An OGC API–Based Framework for Scalable and Interoperable Urban Digital Twin Ecosystems: Insights from the OGC Urban Digital Twins Interoperability Pilot

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Abstract

Urban Digital Twins are powerful tools designed to replicate and analyze the dynamics of urban environments, supporting more informed planning, management, and decision-making. However, their development is often challenged by issues in data interoperability, system integration, and scalability. This paper explores the pivotal role and technical implementation of new-generation Open Geospatial Consortium (OGC) APIs—Features, 3D GeoVolumes, Tiles, and SensorThings—in fostering seamless, lightweight, and scalable data exchange to overcome these barriers. These modern, RESTful APIs surpass older standards like WFS and WMS by simplifying integration and enhancing compatibility with diverse data sources, such as 3D city models in CityGML, IoT sensor data, and geo-referenced imagery. Through the OGC Urban Digital Twin Interoperability Pilot (UDTIP), the paper illustrates the practical application of these APIs in two use cases: urban traffic noise modeling and Geo-AI analysis. By integrating 3D city models, traffic profiles, sensor data, and imagery, UDTIP enables noise simulation and advanced tasks like object detection and road surface classification. Its modular architecture supports efficient data exchange across vector, raster, sensor, and training datasets, leading to impactful geovisualizations powered by CesiumJS, which renders noise patterns and urban features as 3D Tiles and point clouds. By harnessing OGC standards in the UDTIP, our OGC API powered data integration and visualization framework establishes a robust, interoperable framework for scalable UDTs, delivering actionable insights for urban planning and management while promoting standardized, future-ready digital twin solutions.

1. Introduction

Urban Digital Twins (UDTs) represent a powerful tool for understanding and managing the complex dynamics of urban environments. However, current UDT implementations often face challenges related to data interoperability, system integration, and scalability. Urban digital twins must integrate data from various sources, such as sensors, 3D models, and IoT devices, which often have different formats and semantics. This heterogeneity complicates data interpretation and integration (Gu et al., 2024, Rafamatanantsoa et al., 2024). Moreover, the complexity of urban environments, with their diverse stakeholders and systems, makes it challenging to achieve interoperability. Stakeholders often struggle to understand and manage the complexity involved in integrating various data sources (Raes et al., 2021). At the core of every UDT is its framework, which serves as the fundamental structure guiding how the virtual city operates. This design functions similarly to an urban master plan, outlining the key systems and technologies needed for collecting, merging, displaying, and interpreting data. It is instrumental in enabling the UDT to work efficiently and cohesively. The value of a thoughtfully developed architecture becomes especially evident when tackling the multifaceted issues that cities routinely face (Lei et al., 2023). To support scalability and seamless interaction across diverse systems, there is an increasing need for an API-based architectural framework. By leveraging standardized Application Programming Interfaces (APIs), UDTs can achieve higher levels of interoperability, enabling flexible integration of heterogeneous data sources, modular tools, and third-party services. This approach not only enhances system adaptability but also future-proofs the UDT ecosystem for evolving technological and stakeholder needs.

Addressing these gaps, the Urban Digital Twin Interoperability Pilot (UDTIP)[1], organized by the Open Geospatial Consortium (OGC), explores the development of a functional and interoperable UDT ecosystem through the integration of diverse urban data and standards-based workflows. The project focuses on two main applications: urban traffic noise modeling and Geo-AI analysis. Noise modeling leverages 3D city models in CityGML format, traffic profiles, and sensor readings to simulate and visualize urban noise levels, providing insights for planning and mitigation strategies. For Geo-AI analysis, camera imagery, INS metadata, and labeled training data are processed to enable object detection and road surface classification tasks within urban environments. Central to the project is the use of OGC APIs to ensure seamless data exchange between modules. By aligning 3D city models, with dynamic information from IoT sensors and AI-driven analysis, the project demonstrates a viable pathway towards scalable and modular urban digital twins. Furthermore, stakeholder engagement with organizations such as the Land and Housing Agency of Korea and the United Nations ensures that the project outcomes address real-world needs and priorities.

