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A Challenge-Led Digital Twin Federation Architecture For Urban Passenger Transport Decarbonisation

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Abstract

Urban transport is one of the largest contributors to global greenhouse gas emissions, and decarbonising transport systems is a key policy objective in many countries. Existing planning tools, when used in isolation, often failed to capture the interplay between dynamic demand and supply in transport systems. This highlights the need for a tool that enables learning-by-doing approaches for planning ambitious decarbonisation targets. Digital twin (DT) concepts have recently been proposed as adaptive decision-support systems that iteratively evaluate different engineering interventions as the physical system evolves. However, in the domain of passenger transportation, research is underrepresented, with limited insights into DTs' definition and design. To address this gap, based on co-design with local stakeholders, this paper presents a conceptual architecture for a digital twin federation (FedDT) for the West Midlands region, UK. The proposed FedDT is designed to support both short-term operational and relatively long-term tactical, strategic mobility planning within a single framework. By integrating an ontology-based knowledge architecture, mobility-demand modelling, multi-level agent-based simulation, optimisation, stakeholder consultation, and modelling & reasoning frameworks, the FedDT enables iterative, bidirectional data exchange between the physical mobility system and its digital counterpart. In addition, the proposed FedDT follows a human-in-the-loop design, thereby ensuring the interests of relevant stakeholders are continuously integrated. The proposed architecture informs the development of key modules, including the Big British Bus Ontology, a multi-modal agent-based mobility simulation with railway integration, and optimisation models for transitioning to electric buses in the West Midlands. Overall, this paper applies and extends existing DT architectures for passenger mobility, provides an architectural foundation for ongoing FedDT module development in the West Midlands, and offers a transferable blueprint for regions seeking to leverage DT technologies to support transport decarbonisation.

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1. Introduction

Transport accounts for around 29% of the UK's domestic greenhouse gas emissions, making it one of the largest emitting sectors in the country, with road vehicles accounting for 89% of the total [7]. With a highly urbanised population and a legally binding 2050 net-zero transport target in the UK [25], there is a clear need for an adaptive decision-supporting tool that can evaluate the dynamically evolving transport system-of-systems and assess decarbonisation interventions iteratively over time [12]. To this end, the concept of digital twins (DT) is particularly well-suited to this target. In its original concept [10], a DT comprises three essential elements: a physical system, its digital counterpart, and the bidirectional exchange of information between the two. Data generated in the physical system are used to construct and update the digital representation as real-world conditions evolve. Meanwhile, the digital system is expected to explore several “what-if” scenarios and offer recommendations for action in the real-world system, thereby creating a closed data-driven feedback loop between monitoring, analysis, and intervention.

Given both the need to reduce uncertainty and risk in predicting the emergent response from complex adaptive transport systems, and the urgency of identifying “no-regrets” investments that can accelerate challenge-led low-cost and inclusive decarbonisation, there is a growing interest in defining an open architecture for model integration. Within this context, recent literature suggests that, instead of building everything from scratch, it is more effective for mobility planning to federate existing algorithms within a classical DT feedback-control loop to form a digital-twin federation (FedDT) [14]. Such a FedDT enables a system-level evaluation of alternative mobility interventions that individual methods alone cannot deliver. However, key design questions remain open, including which functional modules should be federated and how information flows and control signals should be organised within the FedDT.

In response, this paper proposes a FedDT architecture for the West Midlands, UK, to support the decarbonisation of the regional mobility system at the lowest costs. The architecture is intended as an overarching vision that guides and coordinates the development of separate modules and the information flow in between. In doing so, this paper sets out a research agenda of separate modules development based on available toolkits for the West Midlands' FedDT implementations in practice. The remainder of the paper is organised as follows. Section 2 demonstrates relevant work on transport digital twins. Section 3 presents the proposed FedDT architecture for the West Midlands, specifying the constituent modules and the information flows between them. Section 4 shows the current development of the individual modules and outlines the next steps towards implementation and evaluation in practice.

2. Relevant Works

The DT concept originated in aerospace engineering by NASA in the 1960s [10]. More recently, building on this original formulation, several studies in transport have developed DTs that construct digital replicas of transport systems from real-world data and use these digital representations to generate recommendations for real-world operations and planning. A substantial part of these transport DTs places strong emphasis on the visual reproduction of transport-system entities [27], such as network layouts, land uses and traffic states. However, the primary focus on visualisation makes these DTs often descriptive, with relatively constrained capabilities for representing the underlying interaction between mobility entities. Thus, the space of relevant “what-if” questions they can address comprehensively remains limited [5].

