4D GIS Visualization of Agentic-AI Models: Urban Digital Twin Scenario-based Mobility Simulations for the New Sarajevo Urban Plan

4D GIS vizualizacije agentskih AI modela: scenarijske simulacije mobilnosti na urbanističkom digitalnom blizancu za novi Urbanistički plan Sarajeva

Michael Walczak[1], Victoria Desponds[2], Hubert Klumpner[3]

1, 2, 3: Chair of Architecture and Urban Design, ETH Zurich, Switzerland

1: walczak@arch.ethz.ch | orcid.org/0009-0009-1934-0885
3: klumpner@arch.ethz.ch | orcid.org/0000-0001-7820-3340
2: desponds@arch.ethz.ch

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Abstract This research describes the Sarajevo Urban Digital Twin (UDT) as an applied tool for city planning and for presenting complex simulation results in an adequate way for a broad audience. Developed within the Urban Transformation Project Sarajevo (UTPS), it explains how traffic simulations from the ETH Zurich (ETHZ) software EnerPol are transformed from raw binary files into time-based scenes in ArcGIS Pro (ESRI). In areas with limited local data, satellite imagery is used to create the base 3D city model. The following sections describe how building footprints and heights are extracted not only to generate Level of Detail 2 (LOD2) models with roof shapes and precise outlines, but also to capture land-cover information essential for the UDT. The automatized workflow converts simulation events into georeferenced features and matches them with the street network, so planners can watch traffic patterns shift throughout the day based on different assumptions regarding population changes. A key purpose of the UDT is to make these data and scenarios visible and understandable for people with different professional backgrounds. By offering a shared visual reference, the model supports planning processes where citizens, experts, and officials need to discuss challenges and agree on policy strategies. The study shows how linking data collection, processing, and clear visual output creates a decision-support tool that helps turn complex urban information into knowledge that can guide real interventions with real stakeholders.

Keywords Urban Digital Twin; AI; simulations; evidence-based; policy making

Sažetak Ovo istraživanje opisuje Urban Digital Twin (UDT) Sarajeva kao primijenjeni alat za urbano planiranje i adekvatnu prezentaciju kompleksnih rezultata simulacija široj publici. Razvijen u okviru projekta Urban Transformation Project Sarajevo (UTPS), rad objašnjava kako se saobraćajne simulacije iz softvera EnerPol sa ETH Zurich (ETHZ) transformišu iz sirovih binarnih datoteka u vremenski zasnovane scene u ArcGIS Pro (ESRI). U područjima s ograničenim lokalnim podacima, satelitski snimci se koriste za kreiranje osnovnog 3D modela grada. U nastavku se opisuje kako se iz gabarita i visina objekata izvlače podaci ne samo za generisanje modela sa Nivoom Detaljnosti 2 (LOD2) koji uključuje oblike krovova i precizne konture, već i za dobivanje informacija o pokrovnom sloju tla koje su ključne za UDT. Automatizirani radni tok pretvara simulacijske događaje u georeferencirane elemente i uparuje ih s mrežom ulica, omogućavajući planerima da posmatraju kako se obrasci saobraćaja mijenjaju tokom dana na osnovu različitih pretpostavki o promjenama populacije. Ključna svrha UDT-a jeste da ovi podaci i scenariji postanu vidljivi i razumljivi ljudima različitih profesionalnih profila. Nudeći zajednički vizuelni referentni okvir, model podržava procese planiranja u kojima građani, stručnjaci i zvaničnici trebaju razgovarati o izazovima i usaglasiti se oko strateških pravaca politika. Studija pokazuje kako povezivanje prikupljanja podataka, njihove obrade i jasnog vizuelnog prikaza stvara alat za podršku odlučivanju koji pomaže pretvoriti kompleksne urbane informacije u znanje koje može voditi ka stvarnim intervencijama sa stvarnim akterima.

Ključne riječi urbanistički digitalni blizanac; AI; simulacije; zasnovano-na-dokazima; donošenje zakona

1 Introduction

Cities around the world are increasingly using urban digital twins as more than just 3D visualizations. They are becoming tools for planning, decision-making, and helping people understand complex urban systems, revealing dependencies that are not recognizable at first sight. Recent developments focus on three main ideas. First, semantic and geometric interoperability allows different types of models, like BIM models, GIS datasets, and simulation outputs, to work together while keeping both the meaning and shape of objects correct (Shareef, 2023). Second, real-time data from sensors can monitor current urban conditions such as traffic flow, air quality, or energy use (Najafi, 2024). Third, simulations and predictive models are used to explore how the city might respond to different changes, for example, shifts in mobility patterns, new transport infrastructure, or population growth. These simulations are based on rules, physics, and observed behavior, and in some cases, AI is applied to fill gaps or estimate uncertainties where data are missing (Teutscher, 2025) (Figure 1).

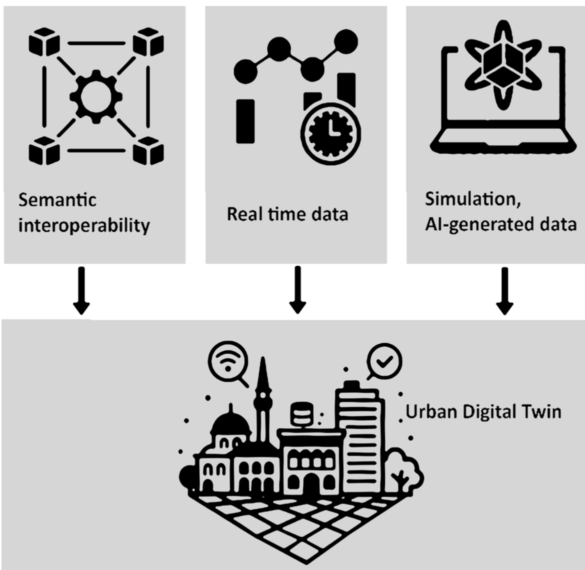

Figure 1 Schematic representation of the core components of an Urban Digital Twin (UDT). Source: Authors, 2025.

Together, these developments turn digital twins from simple replicas into interactive tools for testing policies, planning infrastructure, and involving citizens and experts in decisions.

The Sarajevo Urban Digital Twin (UDT) was developed as part of the Urban Transformation Project Sarajevo (UTPS) using ESRI ArcGIS Pro. It integrates agent-based traffic simulations from EnerPol. More details of EnerPol and the agent-based population model, and the agent-based, multi-modal, queue-based traffic model with which the Sarajevo UDT is coupled, can be found elsewhere (Walczak et al. 2025). Where local data is limited, satellite imagery is used to construct the base 3D city model. Building footprints and heights are extracted to generate Level of Detail 2 (LOD2) models, including roof shapes, precise outlines, building segmentation, and land cover information.

Building and using urban digital twins comes with several challenges. Differences between data formats, very large models, and linking detailed simulation outputs to visualizations all need to be managed while keeping data accurate and traceable. In the case of the Sarajevo UDT the raw binary outputs from agent-based traffic simulations are transformed into georeferenced features that can be displayed in a 3D GIS scene. This transformation generates extremely large datasets that are often too big to load fully into a single ArcGIS Pro scene, particularly when time is included as a fourth dimension, making the model dynamic and continuously changing, for example, with traffic flows. With the resources and tools currently available, only shorter time sequences can be visualized at a time, and the data must be aggregated, which inevitably leads to some loss of detail and resolution.

