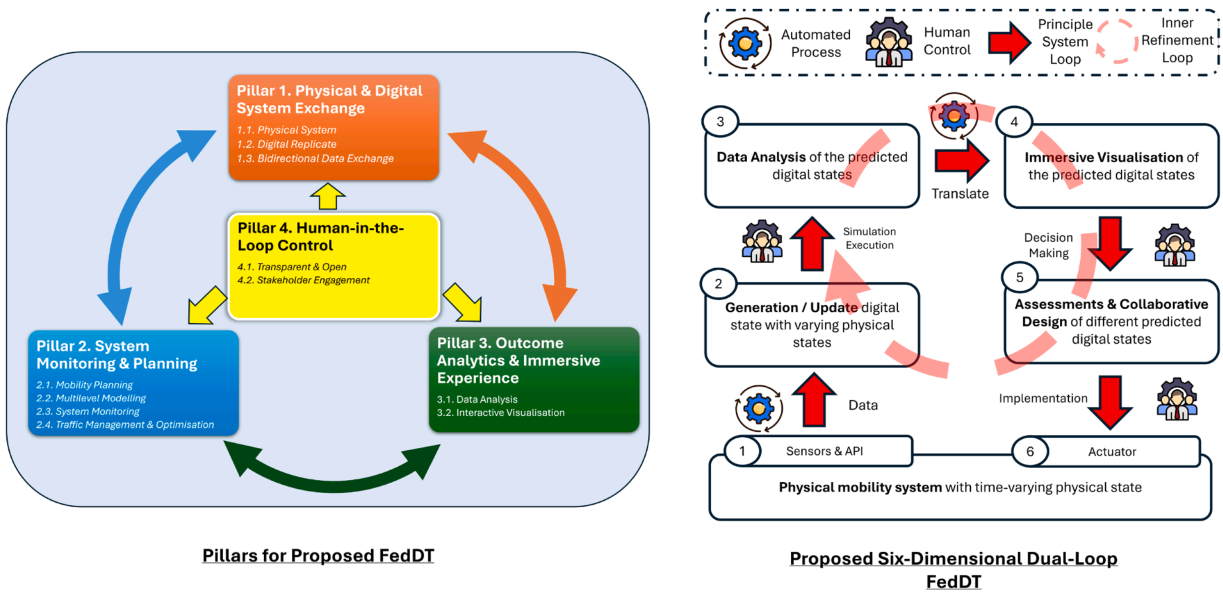

Fig. 1. The conceptual framework for Digital Twin Federations (FedDTs) uses two perspectives to support comprehensive urban assessments. On the left side, the four pillars of FedDT lay out the foundational capabilities that distinguish FedDT from conventional tools in mobility planning. On the right side, building on these pillars, we demonstrate the concept of the six-dimensional dual-loop FedDT, enabling more comprehensive assessment and refinement of interventions for mobility systems.

digital replicate, whereas the inner refinement loop is responsible for systematic evaluation of the impacts of different interventions until a consolidated set of stakeholder-aligned design alternatives is achieved. Furthermore, the left of Fig. 1 illustrates four pillars for the proposed FedDT: the **1) Physical & Digital System Exchange**, **2) System Monitoring & Planning**, and **3) Outcome Evaluation & Immersive Experience** influence one another in a cyclical interplay of information exchange, whereas crucially, they are governed by **4) Human-in-the-Loop Control** throughout the whole FedDT lifecycle. By codifying how human-in-the-loop control works, we also improve transparency in DT systems, where both automated steps and human decisions play a role and support replication. In the coming sections, we will describe these pillars in detail. Finally, synthesising these pillars, Section 3.5 offers a concise, domain-specific definition of the proposed FedDT, thereby establishing a conceptual foundation for the FedDT's system architectural design and implementation.

For benchmarking FedDT relative to state-of-the-art mobility research, in Section 1 of Appendix B Supplementary Material, we compare the 4 proposed FedDT pillars with existing DT studies for urban mobility, highlighting how FedDT offers a more comprehensive assessment capability that is lacking in the existing DT literature. Furthermore, Table 1 provides a structured comparison of state-of-the-art non-DT techniques for mobility planning (e.g., multi-modal mobility simulation, behaviour analysis), summarising their typical outputs and gaps in practice. It then explicitly links these gaps to the FedDT pillars/features, clarifying where the added value lies compared to these techniques.

3.1. *Pillar 1: Physical & digital system exchange*

The **Physical & Digital System Exchange** pillar encapsulates the original definition for DT with three features: *the physical mobility system*, its *digital representation*, plus *the bidirectional information exchange* between them. As demonstrated in Fig. 2, heterogeneous mobility data is collected from the real-world mobility system, such as individual travel behaviours, traffic volumes, mobility infrastructures, and multimodal mobility services. These data are then integrated into the digital replicates, producing a snapshot of the real-world mobility state. This state is used as an input for analytical tools in FedDT. Once preferred interventions are identified after analysis, they will be translated into actionable measures for the real-world mobility system. Hence, **Physical & Digital System Exchange** serves as the foundation for designing, testing, evaluating and ultimately implementing different interventions. Subsequently, the adapted physical mobility system generates new data to restart the cyclical process of FedDT evaluations.

It should be noted that, in real-world implementations, a key challenge in multi-source mobility data ingestion (e.g. sensors, application programming interfaces) lies in the data heterogeneity in factors such as format and sampling frequency. While a full technical solution is beyond the scope of this work, a practical approach is to adopt a resolution-preserving principle, as implemented in the generic Open Digital Twin Platform (ODTP) (Grübel et al., 2023). Essentially, rather than unifying all data into a small set of predefined formats or resolutions, data are ingested and stored at their native granularity. Additional processing components are placed between data ingestion and module execution, then transform the data into the formats and resolutions required by downstream analytical modules.

Table 1
Benchmarking state-of-the-art techniques in mobility planning and the added value of FedDT.

Technique	Typical outputs	Example methods	Gaps in practice	Primary FedDT Pillars/Features addressing gaps
Mobility simulation	Mobility system performance indicators (e.g., flows, mode shares) with spatio-temporal congestion patterns; cross-scenario comparison.	Trip-based models; activity-based models; agent-based models.	Limited continuous updating; limited cross-system interactions; human interventions remain implicit.	Physical & Digital System Exchange; Multilevel Modelling; Stakeholder Engagement.
Integrated multi-model simulation	Beyond mobility-only outputs, bidirectional cross-domain impacts (e.g., energy/land use) for what-if analysis beyond transport-only KPIs.	Platforms such as BEAM CORE; POLARIS; SimMobility.	Limited continuous updating; human interventions remain implicit; outputs hard to interpret for non-experts; limited support for optimal intervention design.	Physical & Digital System Exchange; Mobility optimisation; Interactive Visualisation; Stakeholder Engagement.
Mobility optimisation	Optimal intervention designs/policies; Pareto frontier; sensitivity across objectives and constraints.	NSGA-II; simulation-based optimisation; metaheuristic search.	Often zone-aggregated with limited behavioural/spatial granularity; may miss system-wide ripple effects beyond objectives; outputs hard to interpret for non-experts.	Multilevel Modelling; Interactive Visualisation.
Mobility Behaviour analysis	Behavioural parameters (e.g., value of time, preferences); personas/segments; responses under mobility interventions.	SP/RP surveys; discrete choice models; focus groups; qualitative analysis.	Limited translation from individual behaviours to system-wide mobility impacts; Limited continuous updating; limited support for optimal intervention designs.	Multilevel Modelling; Mobility optimisation.
Stakeholder Collaborative Planning	Stakeholder-ranked design alternatives; Qualitative KPIs and design alternatives.	Co-design workshops; 3D or XR-based Visual Evaluations; Multi-criteria Analysis.	Feedback is often perception-led with limited quantitative support; limited KPI-quantified trade-off assessment.	Physical & Digital System Exchange; Mobility optimisation; Multilevel Modelling; Mobility Data Analysis.