In contrast, another strand of DT research focuses more on the mathematical modelling of interactions between transport infrastructure and users, thereby providing stronger data-driven analytical capabilities for exploring “what-if” scenarios [18]. Nevertheless, the distinction between these DT-based research and conventional transport simulations equipped with an improved data pipeline remains ambiguous. More recently, several works have begun to couple advanced visualisation with other analytical components (e.g. simulation models, traffic control algorithms) within a DT feedback loop. These hybrid DTs aim to integrate the complementary strengths of each method and support multi-perspective assessments of how various interventions impact mobility systems. Nonetheless, these implementations have so far tended to concentrate on specific sub-systems within transport, such as intelligent vehicular systems [21] and public transport management [2]. Consequently, they fall short of capturing the system-wide impacts of transport interventions, which are crucial for informing long-term decisions on issues such as transport decarbonisation. As illustrated by [20], persistent gaps remain in decarbonisation-oriented DT design, multi-modal integration

within a federated transport system-of-systems, socio-technical-economic representations of transition pathways, and cross-sector coupling with transport systems (e.g. the transport–energy nexus).

Effectively combining various digital twins of different aspects of mobility systems requires DT Federation (FedDT), which enables a system-level evaluation that individual methods alone cannot tackle. Compared to conventional transport simulations, a FedDT is distinguished by a continuously updated closed-loop information loop that links the physical mobility system with federated digital replicas, integrating data and methods to enable system-level evaluations that a single module cannot deliver. Based on the co-design with different stakeholders, [14] presents the definition of a FedT as:

A dynamic social-techno-economic-decarbonisation multi-objective optimisation ecosystem built from several existing modules to represent a complex composition of real-world systems for mobility stakeholders and policymakers. Human factors distinguish FedDTs from automated DTs by embedding structured human control into the design, evaluation, and implementation of interventions. Furthermore, Multilevel modelling allows FedDT to represent different states of mobility systems at multiple spatial–temporal resolutions and maintain bidirectional data exchange with all components in the physical mobility system for real-time monitoring, short-term optimisation and long-term planning. Finally, FedDT’s outcome evaluation combines advanced data analysis with interactive visualisation for the interpretation and exploration of data-driven outputs. Therefore, mobility stakeholders (both persons and institutions) are actively included and engaged in FedDT’s decision-making process.

[14] also demonstrates a FedDT functional architecture that integrates different modules into a comprehensive framework, enabling iterative, bidirectional data exchange between the physical mobility system and its digital replicates. Nevertheless, due to its human-in-the-loop design, the FedDT architecture proposed is primarily oriented towards medium- to long-term transport planning, whereas its role in operational decision support covering short-term timescales that require rapid action, such as disruption response, remains under-specified. Secondly, for a specific region, further work is required to translate the architecture into implementable methods by specifying the detailed methodologies, data interfaces and toolchains within each module.

3. Digital Twin Federation Architecture for the West Midlands

To address the gaps proposed in Section 2, this paper operationalises the respective modules using real-world toolkits that are being developed within TransiT, the UK national research hub. In addition, we extend the original architecture by introducing a “data lake” to support operational transport planning tasks that require rapid action, thereby complementing the primarily human-in-the-loop orientation of the initial FedDT design with a more responsive, data-driven layer for short-term decision-making.

The proposed FedDT architecture focuses on the West Midlands in England, a heavily urbanised region encompassing the metropolitan areas of Birmingham, Coventry, and their surrounding towns. The West Midlands forms one of the three Challenge-Led Demonstrators within the TransiT hub, where local authorities and transport planners seek to utilise state-of-the-art digital technologies to propose, model, and evaluate the impacts of changes to the mobility interventions outlined in the Carbon Assessment Playbook on the local multimodal mobility network. Currently, the planning of decarbonisation strategies in the West Midlands relies on estimated, static values [4]. There is therefore a need for a more dynamic, learning-by-doing decision-support tool to assist local authorities in managing the transition towards a decarbonised mobility system.