[1] https://www.ogc.org/initiatives/ogc-urban-digital-twin-interoperability/

2. State of the Arts

Urban Digital Twins, which have emerged as transformative tools for modeling, analyzing, and managing the multifaceted dynamics of urban systems, are reshaping how cities are understood and governed. By creating virtual replicas of physical urban environments, UDTs enable stakeholders to simulate scenarios, optimize resource allocation, and inform decision-making. However, the development of scalable and interoperable UDTs faces significant challenges, including data heterogeneity, system integration, and stakeholder coordination (Rönsdorf et al., 2024). Interoperability lies at the heart of scalable and sustainable UDT ecosystems, enabling diverse datasets, platforms, and analytical services to operate cohesively across institutional and technical boundaries. As urban data becomes increasingly heterogeneous—with inputs ranging from 3D geospatial models and static cadastral records to dynamic real-time streams from IoT sensors and edge devices—the need for standardized data representations and interfaces has become a central focus of research and implementation efforts.

Recognize the growing need for dynamic geospatial datasets and interoperable web-based frameworks, the Open Geospatial Consortium —a leading authority in open geospatial standards—has long championed the development of standardized solutions to enhance the precision and accessibility of spatial decision-making. Over the past decades, the OGC has established foundational web service standards such as the Catalogue Service, Web Feature Service (WFS), Web Coverage Service (WCS), Web Mapping Service (WMS), Web Processing Service (WPS) (OGC, 2015), and the Sensor Web Enablement (SWE) initiative (Reed et al., 2013). In response to evolving technological demands, the OGC published the OGC API Whitepaper in 2017 (Percivall et al., 2017), introducing a new vision for modern geospatial APIs. This marked a shift from traditional service-oriented approaches to more resource-centric, web-native paradigms. Emphasising simplicity, modular design and pro developer, the new generation of OGC APIs was conceived to align with contemporary web architectures and scalable cloud-based ecosystems.

OGC API standards such as Features, Tiles, and Processes are gradually replacing their legacy counterparts (e.g., WFS and WPS), offering lightweight, RESTful interfaces better suited for modern applications (Santhanavanich et al., 2024). These APIs support modular “core and extensions” development, enabling flexible implementation and wide adoption across platforms. Rather than treating services as monolithic endpoints, the new approach breaks them into reusable building blocks optimized for interoperability, discoverability, and integration with diverse information systems. Designed to facilitate seamless access to vector and raster data, streaming capabilities, and integration with cloud-native applications, these APIs significantly lower the barriers to cross-platform geospatial interoperability. In particular, the OGC SensorThings API plays a vital role in handling real-time sensor data. It provides a standard interface for accessing observations, managing sensor metadata, and linking dynamic measurements to static geospatial features. This is particularly relevant for traffic and environmental monitoring applications, where live data—such as vehicle flow, noise levels, and air quality—must be continuously correlated with the spatial context of the built environment. The OGC API suite is rapidly expanding, with active development underway on standards such as Styles, Maps, Routes, Joins, 3D GeoVolumes, Environmental Data Retrieval, and more, laying the groundwork for a truly interoperable and future-proof geospatial web.

Beyond syntactic integration, semantic interoperability has gained attention, particularly as digital twins increasingly rely on AI and machine learning algorithms that require consistent, interpretable inputs. Linked data technologies, such as Resource Description Framework (RDF) and Web Ontology Language (OWL), are now being employed to annotate spatial datasets with machine-readable semantics, enabling cross-domain reasoning and automated data linking. These approaches are particularly useful when combining geospatial data with statistical or environmental datasets, ensuring alignment in terminology, measurement units, and classification systems. To support modularity and flexibility in system design, recent research advocates for microservices-based architectures and containerized deployments, allowing individual components of a UDT—such as traffic simulation engines, noise propagation models, or Geo-AI inference services—to be developed, maintained, and scaled independently. These principles are exemplified in this article as part of the Urban Digital Twin Interoperability Pilot (UDTIP), coordinated by the OGC, which demonstrates how loosely coupled, standards-compliant components can be orchestrated into a cohesive, yet flexible, digital twin workflow. In this architecture, CityGML-based 3D urban models are and dynamically linked to live data streams via OGC APIs, while Geo-AI components operate as plug-in services that consume spatially enabled training data and return analytical outputs through standard process interfaces.