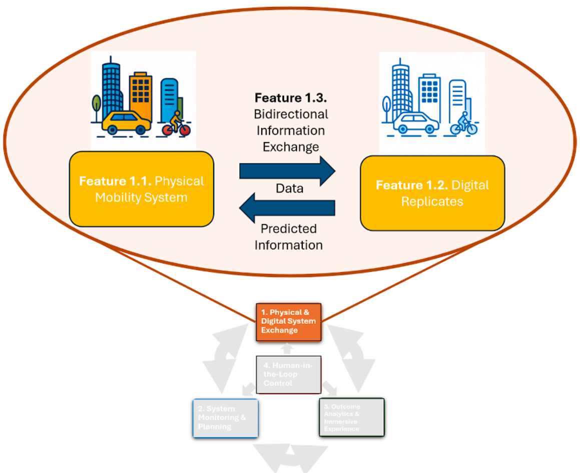

Fig. 2. Information exchange between physical mobility system and digital replicate as defined in features 1.1 to 1.3 of the first pillar.

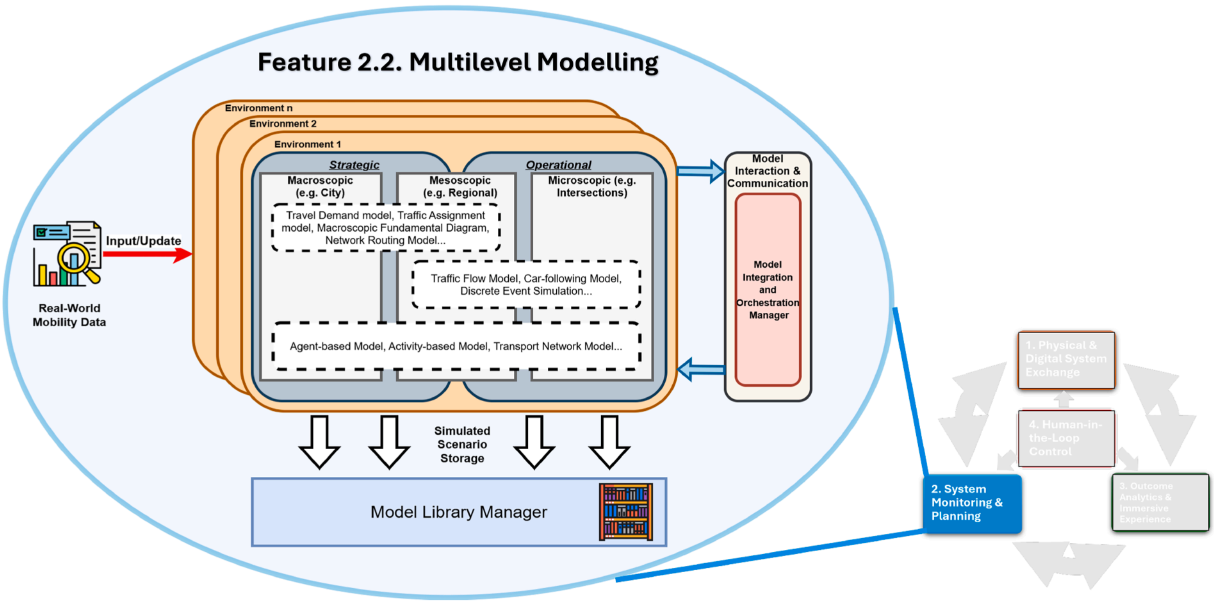

Fig. 3. Multilevel mobility simulation for mobility planning as described in feature 2.2 of FedDT. We also listed potential modelling techniques depending on the appropriate simulation scales in detail.

3.2. Pillar 2: System monitoring & planning

Comprehensive assessments of the impact of interventions on the mobility system are a key goal of FedDT. However, to understand interventions, we require both advanced analytical capability and an in-depth understanding of the current and predicted state to draw insights from the impact interventions could have. The second pillar of the FedDT is **System Monitoring & Planning**, which supports mobility planners with four features: *mobility planning*, *multilevel simulation*, *system monitoring* and *traffic management & optimisation*.

3.2.1. Features 2.1 & 2.2: Mobility planning and multilevel modelling

Supporting *mobility planning* is a critical ability for the FedDT by predicting the impact of multiple interventions on different aspects of urban mobility systems at different timescales. Conventionally, planners rely on simulation for performing such what-if analyses. Yet, urban mobility is a multilevel phenomenon with complex feedback loops connecting hierarchical systems at different spatial, temporal, and behavioural levels. Therefore, for the proposed FedDT, *Multilevel Modelling* is also necessary to ensure that each component within the mobility system can communicate and collaborate within the digital system-of-system (Czekster et al., 2024).

As demonstrated in Fig. 3, multilevel modelling simulates mobility systems in different environments (orange blocks), which represent factors not part of the mobility system but indirectly influence its operation (Sami Irfan et al., 2024), such as workdays and weekends. Within each environment layer, simulations vary by modelling scales and techniques are coupled to ensure a comprehensive understanding of mobility behaviours under specific contextual conditions. Strategic models primarily concern long-term decisions, whereas operational models focus on managing short-term operations. Most importantly, each simulation will be managed by the *Model Integration and Orchestration Manager* (MIOM) to facilitate connections and communication between simulations (Li et al., 2025). Compared to single-layer simulations at specific timescales, multilevel modelling delivers substantial benefits for comprehensively evaluating intervention impacts across different horizons. For example, a standalone mesoscopic simulation could efficiently evaluate the system-level impact of an intervention across an entire city but lacks detailed granularity (e.g. at specific intersections), whereas a microscopic simulation can be used to understand detailed interactions within the constrained study areas but typically requires detailed traffic flow data that is often unavailable in the real world. Within the FedDT, outputs from the macroscopic model can serve as complementary inputs to the microscopic model, enabling high-resolution analysis of mobility behaviours under the proposed intervention.

Such data exchange across scales and environments in the FedDT not only fills empirical data gaps but also ensures analytical scalability (Belfadel et al., 2023). While the detailed MIOM technical implementations are beyond the scope of this work, there are typically three established design patterns (Brugière et al., 2022): 1) the zoom pattern, which uses transition functions to aggregate and disaggregate data between levels and executes simulations sequentially; 2) the Russian doll pattern, which runs levels in parallel but requires tight coupling and monolithic integration between simulations; and 3) the collaborative pattern, where different levels directly feed each other inputs in a concurrent simulation environment. As each pattern offers different advantages and limitations, the multilevel coupling of MIOM could be realised through existing tools such as ODTP (Grübel et al., 2023), where models' interconnections are established according to the Open Digital Twin Workflow Standard (ODTWS) (Grübel et al., 2024). In this setting, ODTWS supports both zoom-style sequential coupling and collaborative exchanges between models. Over time, the set of available bridges between simulators can be expanded, thereby increasing the number of systems that can interoperate within the FedDT federation.

3.2.2. Features 2.3 & 2.4: System monitoring and traffic management & optimisation

Besides generating/updating the multilevel modelling, the real-world mobility data ingested into the FedDT should also support two additional functions for *System Monitoring* and *traffic management & optimisation*. Firstly, these data should be continuously analysed to monitor the performance of the mobility system. If disruptions (e.g., errors, unexpected events, emergencies) are detected after a configured threshold, the FedDT should immediately notify relevant users to take corrective action (Ivanov et al., 2020; Abouelrous et al., 2023). Furthermore, the real-time data could also be utilised for traffic management and mobility system optimisation, such as adaptive traffic control, traffic flow prediction (Ali et al., 2025a), real-time traffic scheduling and routing, accident prediction & management, and mobility system optimisation.

Additionally, by integrating the outcome of traffic management and optimisation as interventions into FedDT's multilevel modelling simulation, planners could comprehensively test their impacts across all relevant performance dimensions under varying simulation scales and environmental conditions. Thereby, FedDT enables more holistic designs than existing tools alone. While conventional optimisation algorithms focus on finding the optimal solutions for a set of specific objectives under given constraints, they do not account for how the optimal solutions affect the wider mobility systems across broader performance dimensions. Hence, FedDT delivers more comprehensive data-driven evidence supporting mobility decision-making in the context of real-time management by integrating it into long-term planning.