The design of the proposed FedDT begins with active stakeholder consultations. In total, 3 rounds of workshops have been carried out involving both academic and industrial stakeholders in the West Midlands¹. The workshop outcomes indicate that stakeholders are primarily interested in interventions that promote shifts towards more sustainable mobility modes, and that they envision the FedDT as a tool supporting both near-real-time monitoring and long-term scenario modelling for a range of “what-if” analyses. They emphasise that the digital system should explicitly represent traveller behaviour and user experience, and that its outputs should be communicated through intuitive

¹ Key stakeholders include: University of Leeds, Durham University, University of Birmingham, Heriot-Watt University, WSP, Transport for West Midlands, Midlands Connect

The stakeholder consultations inform the FedDT functions, module components, and KPIs of great concern. Real-world data (representing both mobility demand and supply) from multiple sources would be ingested into **Module 1. Mobility Data Ingestion Module**.

However, as more datasets and systems become involved, these heterogeneous datasets can easily lead to a fragmented data structure. Additionally, in a complex mobility system, most entities also influence and are influenced by one another, and datasets use different definitions for similar concepts. Without an explicit data architecture, these cross-cutting relationships remain implicit, making it difficult to understand how data should be combined and reused across modules. Therefore, **Mobility system ontology** within Module 1 represents a set of concepts and categories in urban mobility that show the properties and relationships between different entities [24]. Specifically, the ontology comprises two components: the terminological ontology (TBox), which defines the concepts and schema (such as mobility services), and the assertion ontology (ABox), which stores specific data instances and maps the actual relationships between them. The value of ontology is twofold: First, it enhances the interpretability of the remaining FedDT modules by making explicit how different mobility-system entities are related. Second, it links real-world data to the digital system, ensuring the latter remains up to date as new data becomes available, which is essential for the bi-directional communication required in a system such as FedDT.

Real-world data are connected to and aligned with the digital system through the ontology. Data describing mobility infrastructure, demand and services are then fed into **Module 2. Multi-level Simulation**, where simulations at different scales are coupled to enable a more comprehensive understanding of mobility behaviours that cannot be captured by any single modelling approach. The design choice reflects the fact that urban mobility inherently consists of several multi-scale (e.g. microscopic vs macroscopic) and multi-temporal (e.g. weekday, weekend) subsystems. For instance, agent-based modelling is well-suited for simulating the interaction between individuals' movements on mobility networks, whereas activity-based modelling simulates individual travel patterns by modelling their specific attributes [19]. Therefore, rather than building a single simulator to provide insights across all levels, with explicit entity definitions and relationships in the ontology, simulations with different techniques and purposes can be federated in the FedDT, enabling integration across subsystems and supporting stakeholder-driven assessments that span different perspectives.

In addition, stakeholders in the West Midlands are interested in the optimised pathway towards mobility decarbonisation. Therefore, **Module 3. A Mobility System Optimisation** concentrates on decarbonisation intervention designs based on the objections and constraints raised via stakeholder consultation. The optimised interventions will be injected as interventions into multi-level simulations for a more comprehensive evaluation of potential ripple effects on urban mobility systems that may not be fully captured by optimisation formulation alone [14].

Several simulated scenarios will offer multi-perspective evidence on KPIs capturing the impacts of different interventions on the West Midlands mobility system. Consequently, in **Module 3. B Simulation Outcome Evaluation**, each scenario is assessed using a unified cost model that aggregates these metrics to estimate the extent to which a given package contributes to a least-cost pathway towards transport decarbonisation. In **Module 4 & 5: Visualisation & Collaborative Decision-Making Modules**, stakeholders who may be affected by the proposed interventions are invited to multi-criteria, multi-stakeholder co-design workshops. These workshops draw on evidence from the ontology, optimisation, simulation outputs, cost-model analysis and interactive visualisations. If adjustments to existing interventions — or entirely new intervention ideas — emerge during these sessions, they are reassessed through the optimisation, simulation, cost-modelling, and visualisation steps described above. This iterative process (the inner refinement loop in Figure 1) continues until a consolidated set of design alternatives is reached that aligns with stakeholders' preferences. Finally, **Module 6: Actuator Module** supports the implementation of selected interventions in the real world. When new issues arise that require decision support from the digital system, the FedDT restarts the loop using updated system status and data generated from the previous iteration, enabling progressive learning across successive planning and implementation cycles.

3.2. FedDT for Short-term Operational Planning

Beyond tactical & strategic middle to long-term planning, the proposed FedDT also establishes a framework for mobility-planning tasks that require quicker feedback — situations where traditional human-in-the-loop processes are too slow. In [14], the Model Library Manager stores simulation outputs, configurations, environments, user-interaction logs and versioned scenarios produced through multi-level simulations. Similarly, real-world mobility data from Mod-

ule 1 are stored in a shared data lake in Figure 1, which supports the development of multiple Modelling & Reasoning Frameworks. These frameworks encompass both formal and machine learning (ML) models, providing an operational layer that delivers results significantly faster than full-scale transport simulations.