Taken together, these developments mark a paradigm shift from monolithic, proprietary systems to open, federated ecosystems built on common data models, and interoperable APIs. This standards-based approach not only reduces integration overhead but also promotes vendor neutrality, reproducibility, and long-term sustainability—critical attributes for public-sector deployments of UDT platforms. Moreover, by aligning with international initiatives such as ISO 191xx series, INSPIRE, and the United Nations’ digital governance frameworks, interoperable UDT solutions position themselves to support cross-border collaborations and global benchmarking efforts. In the context of this paper, such interoperability has been operationalized in a modular pipeline for traffic noise modeling and Geo-AI analysis, showcasing how diverse spatial and temporal datasets can be harmonized to produce actionable insights for urban planning, mobility, and public health decision-making. As UDT ecosystems continue to expand in scale and complexity, the ability to ensure seamless, standards-driven interoperability will remain a cornerstone of their scientific, technical, and societal impact.

3. System Architecture and Methodology

The system architecture is designed around several key components that interoperate to form a unified urban digital twin ecosystem. Illustrated in Fig. 1, the overall architecture integrates 3D building models, terrain models, sensor observations, simulation outputs, and Geo-AI results into a web-based application. Data interoperability is achieved through a combination of OGC API-Features, OGC API-3D GeoVolumes, and OGC API-Tiles, with a Node.js server acting as the backend for managing data flows between modules.

The following modules are central to the project:

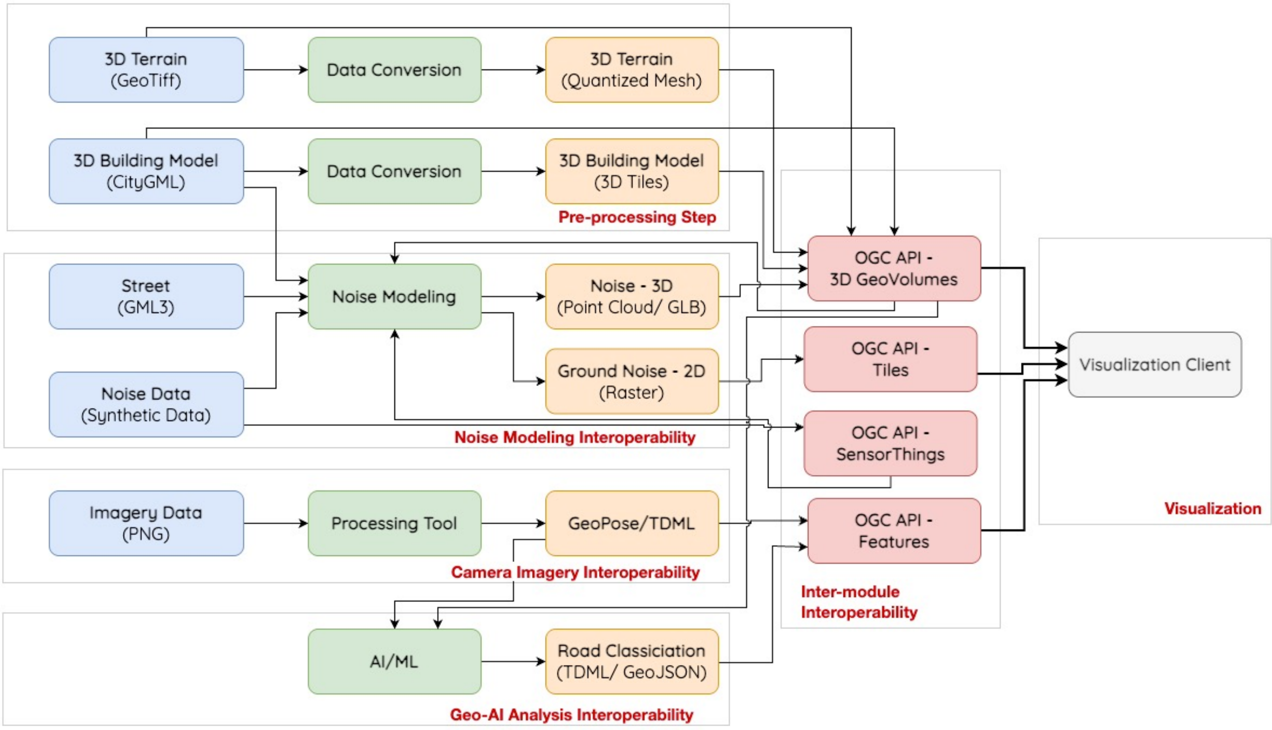

Figure 1. Workflow overview: Overall Architecture Integrating 3D City Models, Noise Simulation Readings, Sensor Data, and Geo-AI Analysis via OGC APIs

3.1 Noise Modeling Interoperability

This module integrates 3D city models in the CityGML format, road network data, traffic profiles, and noise sensor readings. The OpenNoise tool (Fogola et al., 2023) within QGIS is used to simulate urban noise propagation for both day and night scenarios at various elevations. The workflow includes converting BIM/CAD data into standardized CityGML, synthesizing noise data from traffic profiles, and directly integrating IoT sensor readings via the SensorThings API standard. This module lays the foundation for improved noise pollution assessments and supports urban planning and noise mitigation strategies.

3.2 Geo-AI Analysis Interoperability

The Geo-AI analysis component processes geo-referenced camera imagery, associated INS metadata (i.e., ISO 19115/19139-compliant metadata used in INSPIRE or national spatial data infrastructures), and labeled training data. This module supports machine learning tasks such as object detection (e.g., identifying obstacles or illegal dumping) and road surface classification. The transformation of INS metadata into the GeoPose format, along with the use of the OGC TrainingDML standard[2], is fundamental to ensure interoperability across machine learning workflows. Emphasis is placed on enhancing data acquisition techniques and synchronization, thereby enabling more accurate training and inference.

3.3 Inter-module Data Exchange

To facilitate smooth integration between the noise modeling, Geo-AI analysis, and visualization components, a robust inter-module data exchange framework is implemented. This framework leverages a suite of new-generation OGC API standards, which represent a modern, modular, and web-friendly evolution of legacy services like WFS and WMS. Unlike their predecessors, these APIs are RESTful, support JSON and HTML out of the box, and are designed for better scalability, cloud compatibility, and easier integration into web and AI pipelines. The following OGC APIs are employed in the system:

- **OGC API Features** enables efficient access and querying of vector data such as training datasets and inference results, offering a lightweight alternative to WFS with native support for JSON and simplified RESTful endpoints.
- **OGC API 3D GeoVolumes** provides standardized access to complex 3D geospatial data (e.g., 3D Tiles), allowing clients to retrieve semantically rich 3D content at multiple levels of detail—something not supported in earlier OGC standards.
- **OGC API Tiles** serves tiled raster and vector data optimized for web-based visualization, replacing WMTS/WMS approaches with a more flexible, developer-friendly interface that supports modern map rendering techniques.
- **OGC SensorThings API** manages both real-time and historical observations from noise sensors. It is specifically designed for the Internet of Things (IoT), enabling structured access to sensor metadata and time-series data using an open, scalable interface.

By adopting these APIs, the framework ensures interoperability, performance, and future-proof integration across modules — benefits that are difficult to achieve with older, SOAP-based or XML-heavy services.

[2] https://www.ogc.org/standards/trainingdml-ai/

3.4 Data Visualization

The visualization of noise modeling outcomes within the digital twin environment plays a critical role in enhancing the comprehension and practical use of noise analysis data. Through intuitive spatial and temporal representations, visualization supports key decision-making processes in urban planning and design. In this project, 3D data visualization is achieved using CesiumJS, an open-source web-based platform. Urban structures are rendered using 3D Tiles, while terrain is visualized through Quantized Mesh data, fully supported by Cesium's rendering engine.