3.3. Pillar 3: Outcome evaluation & immersive experience

To transform the disaggregated outcomes from analytical modules into knowledge and insights that guide decision-making for mobility stakeholders, we present the third pillar of the proposed FedDT: **Outcome Evaluation & Immersive Experience**. Unlike conventional tools, where outcome demonstration mainly stands for “display generated information from analytical modules to users”, Pillar 3 comprises two interrelated features: *data analysis* and *interactive visualisation*.

3.3.1. Feature 3.1: Data analysis

The *data analysis* feature primarily concerns access to the interpretation of data processed by FedDT. This provides aggregation of data generated from analytical models in pillar 2 to interpret four analysis dimensions: descriptive, diagnostic, predictive and comparative (Zomerdijk et al., 2024). The descriptive analysis component aggregates raw data to provide an overview of mobility patterns in the physical mobility system. Then, the diagnostic analysis component examines the underlying correlations among factors to identify the “reasons and results” behind observed aggregated patterns. For instance, is the increase in traffic congestion due to a surge in travel demand in specific regions or a systemic lack of road infrastructure across the entire network? Next, the predictive component primarily addresses the question of”what will happen” to project future trends in the mobility systems. Last but not least, regardless of planning or monitoring, the comparative component is essential for cross-analysing the different scenarios in the digital system. For example, trade-off evaluations of potential benefits and drawbacks between different simulated scenarios.

3.3.2. Feature 3.2: Interactive visualisation

With the insights generated from *data analysis*, the *interactive visualisation* feature serves as the primary interface between FedDT users and the underlying digital system. As demonstrated in Fig. 4, visualisation in the proposed FedDT should facilitate a two-way communication loop. Specifically, the arrow from digital information to human insights (left to right) represents the transmission of analytical outcomes into comprehensible insights. On the other hand, the *interactive visualisation* also enables the incorporation of human experiences and perception of the tested scenarios as digital information into FedDT's final decision-making process (indicated by the right-to-left arrow in Fig. 4). The first channel is through interactive dashboards, which allow stakeholders to directly adjust simulation configurations to experiment with different mobility interventions and receive real-time feedback on potential impacts.

Additionally, the second channel is the adoption of immersive reality (XR). Some recent mobility research has adopted XR for understanding urban mobility systems (Xu et al., 2022; Feng et al., 2024) and have illustrated three primary advantages of XR compared to conventional approaches: allowing more realistic assessments of multiple and simultaneous mobility conditions, identifying attributes that can only be captured through direct user experience or actions from others, and without violating individual privacy (Agudelo-Vélez et al., 2021; Papyshev and Yarime, 2021; Yin and Cherchi, 2024). In much of the existing research, the application of XR tends to be limited to demonstrating or surveying mobility phenomena, rather than being comprehensively embedded into the final decision-making process. By making the interaction with data experiential, XR provides more intuitive modes of comprehension that can help underpin co-design. Therefore, the proposed FedDTs offer a potential avenue to integrate XR into the decision-making of mobility research: data from selected scenarios under mobility interventions is embedded in high-fidelity visualisations to generate relevant XR-based environments that reflect potential changes. Relevant mobility stakeholders could be invited to experience the XR-based simulation environments and offer feedback on their acceptance, behavioural shifts, and perceptions of the proposed interventions. The feedback is collected as digital information and serves as an important factor for final decision-making. Integrating XR into the proposed FedDT is particularly important because, while simulations offer analytical capabilities via mathematical models, it is difficult to capture all aspects of urban mobility shifts (e.g., personal preferences, real-time interactions) across different individuals or groups. Therefore, XR could complement model-based outputs by providing more realistic, nuanced inputs to represent shifts in individual behaviours under the proposed interventions, enabling more comprehensive decision-making in urban mobility systems.

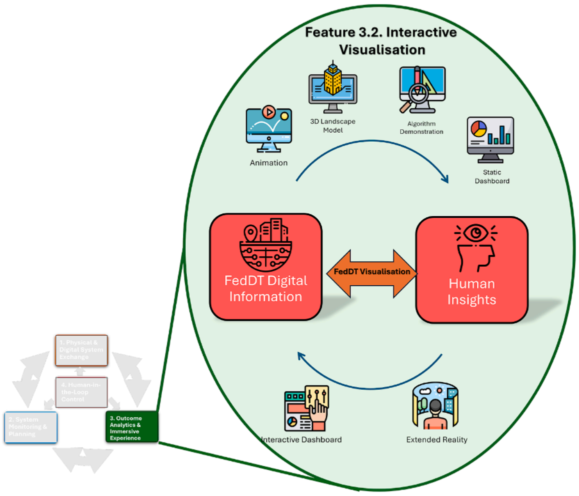

Fig. 4. Interactive visualisations as described in feature 3.2 of FedDT.

3.4. Pillar 4: Human-in-the-loop control

One common misconception about DTs that the FedDT addresses is that they are designed to be purely autonomous for system optimisation and decision-making. Consequently, several existing urban mobility DT studies overlook human participation throughout the DT lifecycle (Fan et al., 2022; Faliagka et al., 2024). However, recent research on DTs' application in other domains has highlighted the need for human-in-the-loop control (Yigitbas et al., 2021). For urban mobility systems, which are shaped by the continuous interaction between mobility infrastructure and a diverse range of stakeholders, **human-in-the-loop control** becomes even more crucial as a pillar for the proposed FedDT (Yigitbas et al., 2021). Opening automated workflows within digital twins to human intervention, using a human-in-the-loop control pattern, combines the strengths of DT automated procedures with the accountability of stakeholder engagement. Pillar 4 is in charge of interacting and monitoring with pillars 1 to 3 for informed decision-making, whereas two features are identified, namely *Transparent & Open* and *stakeholder Engagement*.

3.4.1. Feature 4.1: Transparent & open

The *Transparent & Open* feature requires that all components within the FedDT - including its architecture, adopted data, analytical workflows and software modules, plus generated outputs - should be developed, published and maintained as openly as possible. *Transparent & Open* enhances FedDT's interoperability and transferability, facilitating integration, communication, and collaboration among developers and policymakers. The urban mobility planning community already has a rich ecosystem of open-source data (e.g., household travel surveys, OpenStreetMap) and toolkits (e.g., MATSim (Horni et al., 2016; Li et al., 2024a)), which serve as a foundation upon which the proposed FedDT can build, extend, and incorporate.

3.4.2. Feature 4.2: Stakeholder engagement

The *stakeholder Engagement* feature stands for common channels where stakeholders could communicate with FedDT to decide the proper assignments to perform (Cuñat Negueroles et al., 2024). The stakeholders comprise citizens, FedDT users, mobility planners, mobility service providers, and all other relevant parties who could potentially be affected by different mobility interventions. Specifically, five engagement channels have been identified as follows. While some of these channels are inspired by established planning practice, the contribution here is to embed them within a single FedDT ecosystem as explicit feedback mechanisms, thereby formalising where stakeholder engagement enters the federated modules designed for socio-technical mobility systems. This helps ensure that the FedDT remains effective and inclusive throughout its operational lifecycle.