For safety-critical operational queries, rigorous mathematical approaches are essential, as they offer stronger guarantees of correctness, completeness and explainability. Candidate techniques include Markovian [26] and bigraph models [1]. Markovian models are well-suited to queries dominated by temporal dynamics, while bigraphs explicitly capture spatial dependencies and network topology [23].

Bigraphs, in particular, can be defined starting from ABM and related data. They incorporate parameters from ABMs — such as low-level events (e.g., individual movements or anomalies) — and elevate them to higher-level abstractions. Rather than predicting minute-by-minute behaviour over a full day, bigraphs represent multiple plausible behavioural patterns of vehicle populations at coarser time scales, each with an associated probability. Because the modeller controls this assignment, we can either mirror ABM outputs or adjust them for resilience testing, “what-if” scenarios and other analyses. For example, if the simulation shows trucks departing along a route every 20 minutes, we can encode this behaviour to estimate delivery times, then test alternative intervals to determine whether all deliveries can still be completed within an acceptable delay. Over the course of a full day, such changes may reduce the fleet size and thus contribute to decarbonization.

Once defined, these models enable the rapid verification of multiple properties or objectives, either individually or simultaneously — regardless of whether they were considered during ABM generation — as long as the model encodes the relevant information. Embedded probabilities allow us to answer questions such as: “This sequence of events achieves objective *A* with probability *p* and objective *B* with probability *q*” or “These sequences are the most likely to satisfy objective *A*” (see [6] for early work in this direction). The notion of short-term analysis is, of course, context-dependent, and extending a model may entail trade-offs between speed of insight and mathematical rigour — for instance, when analysing the effect of closing a lane for several months of maintenance.

Bigraphs support probabilistic analysis by exporting their full transition systems to Markovian models. However, when spatial abstraction is not essential, it may be more efficient to generate Markovian models directly. These models can be derived explicitly from ABM simulation outputs or implicitly when an interaction structure is predefined, and only the parameters are inferred from the ABM outputs, after which they can be analysed.

When planners pose questions requiring rapid answers—especially during disruptions—the system selects a modelling & reasoning framework based on the event types and real-world data collected from information maps (e.g. sensors). This framework then provides fast KPI estimates for the impacts of alternative interventions. For queries that do not require strict formal guarantees but do require high-fidelity prediction or pattern discovery across large, complex datasets—such as real-time analysis of highly granular models — ML approaches may be used. For example, [22] integrates Graph Neural Networks with Transformer-based attention mechanisms.

Regardless of the reasoning method selected, the resulting KPIs feed into cost models for evaluation, and the interventions with the lowest cost toward transport decarbonisation are implemented in the real mobility system.

4. Outcomes and future works

This paper presents a conceptual architecture for a digital twin federation that supports passenger mobility planning in the West Midlands, UK. The architecture is informed by active stakeholder consultations in the region and is structured around four pillar features: physical-digital system exchange, system monitoring and planning, outcome evaluation, and immersive experiences, as well as human-in-the-loop control. Unlike most existing DT work in mobility planning, the proposed FedDT is designed to support both long-term, stakeholder-informed planning and short-term operational decision-making that requires rapid response.

The proposed architecture is intended to support real-world mobility recommendations in the West Midlands. Stakeholders are particularly interested in using the FedDT to understand current mobility patterns in Birmingham, with a specific focus on the Queen Elizabeth Hospital and the University of Birmingham region. The proposed FedDT should be used as a decision-support tool for identifying and evaluating interventions that promote travellers shifting to more sustainable transport modes, and for understanding the operational and infrastructural changes required to enable greater adoption of public transport and railway transport in this area. In response to these requirements, the following modules have been developed:

- The Big British Bus Ontology (B³O)** (Module 1. Mobility Data Ingestion Module): Currently, key sources of bus operations in Great Britain are stored in silos, adopt different schemas, and even use inconsistent definitions of similar concepts. The B³O provides a unified ontology that links bus data from heterogeneous sources, including Bus Times [3], DVLA [9] and GTFS [11]. For instance, the B³O enables cross-source identification of which specific vehicles operate which services and trips and are actually observed running on the road, supporting queries such as: “Which bus fleets operated a given service on a particular day?” Therefore, information about bus operation data can be aligned with each shared entity and serve as data input for other modules (e.g., cost assessments, simulation, optimisation) in the FedDT.
- MATSim & BRaVE Co-Simulation for the West Midlands** (Module 2. Multi-level Simulation): Agent-based modelling (ABM) is selected as the primary simulation for the FedDT in response to stakeholders’ interest in understanding the impact of interventions on the individual level. As one of the most widely adopted ABM toolkits [15], MATSim [13] is being utilised as one layer within the multi-level simulation for modelling multi-modal mobility systems in the West Midlands at the agent-based level. A MATSim scenario has been generated, incorporating a state-of-the-art synthetic travel demand dataset for the region. Stakeholders in the West Midlands are keen to assess interventions aimed at increasing rail penetration. Although MATSim’s existing rail simulator, railsim, is capable of representing the spatial dimensions of rail lines alongside train acceleration and deceleration and both fixed- and moving-block signalling concepts [17], it does not yet support several key operational functions essential for realistic railway performance modelling. These include interlocking logic, switching operations, communication systems, and the behaviours of drivers and signalers. In contrast, the microscopic railway simulator BRaVE [8] has already been applied in several rail-focused projects in the West Midlands. BRaVE models rail infrastructure, interlocking, train physics, and timetables and simulates train movements at fine temporal resolutions (typically one-second steps). This allows for the evaluation of timetable performance under both physical and signalling constraints with high fidelity. To leverage the strengths of both tools, a federation between MATSim and BRaVE is implemented. A custom MATSim mobsim engine has been developed synchronise time between the two simulators and to intercept rail legs and transmit the relevant passenger and trip information to BRaVE as JSON-formatted messages over a UDP socket. Within BRaVE, an appropriate platform is selected based on the scheduled services to the agents’ intended destinations; trains simulated in BRaVE then pick up these passengers with a configurable boarding rate, and transport them to the destination according to the rail leg. Once passengers arrive at their destinations, the same JSON/UDP mechanism is used to transmit from BRaVE to MATSim, where the custom mobsim engine completes the rail leg, returning control of the agent back to MATSim. As a result, agents’ rail travel times within MATSim are aligned with the operational patterns simulated in BRaVE, enabling a more representative, fully multimodal urban mobility scenario for the West Midlands.
- EBus Optimisation & Cost Model Towards Decarbonisation** (Module 3.A Mobility System Optimisation & Module 3.B Simulation Outcome Evaluation): In response to stakeholders’ interests and informed by bus data from ontology, an optimisation framework for electrified bus fleet composition across different transition stages towards the West Midlands’ 2050 net-zero ambition is being developed. Key inputs include fleet size, route distances, energy consumption and prices, vehicle depreciation, and depot charging infrastructure costs. The optimisation model aims to minimise total system cost while ensuring required service levels are maintained, and depot charging capacity is not exceeded. The resulting eBus deployment strategies will be injected into the multi-level simulation to explore wider system impacts that may not be fully captured by the optimisation formulation alone, such as passenger acceptance under the new bus operational schemes. Simulation outputs will then feed into a cost model (currently under development) to estimate the societal costs of these interventions, providing evidence for subsequent stakeholder consultations and actuation.

Overall, the proposed FedDT architecture for the West Midlands, developed within our ongoing project, has the potential to serve as a valuable decision-supporting tool for the region’s transition towards a decarbonised transport system. Still, our work holds several limitations, including but not limited to:

- While the toolkits and information flows for the long-term planning process (red lines in Figure 1) are relatively well defined, the operational, short-term planning process remains more conceptual. Several questions require

further investigation: Which ML methods are most appropriate for training on data drawn from the data lake? How probabilistic evaluations produced by the modelling-and-reasoning frameworks (e.g. bigraph) should be translated into actionable real-world responses? We acknowledge these limitations. At this stage, our efforts have focused on developing the individual modules (i.e. methods for providing data input in the data lake). Once these components reach sufficient maturity, their integration and the practical implementation will be addressed in future works.

- We have specified the functions of FedDT's modules and the information flows between them, demonstrating that these modules can complement each other to provide a more comprehensive system-wide assessment. However, the realisation of a fully operational FedDT ultimately depends on how these modules are assembled into a maintainable and evolvable software system. In practice, the FedDT is likely to be integrated by loosely coupled, replaceable modules with a common application layer, similar to the microservice design principles for supporting module communication and substitution. Unfortunately, this issue extends beyond a purely transportation planning problem [16]. Addressing this limitation remains a crucial direction for future work in software engineering and cyber-physical systems.

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