Sarajevo provides a compelling context for this UDT. Its narrow valley morphology, legacy heating systems, and winter inversion events cause episodic air pollution and traffic bottlenecks, affecting public health and economic activity. At the same time, ongoing initiatives such as the UTPS provide an opportunity to test data driven planning scenarios and assess potential interventions.

Applied to Sarajevo, the UDT supports both short term and long-term planning. Planners can test immediate changes, such as traffic rerouting or infrastructure upgrades, and observe potential effects before implementation. Over longer horizons, it can simulate different scenarios, enabling comparison for informed strategic decisions. These capabilities make the digital twin a versatile tool for operational planning as well as long term urban development. The workflow developed for Sarajevo is described in detail in the following sections.

The article is structured as follows. Section 1 reviews debates on UDTs. Section 2 describes Sarajevo and the UTPS. Section 3 details the data model, mapping, and technical implementation. Section 4 presents scenario results. Section 5 discusses governance and scalability. Section 6 concludes with lessons learned and future directions.

2 Theoretical Framework and State of the Art

2.1 Defining UDTs

The concept of the DT originates from aerospace engineering, where digital replicas of physical systems are employed to monitor, test, and optimize performance (Simio, 2025). In the urban context, an Urban UDT can be defined as a dynamic, multi-scale, and semantically enriched digital model of a city that is constantly updated with real-world data streams (Peldon, 2024).

Unlike static 3D city models, UDTs are distinguished by bidirectional data exchange between the physical city and its digital counterpart, the integration of heterogeneous domains such as buildings, infrastructure, energy, environment, and mobility, and the capability to support predictive scenario testing for informed decision-making (Mazetto, 2024).

Recent literature emphasizes that UDTs go beyond detailed GIS environments, functioning as socio-technical systems that combine data models, simulation engines, governance frameworks, and user interfaces. This perspective highlights their role as active planning instruments rather than mere visualization tools (Ruohomäki, 2023; Magnasoft, 2025).

2.2 Current Innovations in UDTs

In the past five years, UDT research and practice have accelerated, driven by advances in data availability, cloud computing, and interoperability standards. The most prominent innovative directions include:

2.2.1 Real-Time Data Integration

Cities such as Singapore, Helsinki, and Rotterdam have piloted integration of IoT sensor data into their digital twins, enabling near real-time updates on traffic flows, energy demand, and environmental conditions. This continuous synchronization transforms the twin into a living model capable of supporting operational decision-making (e.g., instant traffic management, disaster response) (Virtanen, 2024; Mazetto, 2024; Adreani, 2024).

2.2.2 Semantic Interoperability

One of the longstanding obstacles in urban informatics is the semantic mismatch between BIM (Building Information Modeling) and GIS (Geoinformation Systems). Current research addresses this gap through standards such as CityGML 3.0 and IFC-to-GIS translation schemas, which allow building-level details to be embedded in city-scale models. Semantic interoperability ensures that UDTs are scalable and reusable across multiple planning domains (Yi Tan, 2023).

2.2.3. Coupling with Simulation Engines

Beyond visualization, UDTs increasingly embed or link to simulation frameworks, such as agent-based models, energy system simulators, or climate impact models. This coupling allows cities to test counterfactual scenarios like the change of heating systems or adding a tram line within the digital twin environment. The Sarajevo project is part of this trajectory, linking ESRI's 3D GIS-Model with EnerPol's high-resolution mobility and energy simulations.

2.2.4. AI and Predictive Analytics

Generative AI and machine learning are increasingly used to fill gaps in urban data, such as estimating building attributes where cadastral records are missing, predicting future conditions, and detecting anomalies in urban systems. By analyzing large datasets, AI can help to make this process fast, efficient and accurate.

In the Sarajevo model, AI and deep learning techniques were applied to segment building footprints into parts with different heights, allowing a more detailed representation of roof shapes and elevations. AI-enhanced digital twins thus combine data-driven inference with simulation, enabling planners to anticipate future conditions and providing probabilistic insights under uncertainty, anticipating the unprecedented.

2.2.5 Participatory and Governance-Oriented Uses

A further innovation is the use of UDTs as participatory platforms. By publishing interactive and immersive 3D environments online, municipalities can involve citizens and stakeholders in co-designing urban futures, increasing transparency and democratizing planning. This approach also requires well-defined governance protocols for data ownership and privacy. As part of the UTPS, the Sarajevo urban digital twin has been made publicly accessible through an online platform that provides information about the new campus development of the University of Sarajevo. The platform was linked to a survey, allowing participants to interact directly with the digital twin and providing an opportunity to collect valuable insights and personal opinions.

2.3 Research Gaps and Challenges

Despite recent advances, several issues remain to be addressed in the implementation of urban digital twins. A central issue is convincing professionals from different fields to work with a single shared model, which requires coordination and trust. Keeping the digital twin up to date depends on either specialists manually updating the model or automized techniques that incorporate changes in the urban fabric. At present, many experts continue to work with their own individual models, leaving a gap between simu-lation outputs, GIS platforms, and planning practice. High-fidelity simulations, such as agent-based traffic models, generate complex outputs that require significant processing before they can be integrated into a digital twin. The steps in between often involve computationally intensive processes. Streamlining these steps would allow different scenarios to be represented quickly and dynamically, making the model more accessible for planning purposes.

These points highlight the importance of demonstrating a replicable workflow in Sarajevo. By building a city-scale 3D model, integrating it with EnerPol simulation outputs, and deploying it as an interactive platform, the project provides a concrete example of how a digital twin can directly support planning decisions while bridging gaps between research, technology, and practice.

2.4 Conceptual Positioning of this Study

This work positions itself within interconnected discussions in the field of UDTs. It highlights the operationalization of DTs, moving beyond prototypes to create decision-support environments that can be used directly by planning institutions. It also demonstrates practical workflows for integrating high-resolution traffic simulations and other data sources into a 3D city model, making complex outputs accessible and interpretable for planning purposes. At the same time, it extends the discourse on urban transformation to medium-sized cities, illustrating how digital twins can support planning in contexts where air pollution, transport inefficiency, and fragmented governance present significant challenges. By addressing these points, the project contributes both methodological innovations, through a replicable technical workflow, and contextual relevance, by applying the digital twin concept to a post-socialist urban environment with pressing mobility and environmental concerns.

The following Section introduces the study area and outlines the urban challenges that motivated the Urban Transformation Project Sarajevo. It also provides an in-depth overview of the project's achievements. The UTPS is a collaborative, multi-year, multi-stakeholder initiative aimed at modernizing the urban planning system in the Canton of Sarajevo. It was developed jointly by ETH Zurich Chair of Architecture and Urban Design, ETH Zurich Laboratory for Energy Conversion, the University of Sarajevo Faculty of Architecture, the Sarajevo Canton Institute of Development and Planning, and ETH Zurich Spin-Off SwissAI, with support from the Swiss State Secretariat for Economic Affairs (SECO).

3 Study Area and Context

3.1 Geographic and Morphological Setting

Sarajevo, the capital of Bosnia and Herzegovina, lies at about 518 m elevation in a narrow east–west valley of the central Dinaric Alps, where the Miljacka River cuts through steep limestone and flysch slopes. Four main municipalities (Stari Grad, Centar, Novo Sarajevo, and Novi Grad) occupy the valley floor, while newer housing districts extend upslope onto surrounding hills and plateaus such as Trebević and Hum. The encircling mountains create strong temperature inversions in winter and leave little flat land for expansion, shaping both traffic patterns and air-quality problems (Walczak 2024).