1) *Problem Definition & KPI Identification*: When using the FedDT, it is necessary to work with stakeholders to define the exact problems to be addressed and the Key Performance Indicators (KPIs) that reflect their priorities. The KPIs drive the design and updating of the relevant FedDT modules (e.g. the multilevel modelling) so that the FedDT can accurately measure what matters most to stakeholders. Simultaneously, stakeholders also collaboratively decide on initial mobility interventions to evaluate. Such a scoping phase lays the seed for the inner refinement loop throughout the FedDT lifecycle for sparking the development and refinement of final interventions;

2) *Corrective Actions under Disruption*: When the respective modules for system monitoring detect disruption (e.g. errors, unexpected events, emergencies) that exceeds predefined thresholds, relevant stakeholders are immediately notified and determine the most appropriate remedial solutions;

3) *Visual Demonstration & Engagement*: The *Outcome Evaluation & Immersive Experience* delivers stakeholders aggregated analyses and interactive visual feedback on the potential impacts of proposed interventions on urban mobility networks. In addition, interactive visualisation tools like XR allow stakeholders to experience projected mobility conditions and offer feedback on their acceptance,

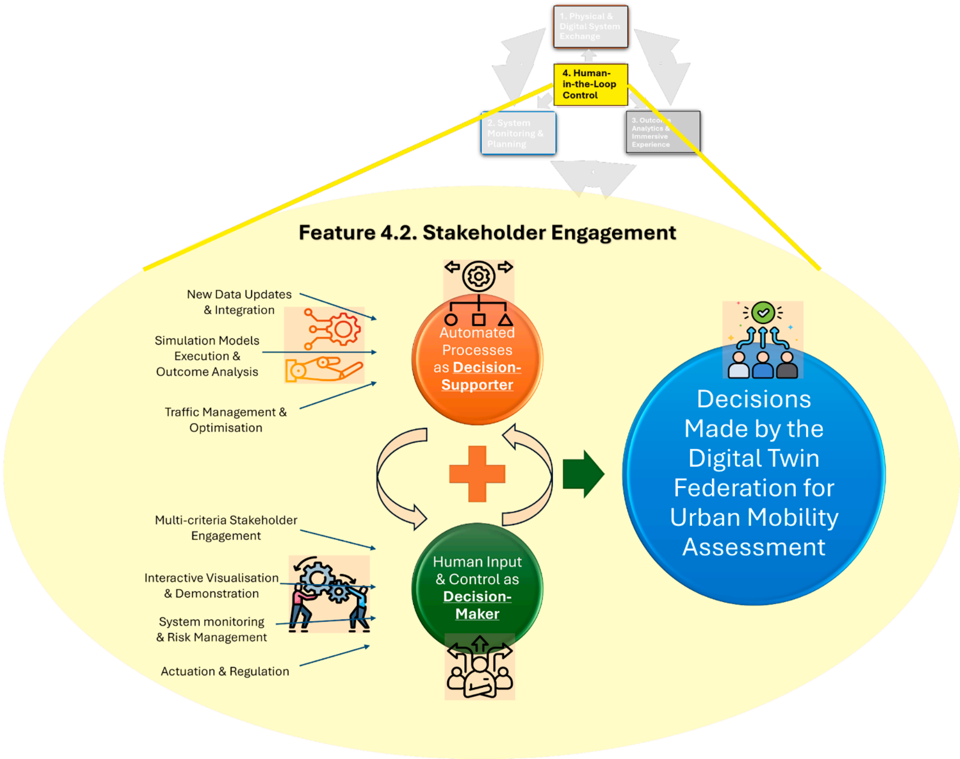

Fig. 5. Joint decision-making between automated process and human control as described in feature 4.2 of FedDT.

behavioural shifts, and perceptions of the proposed interventions. This feedback could be systematically captured and reintegrated, guiding the iterative refinement of intervention scenarios and supporting evidence-based decision-making. In this way, XR is embedded as a feedback mechanism inside the federation, rather than being used as a standalone visualisation layer external to the decision loop.

4) *KPI Adjustment & Scenario Evaluation*: Based on stakeholders' evaluation from visual demonstration and engagement, various design alternatives will be evaluated by KPIs jointly defined by mobility stakeholders (Li et al., 2023b). This process can be operationalised through the Multi-Criteria Multi-Stakeholder (MAMCA) workshops, in which stakeholder-defined criteria, weights, and preferences are translated into an explicit ranking of alternatives. In this way, preferences are incorporated into the evaluation loop with evidence from other federated digital modules, thereby enabling consensus-building across stakeholder groups.

5) *Executions of Selected Interventions*: Once a preferred designed alternative has been chosen, relevant stakeholders would translate the proposed digital interventions into tangible action in the physical urban mobility systems.

In general, as demonstrated in Fig. 5, the final decisions made by the FedDT are the product of a joint process between automated processes and human control. The automated processes serve as a decision supporter, which generates data and predictions about the potential impacts of different interventions. However, the proposed FedDT is still considered a socio-technical system; meaningful human control is even more crucial for preserving ethical accountability and the intrinsic value of human participation in decision-making (Bruynseels et al., 2018). In other words, based on the outcome of the automated process, humans (i.e., stakeholders) retain ultimate decision-making authority over which interventions to approve, adapt, or discard.

3.5. *Definition of the digital twin federation for urban mobility assessment*

The four pillars of FedDT distinguish it from existing toolkits used in mobility planning (Ambra and MacHaris, 2020; Li et al., 2020). Based on this detailed demonstration through pillars, we provide the definition of a FedDT as:

Definition 3.1 (Digital Twin Federation for Urban Mobility Assessment)**.**

A Digital Twin *(DT) represents a specific component within a complex system by digitally replicating its physical state and enabling actuation to change the physical reality. A DTs* Federation *integrates multiple DTs to comprehensively capture high-order interactions within complex systems. Hence, a* Digital Twin Federation for Urban Mobility Assessment *(FedDT) is a dynamic socio-technical ecosystem,* ***with the following key elements:***

- *FedDT comprises the real-world urban mobility system and its digital counterparts that are built from several existing modules. Real-world and digital systems are connected through* bidirectional information exchange*, where the physical system provides updates to the digital federation, and the digital federation feeds back assessments to support the* iterative refinement *of interventions and decision-making.*
- Multilevel modelling *enables FedDT to represent different states of mobility systems at multiple spatial-temporal resolutions and maintain information exchange with components in the physical mobility system for real-time, short-term, and long-term monitoring, optimisation, and planning.*
- *FedDT's outcome evaluation combines advanced data analysis with* interactive visualisation *for the interpretation and exploration of data-driven outputs.*
- Human-in-the-loop Control *distinguishes FedDTs from automated DTs by embedding structured human control into intervention design, evaluation and implementation, so that contextual knowledge, ethical considerations, and stakeholder preferences are integral to the final decisions made with FedDT.*
- *Therefore, mobility stakeholders (both persons and institutions) are actively included and engaged in FedDT's decision-making process.*

4. Digital twin federation for urban mobility assessment: A functional architecture & use case example

Based on the proposed FedDT pillars and the relevant literature, a draft architecture was designed to realise the proposed FedDT pillars in a comprehensive framework. Furthermore, we operationalised the FedDT proof-of-concept with five co-design workshops and consultations carried out between June 2024 and April 2025. For each session, we invited a consortium of mobility stakeholders, urban planners, local municipalities, private sectors and academic institutions in the Netherlands, where the detailed list of organisations involved and the iterative co-design process are described in A. A resulting workflow for the result co-designed FedDT is shown in Fig. 6. The two different FedDT loops are shown: the principal system loop representing physical & digital system exchange. Additionally, within the FedDT system, there is an inner refinement loop: policymakers and stakeholders can iterate mobility interventions before the outcome is acceptable and implemented in the real world. Furthermore, Section 4.1 details Fig. 6 by presenting a functional architecture of the proposed FedDT. The purpose of establishing this architecture is threefold: Firstly, it offers a structured, high-level blueprint for how the key components and modules within the FedDT should be organised and interconnected; Then, it guides future development of the FedDT by illustrating the information flow necessary for FedDT Application Programming Interfaces (API) definition and executions in practice (Wang et al., 2022a); Third, the functional architecture would serve as a reference to enhance reproducibility for consistent implementation across urban mobility assessment in diverse regions and contexts.

In Section 4.2, we present a proof-of-concept application framework for our FedDT functional architecture by applying it to a real-world mobility use case in Amsterdam's Zuidas region. This use case not only validates the FedDT design but also lays out a research agenda for its further development in support of a low-car city transition. Furthermore, the use case also serves as a benchmark that illustrates how our FedDT architecture can be applied to various other regions for mobility assessments.

4.1. FedDT functional architecture

Fig. 7 presents a functional architecture for the proposed FedDT for urban mobility assessment by considering the detailed functions within separate modules and the diverse mobility stakeholders who interact with the architecture (upper yellow section of Fig. 7). These interactions occur in line with human-in-the-loop control at specific module components to support the FedDT inner refinement loop throughout its lifecycle.