A 3D visualization client integrates urban noise datasets provided via OGC API services—particularly those generated in the Inter-module Data Exchange—by efficiently merging multiple geospatial data sources. This integration produces detailed visualizations that include 3D Building Models (high-resolution building models rendered in 3D Tiles for realistic urban representation), GeoTiff Digital Elevation Model (DEM) data (3D terrain visualized in Quantized Mesh format to create a realistic ground surface), 3D Noise Dispersion Data (noise simulation results visualized as 3D Tiles in a point cloud format to depict vertical noise distribution), and Ground-Level Noise Data (raster tiles illustrating surface-level noise variations). The noise dataset is developed in two distinct versions. The first version represents noise as a point cloud, illustrating multi-level dispersion throughout the 3D space (see Figure 2). The later version projects the noise values directly onto the surfaces of the 3D building models, enabling a more accurate visualization of noise intensities on facades and structural building elements (see Figure 3). Additionally, data delivered by the OGC API-Features from the GeoAI-classified road type analysis is also visualized on the client (see Figure 4).

This comprehensive approach enables an immersive exploration of the urban environment by providing a multi-dimensional

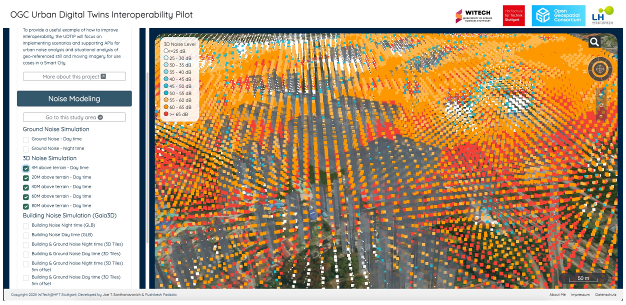

Figure 2. UDTIP Client Visualizing 3D City Model with 3D Multi-Level Noise Data as point cloud.

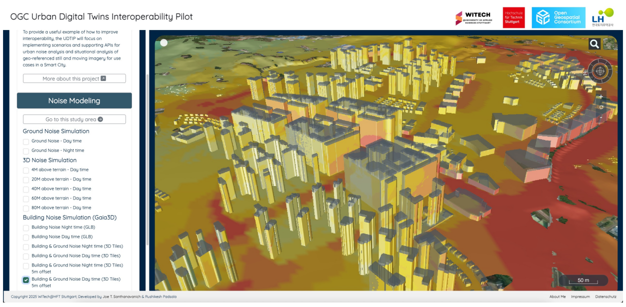

Figure 3. UDTIP Client Visualizing 3D City Model with Noise Simulated on 3D Building Model.

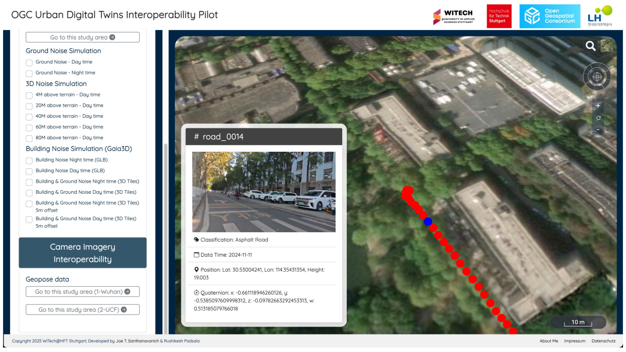

Figure 4. Visualization of GeoAI-classified road types in the UDTIP Client.

view of noise propagation and its potential impact. Built upon the CesiumJS library with a streamlined web architecture, the visualization client effectively demonstrates urban noise simulations within the digital twin context. It not only facilitates the interpretation of complex geospatial datasets but also highlights the advantages of integrating OGC standards, ultimately offering actionable insights for planners, researchers, and stakeholders while showcasing the power of interoperable geospatial services in advancing urban analysis and planning.

4. Discussion

The implementation of OGC API powered data integration and visualization pipeline in the Urban Digital Twin Interoperability Pilot (UDTIP) represented a concerted effort to address the inherent complexities of integrating diverse data sources and systems within urban digital twin environments, leveraging open geospatial standards to forge a path towards enhanced interoperability and scalability. This discussion critically examines the enabling role of OGC standards, delves into the specific insights and challenges encountered in noise modeling and GeoAI analysis, highlights the impact of visualization, and explores broader implications and future directions for UDTs.