Development on these steep, geologically unstable hillsides increase susceptibility to rainfall-triggered landslides, a recurring hazard in neighborhoods like Širokača and Bistrik. Unregulated construction and deforestation further destabilize slopes, making careful geospatial analysis and digital-twin monitoring essential for sustainable planning.

3.2 Demographic and Urban Development Trends

The Sarajevo metropolitan area is home to about 400,000 residents, concentrated along the valley's east–west corridor. Post-war reconstruction and economic transition produced a heterogeneous urban fabric in which high-density residential blocks sit alongside hillside neighborhoods that began as informal settlements (Figure 2). Many of these areas have since been gradually formalized through municipal planning and infrastructure upgrades, though building standards and service quality remain uneven. In recent years the population has grown only slowly but rising car ownership and limited public-transport capacity continue to generate congestion hotspots that shift over the course of the day, conditions well suited to scenario-based mobility modeling within a DT.

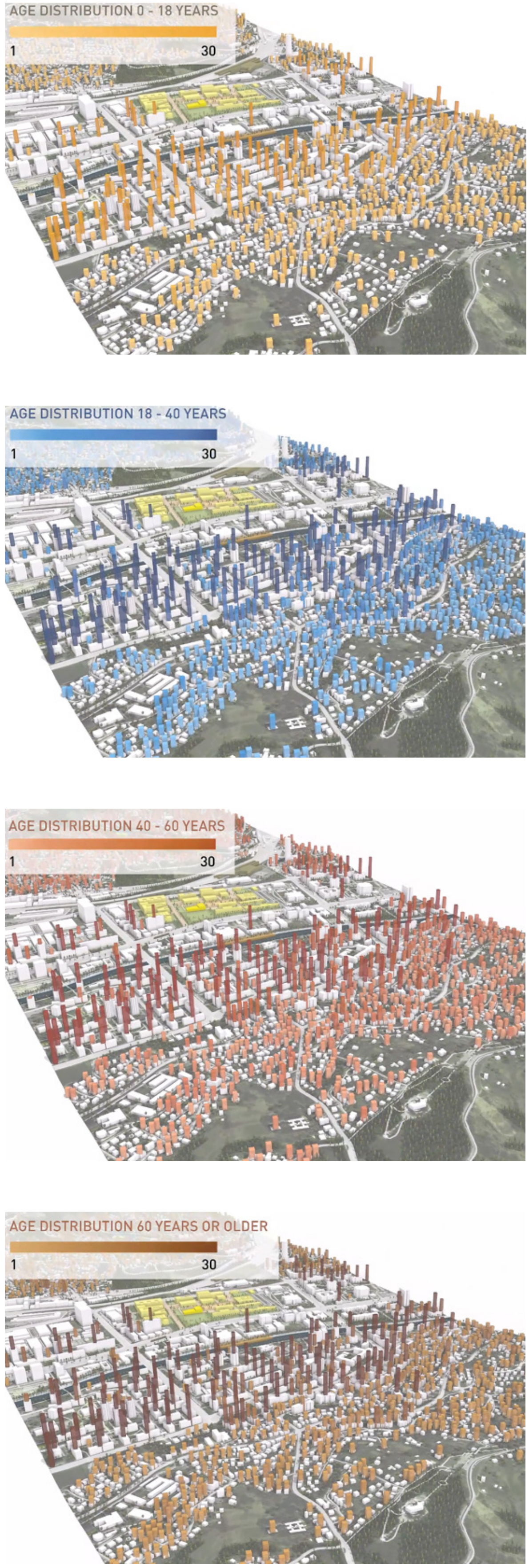

Figure 2 Population distribution in Centar, Sarajevo: ages 0–18, ages 18–40, ages 40–60, ages 60 and above. Source: Authors, 2025.

3.3 Mobility Challenges

Mobility is one of Sarajevo's most urgent planning challenges. Traffic congestion is a recurring issue along the city's central artery connecting Stari Grad to Ilidža, intensified by limited lateral connections across the valley. The public transport network still relies heavily on its historic tram corridor, but suffers from ageing vehicles, narrow coverage, and weak integration with bus and minibus services. Over the past two decades, car ownership has grown significantly, contributing not only to severe congestion but also to worsening air quality (BHAS).

Seasonal tourism further stresses mobility networks. In 2024, Sarajevo Canton saw a large increase in tourist arrivals, putting extra load on transport infrastructure especially during weekends and holiday periods (BHAS).

There are ongoing improvements: Sarajevo has launched a tram modernization project, with new tram tracks and vehicles, extensions to tram lines (for example toward Hrasnica), and investment in trolleybuses to improve system capacity and environmental performance.

An UDT, which integrates agent-based traffic simulations, can help clarify these dynamics. By comparing baseline conditions with scenarios like upgraded tram service or shifts toward walking, cycling or shared mobility, planners can see how interventions may reduce congestion, improve air quality, and make mobility more resilient.

3.4 Energy and Environmental Pressures

Sarajevo experiences some of the highest winter air pollution levels in Europe, with concentrations of fine particulate matter ($PM_{2.5}$ and PM_{10}) frequently exceeding World Health Organization guidelines. Emissions originate from multiple sources (Walczak 2024). The district-heating system relies primarily on natural gas and fuel oil, while older buildings continue to burn wood or coal. The national power grid is dominated by coal-fired generation, and vehicular traffic contributes additional pollutants. The city's narrow valley topography traps emissions under temperature inversions, prolonging episodes of poor air quality (Walczak 2024).

The resulting health impacts are considerable, including elevated rates of respiratory and cardiovascular diseases and increased hospital admissions, particularly among vulnerable populations. Efforts to modernize heating networks, expand public transport, and promote cleaner fuels have been initiated, but progress remains uneven (AP News 2023; Balkan Green Energy News 2022).

The UDT of Sarajevo integrates building-energy data and traffic flows, and meteorological conditions. By incorporating the detailed 3D building model with accurate roof geometries, it allows the calculation of solar potential on individual roofs, supporting the identification of alternative energy sources and the reduction of reliance on polluting fuels. Such UDTs also enable scenario testing for interventions such as large-scale building retrofits and adaptive traffic management, facilitating evaluation of the most effective strategies before implementation.

3.5 Governance and Planning Capacity

Urban planning responsibilities in Sarajevo are shaped by an institutional and political landscape for land use, transport, and environmental management distributed among the Sarajevo Canton, the City of Sarajevo, and multiple municipal administrations.

In this context, the UDT provides a shared platform that bridges administrative silos, aligns stakeholders around a common understanding of the urban environment, and supports evidence-based, coordinated decision-making despite political, institutional, and social fragmentation.

The proposed theory of change here is shifting from a vertical silo to a horizontal collaborative environment. Moreover, it can actively involve the population by providing accessible visualizations and interactive tools, enabling citizens to engage with planning scenarios and contribute to discussions on urban development.

3.6 Data Availability and Digitalization Efforts

Sarajevo has gradually expanded its digital data infrastructure, including cadastral building footprints, transport network datasets, and environmental monitoring stations. However, datasets are often inconsistent in quality, resolution, and accessibility. These gaps necessitate data fusion strategies, combining official records, open data, and modeled estimates. The Sarajevo UDT project addresses this through the integration of EnerPol's simulation outputs, which supplement sparse observations with calibrated predictions of traffic flows and emissions.

The ongoing LiDAR project led by the Federal Administration for Geodetic and Real Property Affairs, financed through EU IPA II 2019 funds, aims to produce high-resolution digital terrain and surface models for the city and surrounding areas. Incorporating LiDAR data into the digital twin would significantly enhance spatial accuracy, including building heights and terrain variations, improving simulations for solar potential, flood risk, and urban heat islands.