The proposed FedDT architecture begins from the physical mobility system, where real-world data revealing urban mobility patterns are collected by **Module 1** *Data Ingestion Module*. Specifically, the data ingestion manager integrates all relevant data into aggregated mobility datasets related to transport demand, network, multi-modal transport services, and the environment & physical condition, which serves as critical input for mobility simulation, traffic management and optimisation, plus mobility system monitoring.

Module 2 *Simulation Management & Storage Module* federates high-fidelity multilevel mobility simulations that differ in simulation techniques, modelling scales and simulated environments, where they are connected via a *Model Integration and Orchestration Manager* to enable seamless communication and data transfer between models. When planners raise questions about the impacts of specific mobility interventions, KPIs reflecting their priorities are first collected. If there are new KPIs that the existing models cannot capture, dedicated simulation modules are then developed and integrated into the multilevel simulations. Planners then specify their interventions of interest, which are then translated into the appropriate simulation parameters. Next, the simulations are executed, resulting in several simulated scenarios incorporating the proposed interventions. In addition to multilevel modelling, all executed simulations will be stored in the *Model Library manager* within the same module. Specifically, for each simulation, it will store outcomes generated, the detailed methods and simulation configurations, the simulation environment, the version of the FedDT, and User Interaction Logs. Together, these components form a comprehensive repository that supports the continuous refinement and validation of simulations executed in the FedDT.

Besides testing various what-if scenarios, **Module 3** *Data Analysis & Optimisation Module* of FedDT also supports functions for mobility operations, such as adaptive traffic control, traffic flow prediction, mobility system optimisation, real-time traffic scheduling and accident management. As demonstrated in Section 3.2.2, the federated structure of the FedDT facilities close integration between *Simulation Management & Storage Module* and *Mobility Management & Optimisation* in three ways: Firstly, when mobility management and optimisation lack mobility data that is inaccessible in real-world, synthetic data from simulation models could be adopted as alternative inputs; Then, for optimisation questions require more adaptive and holistic evaluation of intervention impacts across multiple performance dimensions, simulation could be integrated as simulation-based optimisation, thereby providing context-sensitive traffic management scheme that capture mobility system dynamics; Finally, after new traffic management and optimisation schemes are formulated, they will be injected as interventions into FedDT's simulation environment for more comprehensive appraisal of potential ripple effects on urban mobility systems that may not be fully captured by optimisation constraints alone. Furthermore, the real-time data ingested is continuously monitored by the *Data Analysis & Optimisation Module*. If disruptions are detected, notifications are immediately sent to the relevant users to take corrective actions. All data generated from simulation/optimisation/traffic management is transmitted into the *Data Analysis Layer* in the *Data Analysis & Optimisation Module*. The insights serve as data-driven references for the visualisation in the coming **Module 4** *Data Visualisation Module*, containing both illustrative and interactive visualisation (Section 3.3.2). All of these demonstrate the potential changes that could be brought to urban mobility systems.

Up to this point, Modules 1 to 4 have provided data-driven decision support demonstrating the impact of various mobility interventions on urban mobility systems. **Module 5** *Collaborative Design & Decision-Making Module* would select the design alternatives that not only meet technical performance criteria but also align with the preferences of diverse mobility stakeholders. The process is adapted from the MAMCA (Multi-Actor Multi-Criteria Analysis) method (Macharis et al., 2010). However, FedDT provides stakeholders with both data-driven insights from simulations plus interactive visualisation; therefore, its decision-making no longer solely relies on stakeholders' assumptions of each intervention. Specifically, **Module 5** invites representatives of each stakeholder group to the workshops for evaluating different scenarios through interactive visualisations. Next, individual evaluations are aggregated to form a consolidated ranking of all design alternatives. Based on the aggregated results, adjustments are made to the initial design alternatives and KPIs. If new intervention/KPI combinations emerge from stakeholders, they are re-evaluated using the simulation, optimisation, data analysis, and visualisation processes described earlier. Such an iterative process (referred to as the inner refinement loop in Figs. 6 and 7) continues until a consolidated set of design alternatives aligning with stakeholders' preferences is achieved.

Finally, **Module 6** *Actuators Module* implements the selected "soft" and "hard" interventions. The FedDT restarts the loop by updating the mobility system's status, monitoring the effects of adopted interventions, collecting new mobility data for scenario updates, and generating new interventions for optimising and decision-making for the updated mobility system (if necessary).

4.2. Proof-of-concept application framework for low-car transformation using the FedDT functional architecture

Urban planners have embarked on a project to redesign the Zuidas area in Amsterdam with the aim of relocating some of the existing road spaces from PVs while preserving the region's accessibility and connectivity. The goal is to encourage the use of shared

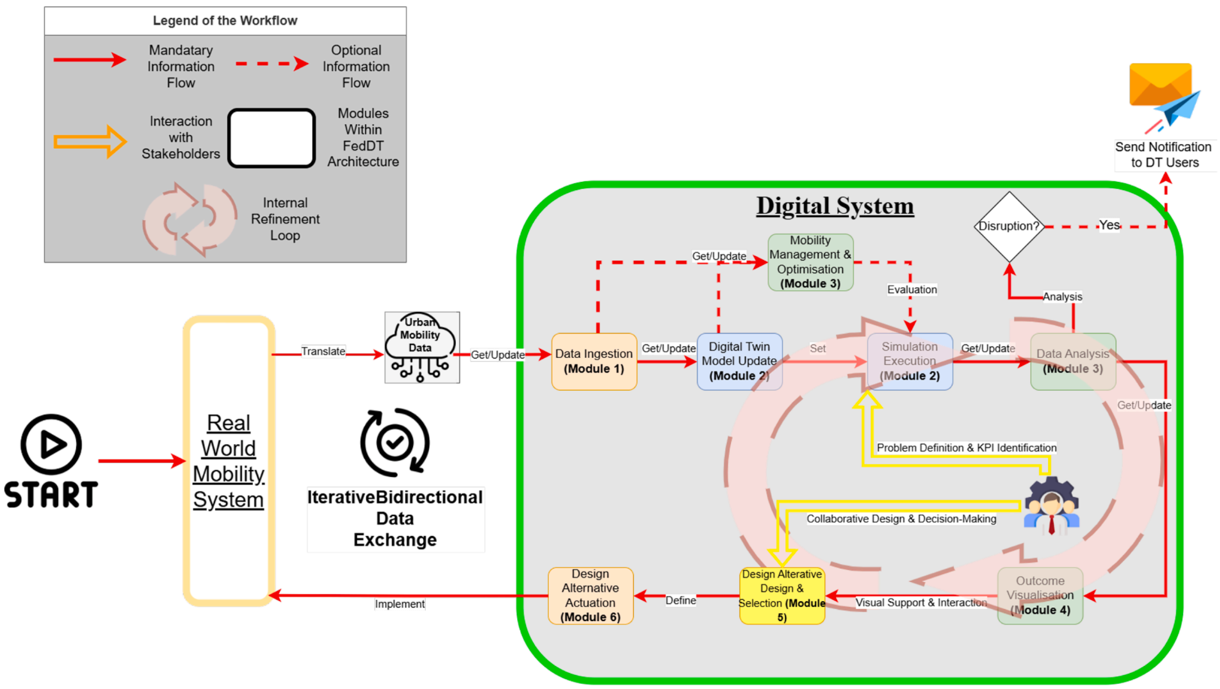

Fig. 6. Workflow of the proposed FedDTs for urban mobility assessments. Each module's colour stands for the corresponding pillar, so it remains consistent with the colour of pillars in Fig. 1 (orange for *Physical & Digital System Exchange*, blue for *System Monitoring & Planning*, green for *Outcome Evaluation & Immersive Experience*, and yellow for *Human-in-the-Loop Control*). The solid red arrows indicate the essential information flows between different modules, which are required every time the FedDT is used for mobility assessments. In contrast, the dashed red arrows represent optional information flows that are not strictly necessary but would be called based on specific analytical needs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