4.1 The Enabling Role of OGC Standards in UDT Interoperability

Current UDT implementations often grapple with the significant challenges of integrating multiple systems and diverse data sources due to a pervasive lack of standardized protocols. Our technical contribution within the UDTIP was specifically designed to improve the interoperability of geospatial data and analyses within Digital Twins and lay the foundations for better interoperability between Digital Twins developed for separate applications. By focusing on urban noise analysis and situational analysis of geo-referenced imagery, the pilot demonstrated practical solutions to these interoperability gaps.

A core achievement of our framework was in leveraging of OGC API standards to facilitate seamless data exchange across modules. The adoption of OGC API-Features for training data and Geo-AI inference results, OGC API-Tiles for raster data access, and OGC API-3D GeoVolumes for 3D data created a robust framework for inter-module communication. This standards-based approach enabled the seamless exchange of data, metadata, and code between different modules, promoting portability and reuse across various urban applications. This effectively established a unified platform for accessing and managing diverse geospatial data, thereby eliminating the need to retrieve data from multiple sources. Such an architectural paradigm is crucial for addressing challenges in areas like noise pollution and object detection, providing a robust foundation for urban planning, management, and analysis.

While existing OGC APIs did not directly fulfill all digital twin interoperability requirements, their conceptualization as "building blocks" presented a unique opportunity to assemble a more appropriate "Digital Twin API" interface. The UDTIP's prototyping efforts contribute valuable insights towards this ideal, serving as a reference model for building UDTs based on OGC standards. This work underscores the critical role of OGC standards in enabling data sharing and integration across complex urban systems.

4.2 The Impact of Visualization

Effective visualization within a digital twin environment is paramount for maximizing the understanding and practical utility of urban analysis data. In the UDTIP, the visualization client effectively harnessed the CesiumJS framework to integrate urban noise data directly from OGC API services, particularly those derived from the Inter-module Data Exchange. This integration seamlessly combined diverse geospatial data formats, including CityGML building models (rendered as 3D Tiles), DEM models (Quantized Mesh), 3D noise dispersion data (3D Tiles point cloud), and ground-level noise data (raster tiles).

The adopted modern website architecture proved advantageous, ensuring accessibility, ease of use, and efficient rendering of 3D models, thus enhancing the overall user experience and enabling an intuitive and immersive exploration of urban environments. Beyond its functional benefits, this visualization implementation serves as a crucial demonstrator, showcasing the value of OGC service interoperability to external stakeholders and providing actionable insights through effective visual representation. Future advancements in visualization should prioritize refining real-time data handling capabilities for dynamic urban scenarios and developing more sophisticated visualization techniques, such as adaptive rendering and advanced legends, to further enhance decision-making processes.

4.3 Broader Implications and Future Directions for Urban Digital Twins

The UDTIP's achievements extend beyond its technical deliverables, offering significant implications for the broader development and application of Urban Digital Twins. The project's emphasis on active engagement with key stakeholders, including the Land and Housing Agency of Korea (sponsors) and the United Nations (users), was instrumental in ensuring that the project outcomes were fit for purpose and directly aligned with real user needs and priorities. This collaborative model is fundamental for fostering the practical uptake and relevance of UDT applications.

The framework developed within the UDTIP holds a promising way of integrating and delivering diverse cross-sectoral urban datasets to future UDTs centred around the development of critical urban infrastructures. Specifically, the pilot's focus on noise pollution and Geo-AI analysis directly contributes to urban health applications, enabling city planners to identify noise hotspots, monitor environmental factors like air quality, and detect health hazards such as illegal dumping. The recommendation to incorporate healthcare use cases in future pilots and survey the Korean healthcare sector for potential industry applications is particularly pertinent, given the significant surge in health expenditure in Korea. Furthermore, UDTs offer considerable potential for natural disaster preparedness and response by integrating real-time sensor data for dynamic situational awareness during emergencies. The interoperability aspects are also highly relevant for the advancement of autonomous vehicles, as the detailed urban environment information provided by UDTs, including insights from Geo-AI analysis on road surface classification, can significantly enhance their perception capabilities.