This development would further support informed planning and environmental management while fostering data sharing and collaboration among stakeholders. (FGU, 2019)

3.7 Urban Transformation Project Sarajevo

The UTPS has achieved several key milestones in modernizing urban planning practices within the Sarajevo Canton. A central outcome is the support in the development of the General Urban Plan 2040 (Walczak et al. 2023) (Figure 3), created through participatory processes involving municipal authorities, urban professionals, and citizens. These processes were crucial for securing public acceptance of the urban plan, fostering dialogue and consensus among diverse stakeholders. The plan not only provides a strategic framework to guide sustainable urban development but also emphasizes improving the safety and resilience of the city, addressing natural hazards such as flooding and landslides.

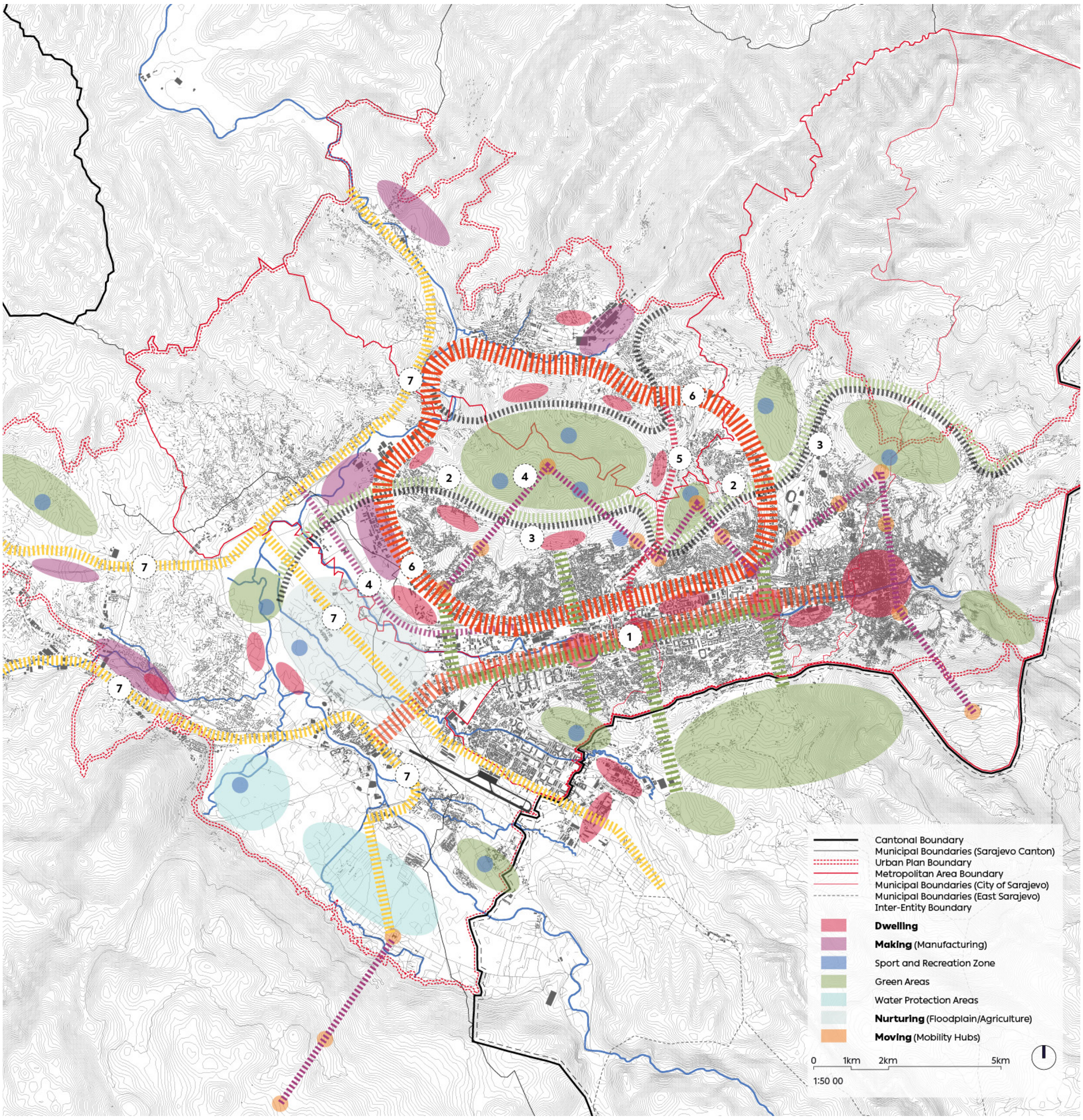

Figure 3 New urban plan describing the urban development around the city hill Hum and Žuč as a green centre. Source: Authors, 2023.

Alongside the urban plan, the UDT of Sarajevo has been established (Walczak et al. 2025). By integrating data from diverse sources, this dynamic model represents the city's infrastructure and environment, enabling evidence-based decision-making and scenario testing for urban development initiatives. Currently, a small-scale urban intervention is being developed for the university campus, which also impacts the revitalization of public spaces in the Marijin Dvor neighborhood. These prototypes serve as experimental grounds for innovative urban solutions and actively involve the local community in shaping the transformation process and show prototypically how the abstract urban plan translates into concrete architectural projects.

The project has further contributed to capacity building through workshops, exhibitions, and collaborative sessions, strengthening the skills of local authorities and urban professionals (Pagani et al. 2025). Collectively, these achievements demonstrate the potential of participatory, data-informed approaches to support sustainable and resilient urban transformation in Sarajevo and provide a model that can be adapted to other medium-sized, post-socialist cities facing similar planning and governance challenges.

3.8 Section Summary

Sarajevo's urban context is defined by morphological constraints, rising mobility demand, severe seasonal air pollution, and fragmented governance. While these conditions pose significant challenges, they also underscore the value of adopting a digital twin as a cross-cutting planning instrument. The Sarajevo case provides not only a critical local application but also a globally relevant demonstration of how digital twin technologies can be mobilized in cities beyond the global flagship examples. The experiences from Sarajevo can guide other post-socialist cities with narrow valleys and limited resources that face similar urban and environmental challenges. The next chapter outlines the methodological framework developed to construct and operationalize the Sarajevo UDT.

4 Methodology

4.1 Conceptual Framework

The Sarajevo UDT is built around a structured workflow that begins with a comprehensive base model of the city. This model includes topography, buildings with detailed roof shapes, streets, trees, public transport networks, energy use, and demographic data, providing a robust foundation for analysis. Agent-based traffic and energy simulations were then conducted using the EnerPol framework. These simulation outputs were processed through Python scripts to transform them into a format compatible with the ArcGIS model and subsequently symbolized into a visually interpretable design. This integration enables dynamic processes, such as traffic flows or energy demand, to be represented directly on the city model.

The approach is designed to be flexible and extendable, allowing additional datasets or future simulation outputs to be incorporated without restructuring the core model. By maintaining this compatibility between simulations and the geospatial environment, the UDT supports clear, interactive representations of complex urban dynamics.

Figure 4 Segmentation of the building footprints to enhance the LOD. Source: Authors, 2025.