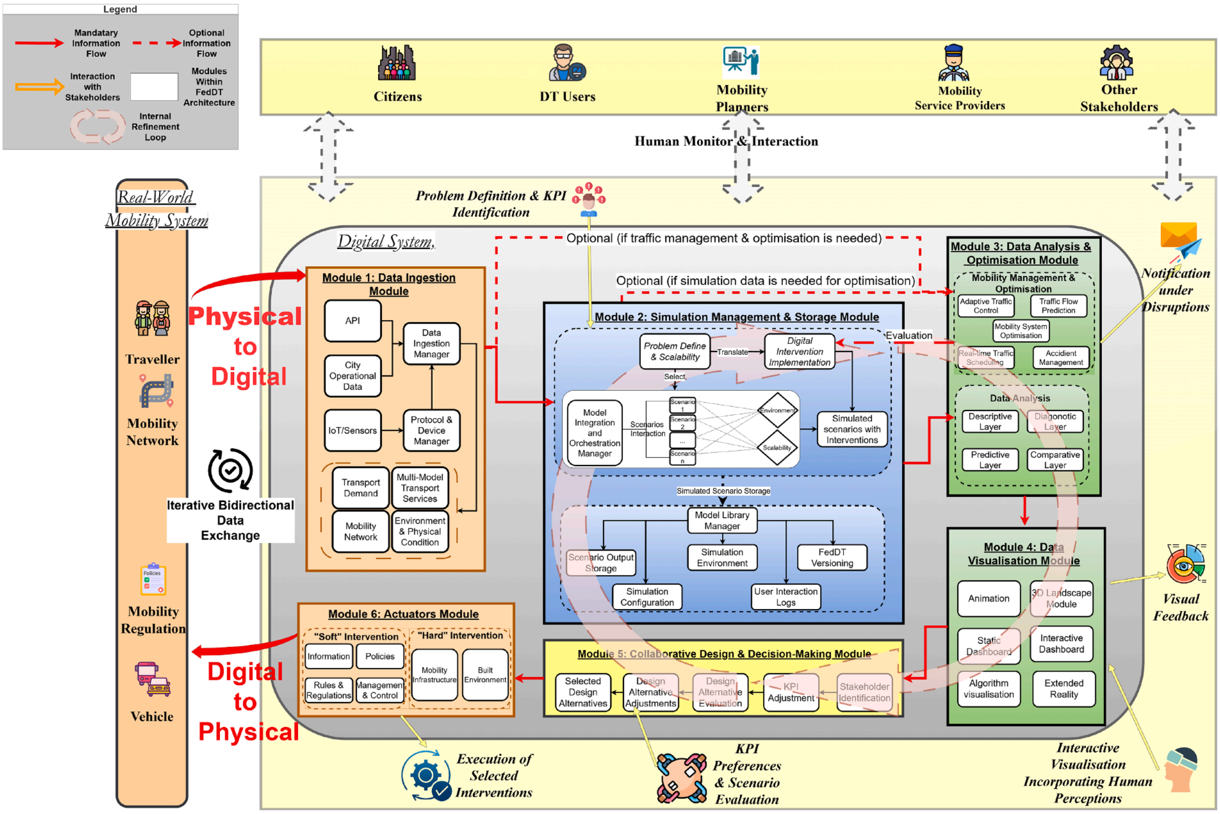

Fig. 7. Functional architecture of the Digital Twin federation for urban mobility assessments based on the proposed concept of 6-dimensional dual-loop FedDT. The legend and colour coding are consistent with Fig. 6. The thin red arrows indicate the automation loop. Interactions with stakeholders occur in line with human-in-the-loop control at specific module components represented by the yellow double-line arrows around the digital system. The inner refinement loop represents the iterative stakeholder interaction with the modules. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and active modes of transportation over PVs. Currently, planning practices in Zuidas primarily rely on 2D mapping and static, macroscopic tour-based traffic models, which focus mainly on vehicular traffic. In the context of recent growth in Zuidas, this motivates a systematic assessment of different low-car interventions whose impacts span multiple scales and objectives, and therefore cannot be assessed through existing tools alone. Therefore, the proposed FedDT concept could be utilised in Zuidas by integrating different tools and involving stakeholders in the decision-making process within a single, dynamic, and human-in-the-loop application framework[1].

From June 2024 to April 2025, five co-design sessions/workshops were held to collaboratively develop a FedDT for Zuidas to reduce PVs by aligning the proposed functional architecture with the region's existing data and tools. The outcome of these co-design sessions is illustrated in Fig. 8, which serves as a research agenda guiding the development and integration of the individual modules. The federation across FedDT modules is planned to be realised via a middleware-based broker layer (Lohman et al., 2023) to support publish-subscribe exchanges of states and results across modules. Nevertheless, the primary focus of this work is to translate the FedDT architecture from a theoretical concept into an application framework for Zuidas. Full deployment and validation of the final Zuidas FedDT remains future work and is discussed in Section 5.

In **Module 1**, the design process began with a mapping of Amsterdam Zuidas' existing data ecosystem. A detailed overview of the data sources to which the Zuidas FedDT could be connected is provided in Section 3 of Appendix B. Based on available data, during the co-design sessions, stakeholders were asked to discuss and identify KPIs to help them decide on the best design alternatives. The identified KPIs include accessibility, quality of mobility, mobility sustainability, spatial quality, safety and operational costs, necessitating the development of new simulation models. Therefore, in **Module 2**, we designed a three-layer simulation framework with a special focus on multimodal interaction. Specifically, the top layer of the proposed simulation framework is the existing Amsterdam multimodal macroscopic traffic model VMA (openresearch.amsterdam, 2025), which provides aggregated traffic flows for PVs, trucks, PT, and bicycles. However, the VMA model's traffic analysis is conducted at the zonal level, making it challenging to analyse interactions between different transport modes in a specific area. Additionally, the VMA model does not adequately capture pedestrian demand. Consequently, an additional pedestrian model is required. Depending on the required insights, the model can

[1] More detailed introduction about Zuidas regions and its motivation towards less PV dependency in Section 2 of Appendix B.

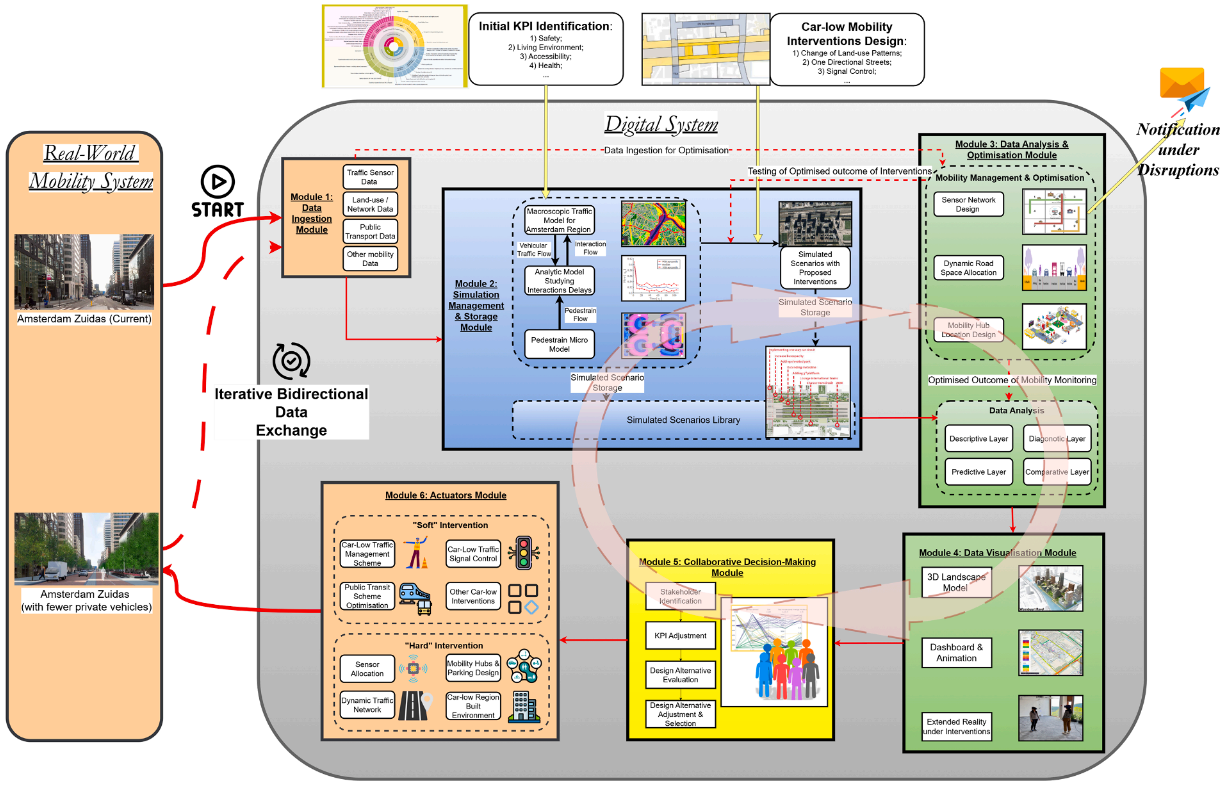

Fig. 8. Use case example of the digital twin federation for A low-car area in Amsterdam, the Netherlands. The legend and colour coding are consistent with Fig. 7.