A cornerstone of the UDTIP's sustainability lies in its foundation in open-source technology, which inherently offers high scalability and extensibility for future projects aiming to build UDTs based on OGC standards. The proposed roadmap for collaboration between OGC, OSGeo, and the UN Open GIS Initiative signifies a forward-looking strategy to establish a sustainable ecosystem for open geospatial solutions, spanning from standard-based development to field application and community building. Despite these advancements, certain limitations and areas for future work remain. The ongoing challenge of bridging the persistent and dynamic information elements within a digital twin such as integrating static 3D models with real-time sensor data or vehicle trajectories continues to be a focus for further research and development. While synthetic data proved useful for initial noise modeling, future efforts must prioritize integrating real sensor data for improved accuracy and more realistic simulations. Similarly, for Geo-AI applications, the need for precise, labeled datasets derived from real-world conditions is paramount to overcome the limitations observed with generic public datasets. Although the scope of this pilot did not necessitate explicit measures for security, privacy, and ethical considerations, it is crucial to acknowledge that future, more expansive UDT implementations, especially those incorporating real-time human or sensitive infrastructure data, will unequivocally require robust measures in these domains. While OGC APIs successfully demonstrated effective intermodule data exchange, future efforts should also concentrate on enhancing data encoding schemas and implementing real-time data management techniques, such as dynamic bypassing and distributed server networks, to strengthen system resilience and expand interoperability across varied operational contexts. Conclusively, the continuous evolution of urban environments necessitates adaptive and flexible digital twin systems that can evolve dynamically with changing requirements and emerging technologies. The UDTIP establishes a strong foundational contribution towards this ongoing development.

5. Conclusion

In conclusion, our contribution within the Open Geospatial Consortium (OGC) Urban Digital Twin Interoperability Pilot (UDTIP) project demonstrates the transformative potential of leveraging new-generation OGC standards to overcome critical challenges in data integration and system interoperability for complex urban applications. We successfully integrated disparate data from urban traffic noise modeling and Geo-AI analysis into a cohesive and unified framework, showcasing a viable pathway towards scalable and modular urban digital twins. This achievement not only supports immediate urban planning needs by enabling insights into noise pollution and advanced tasks like object detection, but also establishes a robust foundation for future enhancements in urban management and decision-making.

The core of our success lies in the strategic adoption of a modular, standards-based approach, emphasizing the pivotal role of OGC APIs such as OGC API - Features, OGC API - 3D GeoVolumes, OGC API - Tiles, and OGC SensorThings API. These modern, RESTful APIs significantly enhance data portability, promote cross-platform collaboration, and simplify integration with diverse data sources, effectively surpassing the limitations of older standards like WFS and WMS. The framework's ability to seamlessly exchange vector, raster, sensor, and training datasets, as exemplified by our noise modeling and Geo-AI analysis use cases, underscores its robustness and adaptability for various urban scenarios.

While the UDTIP successfully demonstrated significant advancements in interoperability, continuous evolution is crucial. Future work will concentrate on bridging the persistent and dynamic information elements within a digital twin, such as integrating static 3D models with real-time sensor data and vehicle trajectories to overcome current limitations with synthetic data. Enhancing data encoding schemas and implementing real-time data management techniques, including dynamic bypassing and distributed server networks, will be vital to strengthen system resilience and expand interoperability across varied operational contexts. Furthermore, as urban digital twins become more pervasive, addressing critical aspects such as security, privacy, and ethical considerations, especially when incorporating real-time human or sensitive infrastructure data, will be paramount.

Beyond the technical advancements, the UDTIP highlights the necessity of a holistic approach that considers not only technological aspects but also organizational and policy frameworks to support the widespread adoption and implementation of these standards across diverse urban environments. The continuous engagement with stakeholders, including the Land and Housing Agency of Korea and the United Nations, has been instrumental in ensuring that the project outcomes address real-world needs and priorities, paving the way for future integrations of cross-sectoral urban datasets, particularly in urban health applications and natural disaster preparedness. By promoting open-source technology and fostering collaboration between organizations like OGC, OSGeo, and the UN Open GIS Initiative, the UDTIP lays a strong foundational contribution towards establishing a sustainable ecosystem for open geospatial solutions and adaptive, flexible digital twin systems that can evolve dynamically with changing requirements and emerging technologies.

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