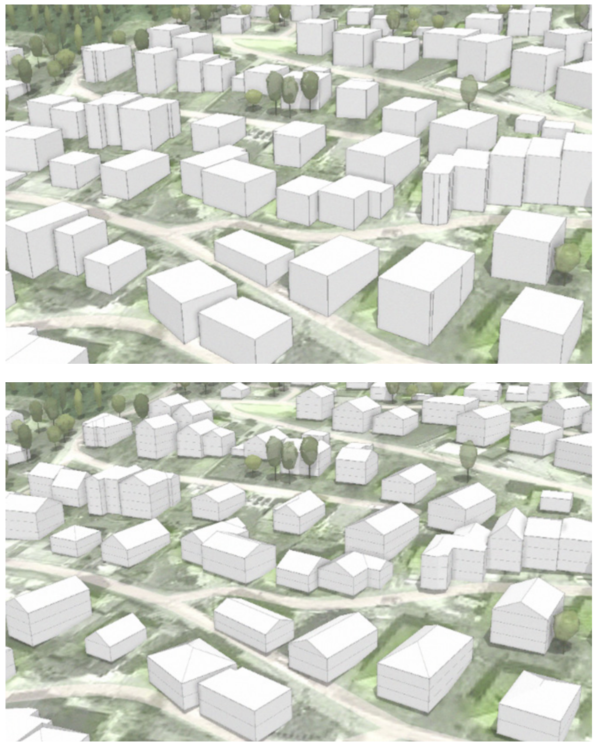

Figure 5 Enhancement from LOD1 to LOD2 through photogrammetry. Source: Authors, 2025.

4.2 Data Sources and Base Model

The Sarajevo UDT was developed using the ESRI ArcGIS Pro platform, a leading solution in the field of geographic information systems. ArcGIS Pro provides extensive tools for data management, analysis, and visualization, along with strong interoperability with other platforms, making it particularly suitable for constructing comprehensive urban models and supporting interdisciplinary applications. In addition, the platform allows models to be published and made accessible online, enabling stakeholders and the public to explore and interact with the digital twin directly through web-based interfaces.

A digital elevation model (DEM) of the grid size of 6m was used to capture the valley morphology. Cadastral building footprints, road and tramway networks, public transportation and demographic data were provided by the planning institute of Sarajevo.

The project was further supported by a sponsorship from the European Space Agency's Network of Resources (NoR), which provided access to high-resolution satellite imagery and a digital surface model (DSM) through the UP42 platform. This support enabled the acquisition of precise datasets like the buildings, where official GIS data were incomplete or of limited quality. In such locations, it proved efficient to derive additional information directly from satellite imagery, allowing for the extraction of critical urban features.

To enhance the representation of buildings, artificial intelligence techniques were applied to satellite imagery. A deep learning model was trained to segment building footprints into smaller components, enabling the construction of a more accurate threedimensional model that reflects variations in roof heights and distinguishes individual roof shapes. This segmentation step was essential for capturing the complex morphology of larger buildings and multi-compartment structures (Figure 4).

Once the building footprints were segmented into smaller, more precise components, the resulting model underwent a cleaning process to remove errors, inconsistencies, and artefacts from the segmentation. Photogrammetry techniques were then applied to derive building heights by subtracting the digital elevation model (DEM), representing the bare terrain, from the digital surface model (DSM), which includes buildings and other surface features. This raster-based approach allowed the calculation of elevations for each building segment, producing a Level of Detail 2 (LOD2) model that captures roof shapes and height variations, providing a more accurate volumetric representation than flat-roof (LOD1) models (Figure 5).

Using our model in ESRI's Image Analyst, we applied a pretrained deep learning model to detect trees in the satellite imagery. The model identified tree crowns based on shape, texture, and spectral patterns, and the results were refined and post processed to enhance accuracy.

These steps produced a comprehensive and robust base model of Sarajevo's urban fabric, offering sufficient precision for subsequent analyses. This includes calculating solar potential on roofs to identify alternative energy solutions, assessing shadow patterns, and integrating with mobility or energy simulations, thereby supporting environmental planning and related initiatives.

4.3 EnerPol Agentic AI Simulations

The EnerPol software developed at ETH Zurich, is an agentic AI modeling environment deployed to simulate Sarajevo's demographic, mobility and energy dynamics. The platform represents individual agents, including inhabitants and vehicles, each governed by behavioural rules, enabling a bottom-up and realistic depiction of urban flows. Temporal granularity is maintained through minute-level timesteps, capturing peak-hour congestion and fluctuations in traffic patterns. Scenario flexibility allows policy interventions — such as vehicle restrictions, tram upgrades, or residential heating

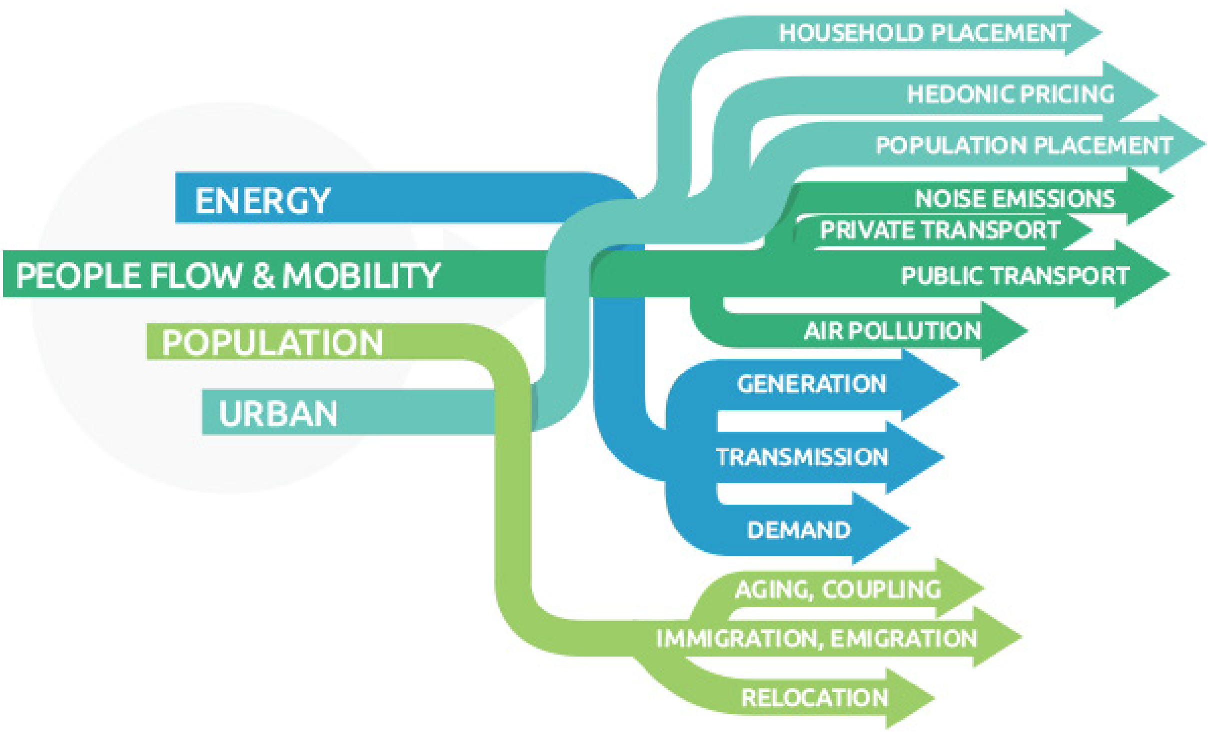

Figure 6 EnerPol framework linking high-resolution modules to enable comprehensive data-driven analysis. Source: Laboratory for Energy Conversion, ETH Zürich, 2019.