choose between the All-or-Nothing model or the NOMAD model (Campanella et al., 2014). While the All-or-Nothing model assumes all pedestrians walk on the route with the smallest perceived cost, the NOMAD model simulates detailed agent-based pedestrian movement at a microscopic level, maximising their utility. Both the VMA and NOMAD/All-or-Nothing assignment models require delays for both cars and pedestrians at intersections to calculate the routes' perceived costs. Therefore, an analytic intersection model between VMA and the pedestrian model is necessary. This requires collecting vehicular and pedestrian volume data at intersections and modelling intersection delays and crowding, while considering interactions between pedestrians and cars under different interventions. Data from **Module 1** will be used for (re) calibration and to enhance the accuracy of the multilevel modelling. Therefore, **Module 2** of the Zuidas FedDT will hold a comprehensive baseline model federation that represents real-world mobility patterns in Zuidas at macroscopic, mesoscopic, and microscopic levels. Initial interventions proposed by Zuidas stakeholders will then be translated into modelling parameters, after which simulations will run to generate digital representations of different scenarios.

Furthermore, data collected from **Module 1** will also be ingested for *Mobility Management & Optimisation* in **Module 3**. For mobility data that is not accessible, data from the calibrated multilevel modelling in **Module 2** could serve as a valuable alternative. The current FedDT architecture for Zuidas focuses on 3 primary optimisation aspects: Sensor Network Design, Dynamic Road Space Allocation, and Mobility Hub Location Design (Li et al., 2024b) [2]. The outcomes from the *Mobility Management & Optimisation* layer can be categorised into two types based on their applicability. The first type includes outcomes intended for real-world mobility monitoring, such as the sensor network allocation strategies. These results primarily enhance data observability. Consequently, they are directly transferred to the *Data Analysis Layer* for subsequent decision-making. The second type comprises optimisation outcomes related to interventions that directly affect mobility systems, such as the locations of mobility hubs. Until this point, the overall impact of these interventions on the mobility systems remains unclear. Therefore, these optimised outcomes are integrated into the multilevel modelling as interventions, ensuring that they are not only locally optimal but also effective in addressing the dynamic patterns of real-world mobility systems.

The outcomes from both the simulations and optimisations are transformed into *Data Analysis Layer*. The analysed data are then passed as input to the **Module 4**, which comprises 3 key components: 3D landscape model, interactive dashboards and animations, and extended reality. Together, in **Module 5**, stakeholders' representatives experience and evaluate scenarios under different interventions. Their feedback on different KPIs could be gathered and aggregated, leading to adjustments to the design alternatives and KPIs that best align with the respective technical, social, and economic priorities. The newly proposed or adjusted interventions re-enter

[2] A more detailed introduction of these traffic management strategies is presented in Section 4 of Appendix B.

the inner refinement loop until a consolidated set of design alternatives aligning with stakeholder interests is achieved. Ultimately, **Module 6** implements the selected design alternatives, namely “hard” and “soft” interventions, as demonstrated in Fig. 8. At present, Zuidas is undergoing multiple construction phases, which makes “hard” interventions relatively easy to implement. This facilitates multiple FedDT iterative cycles. Following implementations, the resulting mobility data under the transformed Zuidas scenario would again be collected by **Module 1**, initiating a new iteration of the FedDT feedback loop for bidirectional data exchange.

5. Discussion & future work

This paper addresses a critical gap in DT research on integrating human engagements into automated processes for socio-technical urban mobility systems. We introduce the concept of Digital Twin Federation (FedDT). Unlike most prior studies, which offer fragmented interpretations of DT implementation, we expand the original DT concept to account for human interaction and decision-making within FedDTs. The unique characteristics of urban mobility systems help us to define 4 conceptual pillars for FedDTs. These pillars are rooted in stakeholder requirements, as we devised them after several consultations with mobility and DT experts. We present a modular functional architecture that unifies existing methodologies and DT instances in the context of mobility, but FedDT is in principle applicable to other socio-technical systems. The functional architecture of FedDT integrates mobility simulation, optimisation, data analysis, immersive visualisation, and multi-criteria, multi-stakeholder analysis into a coherent system for comprehensive, data-driven urban mobility decision-making that enables human-in-the-loop control.

Nevertheless, this article presents a high-level vision with the underlying key assumption that the technical specifications within each federated module can be developed and integrated effectively. For instance, we do not describe in detail the data fusion algorithms required for seamless integration of heterogeneous data within each module, nor do we provide implementation details on the cyber-physical infrastructure and cybersecurity measures required for the FedDT. Nevertheless, Cybersecurity is particularly critical for cyber-physical digital-twin deployments (Sharafian et al., 2025), where the technology is essential for ensuring that the FedDT can be reliably deployed, scaled and maintained in real-world environments.

Our future research directions within the research agenda focus on expanding the Amsterdam Zuidas FedDT use case to demonstrate the capabilities of FedDT, and we envison three main future works:

1) **Synchronisation between Multilevel Models**: The interaction between simulations offers substantial benefits of supporting intervention assessment at different scales, but ensuring seamless synchronisation between models presents significant challenges. This is because each simulation layer is developed with distinct specifications, assumptions and calibration techniques, which can lead to discrepancies when integrating outputs. This calls for advanced data fusion techniques and standardised communication protocols to dynamically align data across models.

2) **Data Availability, Privacy and Security**: Continuous updates of the FedDT rely on integrating data from various sources. Challenges include maintaining data availability, managing missed data, and ensuring data privacy and security (Micallef et al., 2023; Li et al., 2023a). This calls for implementing privacy-preserving data ingestion pipelines and scalable computing infrastructure (Ali et al., 2025b). More importantly, efforts from all institutions to promote open data initiatives are also necessary to create a collaborative ecosystem that continuously supports the FedDT with reliable and transparent information;

3) **Stakeholder Trust and Real-World Implementation**: Last but not least, ensuring that the decisions made by the FedDT are trusted and approved by real-world urban planners remains a critical challenge. This is essential as otherwise, the proposed system becomes merely a “digital shadow” (Abouelrous et al., 2023). Although the FedDT architecture embeds strong human-in-the-loop control to advance communication with stakeholders, questions remain about whether the generated design alternatives can be translated into actionable policies and gain broader acceptance. Potential solutions include implementing advanced validation methods that benchmark FedDT outcomes against empirical data and establishing transparent communication protocols between the FedDT and the general public.

Overall, the proposed Zuidas use case in our ongoing project would serve as a pilot and demonstration of the FedDT architecture. By integrating the FedDT into real-world practice and working closely with large groups of consortiums, our pilot will build trust and demonstrate tangible benefits of the FedDT compared to existing tools. Ultimately, these efforts will pave the way for broader adoption of the FedDT architecture in other regions to effectively guide sustainable urban mobility.