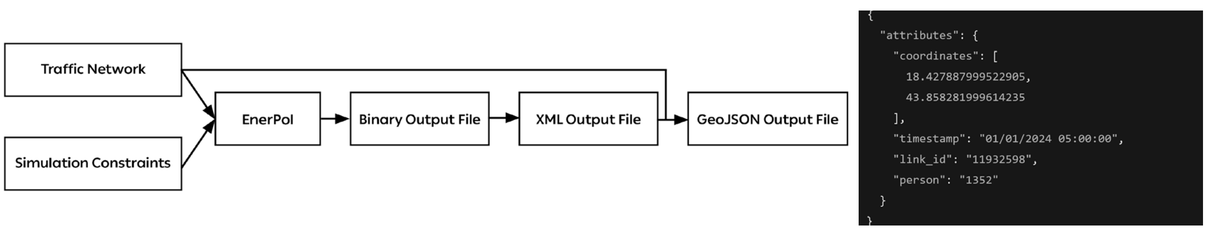

Figure 7a Procedure to make data outputs compatible with GIS environments. Source: Authors, 2025.;
7b Feature attributes of the postprocessed simulation output. Source: Authors, 2025.

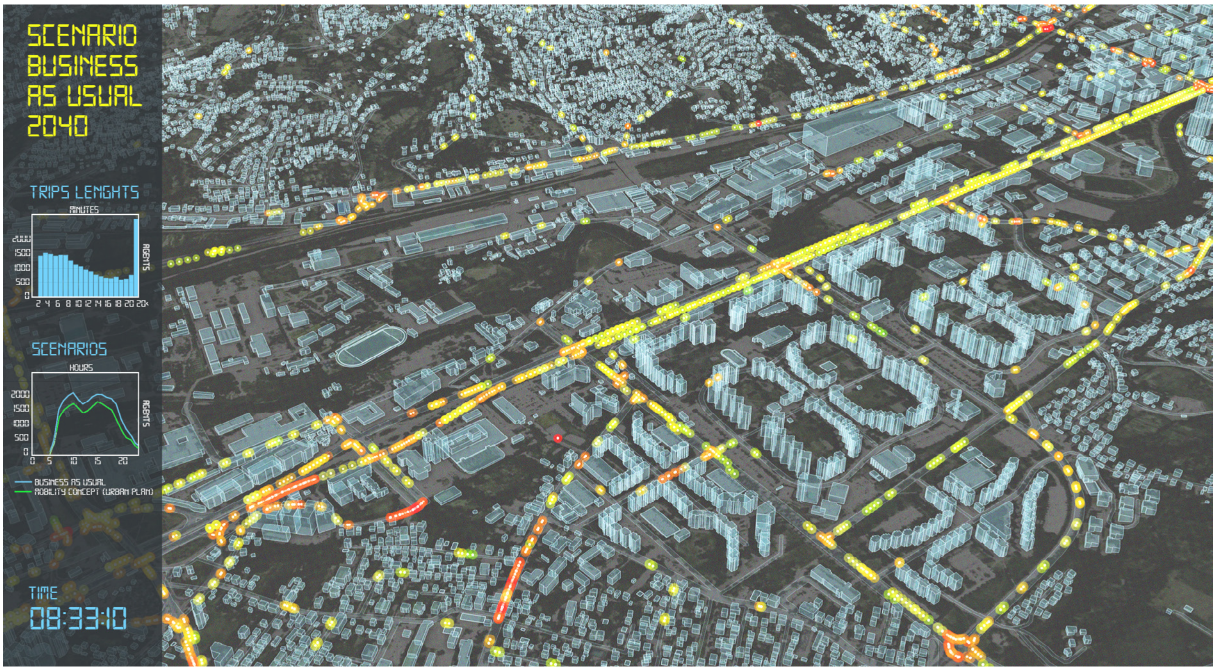

Figure 8 Traffic simulation data in 4D GIS environment. Source: Authors, 2025.

retrofits — to be encoded as alternative behavioural or infrastructural parameters.

Traffic simulations are calibrated with local traffic counts and household survey data to reflect actual mobility patterns. In parallel, energy scenarios, particularly residential heating demand, are modeled to estimate consumption across building typologies and fuel types. By combining traffic and energy output with information on vehicle fleet composition and heating technologies, the platform generates spatially referenced emissions estimates for pollutants such as fine particulate matter (PM) and nitrogen oxides (NOx).

Outputs from EnerPol include origin–destination matrices, traffic density maps expressed in vehicles per hour per link, energy consumption by building and heating type, and emissions distributions linked to road segments and building clusters, see figure 6.

More information on EnerPol and the agent-based model can be found elsewhere, Pagani et al. (2023).

4.4 Coupling Simulations with 3D Environment

Direct conversion from EnerPol's native binary files to a georeferenced GeoJSON was not possible. Instead, the binary files were first transformed into XML using pre-existing conversion scripts. These XML files provide a human-readable record of agent "events," each linked to a timestamp and a network segment identifier rather than explicit geographic coordinates. Geographic coordinates and routing information for streets and rail sections were maintained separately in a GeoPackage file (Figure 7a).

During post-processing, each event in the XML was matched with its corresponding network segment in the GeoPackage, retrieving accurate spatial coordinates. This process transformed abstract event data into spatially located features, each defined by a coordinate pair, timestamp, agent ID, and network segment ID. Due to the computational demands of these operations, post-processing was performed on ETH Zurich's supercomputer, the Euler Cluster, ensuring efficient handling of the large-scale simulation datasets (Figure 7b).

Once georeferenced, the processed data was imported as a feature class into the GIS base model. Points were symbolized according to velocity, with slow-moving agents represented in red and faster-moving agents in green, providing a visual representation of traffic congestion along road segments. The feature class was enabled for temporal display, allowing a time slide to show the evolution of traffic within defined intervals. The final visualization was exported as an animation, serving as a ready-to-use tool for presentations, stakeholder discussions, and further scenario analyses.

4.4.1 Innovative Coupling Aspects

The integration workflow supports dynamic spatio-temporal visualization, enabling users to "play" simulation scenarios over time. Interactive dashboards provide key metrics, including travel time, emissions, and exposure, directly linked to spatial outputs (Figure 8).

ESRI Experience Builder is being developed to present these results in a participatory format, connecting technical analyses with stakeholder engagement and public dialogue. This combination of precise post-processing, 4D visualization, and interactive dissemination demonstrates a novel approach to coupling agent-based simulation outputs with urban digital twin environments, while ongoing work aims to further enhance accessibility and user interaction.