6. Conclusion

In recent years, DT technology has gained significant interest across various sectors. In urban mobility, several toolkits and DT instances are available, each focusing on specific aspects. However, mobility is a complex system comprising multiple independent components, and existing tools alone are often insufficient to fully capture the interplay among these components across different scales. As many cities transition to more sustainable, intelligent mobility systems, there is a growing need for advanced tools that comprehensively assess the impact of diverse interventions and support informed decision-making. An integrated digital twin federation that unifies disparate tools / DT instances into a single, cohesive framework serves as the most efficient solution for addressing these multifaceted challenges. Therefore, this paper presented a definition of FedDT based on four pillars: physical & digital exchange, system monitoring & planning, outcome evaluation & immersive experience, and human-in-the-loop control. Collectively, these pillars formed a new FedDT concept that provides a foundation for the proposed FedDT architecture towards more comprehensive, data-driven urban mobility assessments. Furthermore, through several consultations with mobility stakeholders and DT experts, we demonstrated a functional FedDT architecture that integrates multiple modules into a unified decision-making framework. The information flow between modules ensures an iterative, bidirectional data exchange between the physical mobility system and its digital counterpart. In addition, stakeholders retain the ultimate decision-making process for the design alternatives with meaningful human controls that are integrated in the FedDT architecture.

We highlight the feasibility of our FedDT concept through real-world adaptation in the Zuidas region of Amsterdam, the Netherlands, bringing together policymakers, planners, and academics. The proof-of-concept application framework builds on real-world toolkits and methodologies to focus on decreasing PV dependency and facilitating the region towards more sustainable low-car mobility systems. At the core of the Zuidas FedDT, a multilevel simulation is proposed, consisting of a macroscopic vehicular traffic model, a microscopic active mode model, plus an analytical model that analyses the interaction between vehicular and active modes around Zuidas. In the future, the mobility data will also be utilised for mobility strategy optimisation, including sensor network design, dynamic road space allocation and mobility hub location design. Together with the initial interventions proposed by stakeholders, optimised mobility strategies are fed back into multilevel simulations to quantify the system-wide impacts of different car-low policy proposals on the Zuidas mobility network. The simulated results are then fed into the data analysis layer for interpretation, with aggregated findings translated into interactive visualisations. Finally, Stakeholders use these interactive visualisations to evaluate and compare interventions, with outcomes synthesised via a multi-criteria, multi-stakeholder analysis. FedDT's integrated human-in-the-loop control allows evaluation participants to propose new interventions or adjustments to existing ones dynamically. Changes are cycled back into the multilevel simulations until consensus emerges on the most favourable design alternatives. Selected interventions of the final policy can then be implemented in the real-world Zuidas mobility system. The continuous policy evaluation through FedDT's bidirectional data exchange restarts as new mobility data is collected and fed back into the digital system.

The FedDT concept and architecture are meant for real-world applications in urban mobility. Therefore, the proposed research agenda for Zuidas is essential for fostering the development of separate modules and establishing a blueprint that guides future integration in urban mobility planning. Future work will delve into the detailed technical and methodological aspects of different modules and their interplays as discussed in Section 5. By addressing these challenges, we anticipate that the FedDT architecture will evolve from a functional framework into a practical, actionable tool that can guide sustainable urban mobility planning in diverse real-world contexts towards a more accessible, inclusive and sustainable future.

CRediT authorship contribution statement

Jingjun Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization; **Jascha Grübel:** Writing – review & editing, Visualization, Investigation, Conceptualization; **Ali Nadi:** Writing – review & editing, Visualization, Investigation; **Maaike Snelder:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization; **Bart van Arem:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization; **Jie Gao:** Writing – review & editing, Visualization, Supervision, Investigation.

Data availability

Data will be made available on request.

Acknowledgement

In this manuscript, generative AI was employed to enhance the quality of our own written input. ChatGPT (o1 & o3-mini-high) was utilised for the purpose of rectifying spelling errors and improving grammatical accuracy. The output from AI has been checked, ensuring that the content has not changed from the original, own-written input. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Supplementary material

Supplementary material associated with this article can be found in the online version at 10.1016/j.tra.2026.105086.

Appendix A. FedDT Co-Design Process: Involved Organisations and Iterative Refinements

XCARCITY[3] is a five-year research programme (2023–2028) that investigates the impacts of low-car interventions on urban mobility systems using digital twin federations. In total, the XCARCITY programme comprises 32 partners, of which 14 contributed directly to the FedDT co-design reported in this paper. As summarised in Table A.2, the involved organisations include 3 research organisations, 5 private business sectors, 3 government organisations, 2 local municipalities and 1 public-private partnership.

Since June 2024, a key challenge in designing the proposed FedDT has been the lack of a shared and operational definition of what a FedDT should encompass in the context of mobility planning. Stakeholders initially held distinct expectations regarding the functions

[3] https://xcarcity.nl/.

Table A.2
Organisations involved in the proposed FedDT Co-design process and roles.

Organisation	Role
AMS Institute	Research Organisation
BAM	Private Business Sector
CROW	Public-Private Partnership
DMI Ecosystem	Governmental Organisation
Geonovum	Governmental Organisation
Gemeente Amsterdam	Local Municipality
Goudappel	Private Business Sector
MapTM	Private Business Sector
Ministerie van Infrastructuur en Waterstaat	Governmental Organisation
Technolution	Private Business Sector
TNO	Research Organisation
TU Delft	Research Organisation
Witteveen en Bos	Private Business Sector
Zuidas Amsterdam	Local Municipality

of FedDT. For instance, some partners prioritised 3D visualisation of transport infrastructures, whereas others are more interested in what-if analysis of transport interventions using modelling and optimisations. This has laid the foundation for the proposed co-design process, which aims to converge these expectations into a coherent functional architecture that federates complementary planning capabilities within a classic DT feedback cycle.

To structure the co-design, we first conducted a systematic review of recent DT developments in transport and mobility planning (July 2024). Based on this review, we drafted an initial FedDT architecture that included modules for data ingestion, simulation and traffic management, scenario storage, data analysis and visualisation, operational and collaborative planning, plus actuation. From August to October 2024, we organised one-to-one meetings with the involved partners to capture 1) their priorities and intended use cases, 2) their expected inputs and outputs, and 3) their feasible technical contributions. Based on these discussions, stakeholders were classified into four practical roles in the FedDT lifecycle: *data providers*, *module/technology developers*, *use-case region*, and *end users*.

From September 2024 to April 2025, we conducted five co-design workshops to iteratively refine the FedDT functional architecture and shape the use case application framework (including the Zuidas use case in Section 4.2). In these workshops, the partners' classification supported structured discussions across stakeholder groups. Specifically, the use-case region and end users defined priority KPIs and required FedDT functions based on local needs and policy requirements. Technology developers translated these requirements into feasible module designs, and data providers aligned the modules with available real-world data. Consequently, the co-design sessions enabled partners to establish an implementable definition and architecture as reported in this manuscript. Due to space constraints, we summarise three key modifications to the FedDT architecture and the Zuidas application framework that emerged from the co-design workshops:

- **Scope consolidation:** Several operational modules that were initially drafted but are not strictly relevant to mobility planning (e.g., intelligent vehicle routing modules) were removed from the architecture after one-to-one meetings with stakeholders, who prioritised strategic urban assessment and policy-oriented scenario evaluation.
- **Formalisation of inner refinement loop:** Zuidas planners emphasised that intervention design is inherently iterative, requiring repeated scenario refinement within the digital systems prior to real-world implementation. This motivated the representation of the inner refinement loop in Figs. 6–8, capturing stakeholder and scenario re-specification feedback into previous modules.
- **Incorporation of Multilevel Simulation:** Stakeholders highlighted that intervention impacts must be assessed consistently across different resolutions, while leveraging existing toolkits rather than rebuilding models from scratch. This motivated the incorporation of multilevel modelling in the FedDT design, allowing for the generation of cross-scale evidence that would be difficult to obtain with standalone tools.

Appendix B. Supplementary Material

Supplementary material for this article is provided as a separate file, including: (1) Comparison Between FedDT Pillars and Existing Mobility DT Literature; (2) Introduction & Motivation Towards Amsterdam Zuidas With Fewer Private Vehicles; (3) Overview of Traffic and Sensor Data for the Proposed Zuidas FedDT Data Ingestion Module; (4) Detailed Introduction for the Mobility Management & Optimisation in Zuidas FedDT.

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