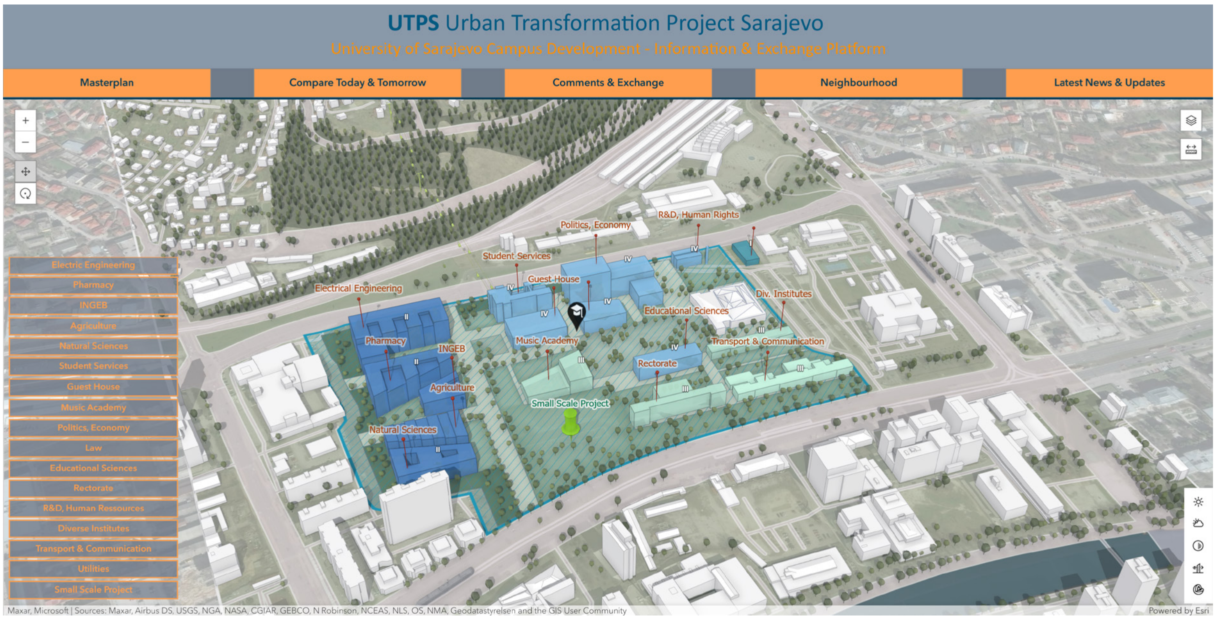

Figure 9 Online information platform showcasing campus development at the University of Sarajevo, with potential future integration of BIM models to provide details on room programs and indoor navigation. Source: Authors, 2025.

4.5 Next steps and future development

4.5.1 Real-Time Potential

While the current UDT operates primarily with modeled scenarios, it allows future integration of real-time data streams, such as air quality sensors, live traffic feeds, and other urban monitoring systems. This could transform the Sarajevo UDT into a near-operational system capable of continuous monitoring and dynamic response.

4.5.2 Scenario Generation

Generative models can be employed to automatically propose alternative planning scenarios. By leveraging tools such as ArcGIS Urban, these scenarios can be analyzed for development potential and linked to quantitative metrics, including infrastructure requirements, energy consumption, population density, and other urban indicators. This enables the visualization of direct consequences associated with different planning interventions.

4.5.3 Participatory Interfaces

The workflow is designed to support participatory planning processes. Stakeholders and citizens can interact with scenarios through accessible web-based portals, enhancing transparency and enabling collective decision-making. The inclusion of BIM models for the faculties of the University of Sarajevo campus further strengthens the model's semantic interoperability and provides a public-facing representation of ongoing campus development within the broader urban context (Figure 9).

4.6 Section Summary

The Sarajevo digital twin methodology integrates ESRI's 3D GIS environment with high-resolution simulation outputs from EnerPol. By combining semantic interoperability and spatio-temporal scenario visualization, this approach reflects current trends in urban digital twin research. Importantly, it demonstrates how advanced simulation and visualization workflows can be operationalized in a medium-sized city facing complex urban challenges, offering both scientific insights and practical contributions to the global discourse on digital twins for urban transformation.

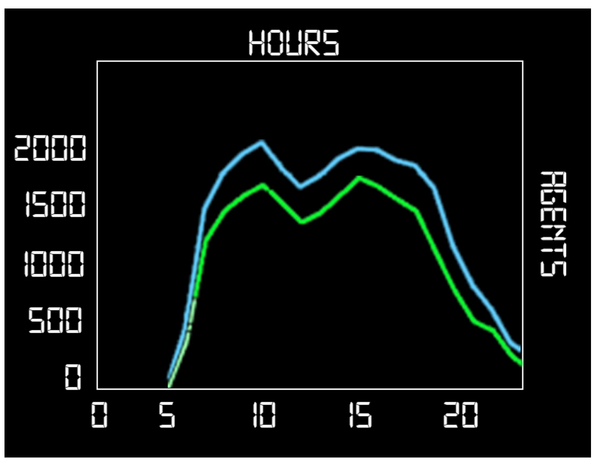

Figure 10 Traffic scenario comparison: blue: Baseline (streets as they are in Sarajevo); green: new urban plan (mobility concept together with all new and existing streets). Source: Authors, 2025.

Figure 11 Public hearing in Sarajevo using the Digital Twin. Source: Authors, 2024.

5 Results

5.1 Overview of the Sarajevo Urban Digital Twin

The implemented Sarajevo UDT provides a city-scale, semantically enriched 3D environment that integrates geo-spatial base data, agent-based mobility and energy simulations and scenario dashboards. The UDT has been successfully deployed within the ESRI ecosystem and is currently being made available online, allowing access for everyone. The result is not a static visualization but a dynamic analytical tool capable of simulating and comparing future policy interventions.

5.2 Scenarios "Business as Usual" and "Growth"

The baseline scenario "Business as Usual" assumes modest population growth, existing levels of infrastructure investment, and continuation of current mobility and energy behavior patterns. Private vehicle use remains dominant while public transport accounts for less than 30 percent of trips. Walking and cycling improve only marginally. Energy demand increases moderately, especially in peri-urban or hillside areas. The challenge of pollution and traffic congestion increased, particularly along major arterial roads and in valleys or basin areas where topography and climate (e.g. inversion) exacerbate air quality issues.

Figure 12 Hack-Archthon at the "Urban Design Studio Sarajevo". Source: Authors, 2023.

In the scenario growth, the population and housing demand rise more sharply; infrastructure (roads, public transport, energy) is expanded, more infill development and densification are assumed, and policies favoring sustainable mobility and energy efficiency are more strongly adopted. Public transport usage increases, energy systems are upgraded (building retrofits, cleaner heating, more efficient supply), and new infrastructure fills gaps, especially in peripheral and hillside zones. The result is that, although traffic congestion and emissions still increase compared to today, their negative impacts are less severe than under Business as Usual; air quality improves relative to the baseline BAU scenario, especially in neighborhoods where interventions are concentrated (Figure 10).

These results provided a robust reference point about traffic for elaborating the urban plan. Based on the insights from these scenarios, the following chapter focuses on the visualization of these different development options, showing how the generated visualizations were used to communicate planning choices during public hearings and to produce media materials supporting the new urban plan.

5.3 Participatory Processes in Sarajevo's Urban Transformation

The participatory processes in Sarajevo's urban transformation were greatly strengthened through the use of advanced simulation tools and community engagement strategies, in collaboration between the Sarajevo Canton Institute of Development and Planning, the University of Sarajevo, and the Chair of Architecture and Urban Design at ETH Zürich. These tools enabled planners, stakeholders, and residents to explore and discuss potential development options in an accessible and tangible way, making the planning process more transparent and inclusive.

5.3.1 Community Engagement and Public Hearings

Visualisations of the city, including both physical and digital models, were central to public hearings across all nine municipalities of Sarajevo (Figure 11). Residents could see projected changes directly overlaid onto a city model, helping them understand the impact of different planning options and provide informed feedback. A web-based digital model further allowed remote participation, ensuring broader engagement for those unable to attend in person.

5.3.2 Educational Initiatives and Collaborative Workshops

Workshops such as the "Hack Archthon" used these visualisations as a basis for collaborative problem-solving, bringing together students, professionals, and local stakeholders. Interactive representations of urban scenarios encouraged discussion, innovation, and a shared understanding of the city's development challenges in the "Urban Design Studio Sarajevo" project space (Figure 12).

5.3.3 Media Outreach and Public Awareness

To further engage the public, visualizations and findings from the urban transformation project were disseminated through various media channels. Television segments were produced to showcase the project's progress and its potential impact on the city's future. These media efforts played a crucial role in raising awareness and garnering support for the urban transformation initiatives.

5.3.4 Section Conclusion

By placing visualisation at the core of participatory processes, ETH Zürich and Sarajevo's local institutions created a model for collaborative urban planning. The ability to see, explore, and discuss future scenarios empowered residents and stakeholders, fostering more informed decision-making and broader public engagement in shaping Sarajevo's urban development.

For a visual representation of the project's impact and community involvement, you can refer to the following video: youtu.be/r84BamC46fo

5.4 Interactive Visualization and Communication

A key goal of the Sarajevo UDT is to create an interactive platform that makes the development process more transparent and allows people to engage with the data. Users will be able to access an online model to explore the results and contribute to the planning process through surveys or other participatory tools.

The interface is currently under development and aims to move beyond static outputs, offering dynamic maps and temporal playback to visualize urban dynamics across different time steps. Scenario dashboards link key performance indicators such as travel times, pollutant emissions, and exposure levels to spatial data, providing both analytical depth and communicative clarity. This interactive platform is intended to support planners, stakeholders, and the wider public in understanding complex urban processes and fostering greater acceptance of the city's development plans.

5.5 Chapter Summary

The Sarajevo UDT demonstrates the feasibility and value of combining 3D GIS models with high-resolution simulations for scenario-based urban planning. The results underscore that no single intervention solves Sarajevo's challenges, but digital twins can illuminate the complex trade-offs and synergies between different urban development strategies. The interactive visualization capacity transforms abstract simulations into actionable planning insights, providing Sarajevo with an example of how medium-sized cities can harness digital twin technologies for evidence-based decision-making.

6 Discussion

6.1 UDTs Beyond Visualization

One of the central debates in the current discourse on UDT in urban planning is whether they serve primarily as visualization platforms or as decision-making instruments. The Sarajevo case demonstrates that the true value lies in the latter. By coupling agent-based simulations of mobility and energy demand with the visualization tools of ESRI, the Sarajevo digital twin exemplifies the shift from descriptive to predictive and prescriptive models. This aligns with the emerging consensus in urban analytics that twins should not only reproduce the present but actively test interventions and anticipate unintended consequences.

6.2 Multi-Domain Integration as a New Paradigm

Globally, most UDT have been developed in siloed domains (transport-focused twins, energy-focused twins, or climate resilience twins). The Sarajevo application demonstrates the added value of cross-domain integration. This multi-domain coupling reflects a new paradigm of digital twins as urban system integrators, a trend echoed in leading projects in Singapore, Helsinki, and Rotterdam. Sarajevo thus contributes to a rare case where such integration is tested in a medium-sized, resource-constrained European city.

6.3 Data Scarcity and AI-Augmented Solutions

A key challenge for many cities outside of global capitals is data scarcity. Sarajevo exemplifies this, with incomplete transport counts, missing building attributes, and sparse emission monitoring. The project demonstrates how AI-assisted data augmentation and model-based inference can fill these gaps while making uncertainty explicit. Globally, this corresponds to a shift toward "approximate but actionable" UDTs, where the priority is not perfect replication but decision-relevant accuracy. Sarajevo contributes to this frontier by testing how far such strategies can be pushed in contexts where comprehensive data infrastructures may remain out of reach.

6.4 Equity and Inclusion in UDT Applications

Critical debates in urban digital twin research emphasize the importance of addressing social dimensions to avoid privileging efficiency over equity. The UDT provides a platform to explore potential impacts on different population groups and to identify areas of social vulnerability. By integrating participatory evaluation, the model can support inclusive planning processes, allowing stakeholders and residents to engage with scenarios and discuss trade-offs. In this way, the Sarajevo twin serves not only as a technological tool but also as a means to foster democratic deliberation and socially aware urban development.

6.5 Governance Innovation through Shared Platforms

Another emerging frontier for urban digital twins lies in their capacity to support governance processes. The Sarajevo UDT has been piloted with the Planning Institute, demonstrating its potential as a boundary object, a shared reference that visualizes the urban plan in a 3D context and facilitates dialogue among agencies, planners, policymakers, and citizens. This highlights the role of digital twins not merely as technical infrastructures but as institutional connectors that can foster coordination and transparency. The Sarajevo experience illustrates how, even in politically and administratively fragmented contexts, a common digital platform can anchor evidence-based discussions, bridge conflicting datasets, and support more collaborative urban decision-making.

6.6 Section Summary

The Sarajevo UDT illustrates the potential of urban digital twins to go beyond simple visualization, offering a platform for predictive analysis, cross-domain integration, and participatory engagement. While many of its capabilities such as real-time data integration, interactive scenario dashboards, and full participatory interfaces are still under development, the project demonstrates the feasibility of linking mobility, energy, and environmental data within a coherent 3D model.

Early interactions and co-creation with the Sarajevo Canton Institute of Development and Planning suggest that such a shared platform can facilitate dialogue across agencies and stakeholders, supporting more informed and transparent discussions even in a fragmented governance context.

The full vision of predictive, socially aware and governance-enabling functionality is currently in development; the Sarajevo case offers valuable lessons for medium-sized cities with limited data and resources. It highlights both the technical and organizational opportunities and challenges of digital twins, pointing toward a cautious but promising path for future urban applications.

7 Conclusion and Outlook

The following conclusions are derived from the authors' direct observations and interpretations, complemented by extensive discussions with local planning authorities, academic researchers, and domain experts. This collaborative process has allowed for a nuanced understanding of the studied context and the identification of key patterns and challenges. While the findings are primarily qualitative in nature, they provide a valuable foundation for subsequent evaluation and validation through a structured methodological framework. Future research could build on these insights by applying systematic assessment tools to measure their broader applicability and effectiveness in similar urban planning contexts.

7.1 Contributions to Urban Planning Practice

For Sarajevo, the UDT provides several practical advantages. It allows planners to explore potential interventions within a single integrated analytical environment. Interdependencies between transport, energy, and urban development become more visible, supporting a more holistic approach to policy and infrastructure design. The UDT also acts as a shared platform that helps reduce institutional fragmentation and facilitates evidence-based discussion among diverse stakeholders. These benefits are particularly valuable given Sarajevo's limited planning resources, complex administrative structure, and ongoing challenges in coordinating urban development initiatives.

7.2 Academic Innovations

Beyond its local relevance, the Sarajevo UDT offers important contributions to the broader academic understanding of urban digital twins. The project demonstrates how AI-assisted data augmentation can enrich models in contexts with incomplete or inconsistent datasets, providing actionable insights for planning. Furthermore, the Sarajevo experience illustrates the role of UDTs as boundary objects: shared, interactive platforms that facilitate dialogue among planners, municipal authorities, policymakers, and citizens. This positions digital twins not only as technical tools but also as instruments that can support more inclusive, coordinated, and transparent urban governance, even in politically and administratively fragmented environments.

7.3 Outlook: Toward the Next Generation of the UDT

Looking ahead, the Sarajevo UDT could develop in several important ways. Adding citizen feedback would help test how interventions affect people's daily lives and social acceptance, not just technical efficiency. Including climate factors like flooding, heat stress, and adaptation measures would make the model more useful for environmental planning. Finally, connecting Sarajevo's twin with regional and national models could help plan changes across energy, transport, and urban systems on a larger scale, such as for example, the Sarajevo Spatial Plan or the Sarajevo Building Codes.

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