# Building Municipal Digital Twin Readiness: From UAV Base Mapping to Operational 3D Geoportal Infrastructure

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**Abstract**

Urban Digital Twins (UDTs) are increasingly adopted to support evidence-based urban planning, municipal management, and municipal decision-making. However, many municipalities still lack the integrated geospatial infrastructure required to transform conventional mapping products into operational digital twin environments. This study proposes a Municipal Digital Twin Readiness Framework that systematically transforms UAV-derived geospatial data into a multi-representation three-dimensional (3D) geospatial infrastructure supporting future digital twin implementation. The framework consists of four sequential stages: (1) geospatial data acquisition and preprocessing using UAV photogrammetry, (2) automated generation of multi-representation 3D urban models through AI-assisted semantic extraction and urban object reconstruction, (3) development of an interoperable spatial data infrastructure based on open-source geospatial technologies, and (4) deployment of an operational web-based 3D geoportal through the UrbanScope platform. The framework was implemented in Cimahi City, Indonesia, demonstrating five progressive Municipal Digital Twin Readiness levels. The proposed approach supports complementary urban representations, including semantic city models, semantic meshes, and neural rendering models, according to different analytical and visualization requirements. The proposed framework provides municipalities with a scalable and replicable pathway for establishing interoperable multi-representation geospatial infrastructures that underpin future Urban Digital Twin ecosystems.

## 1. Introduction

The rapid development of Urban Digital Twins (UDTs) has highlighted the need for interoperable geospatial infrastructures capable of integrating heterogeneous urban information. By combining geospatial information, three-dimensional (3D) urban models, sensor observations, and interactive visualization environments, UDTs enable cities to monitor, analyse, simulate, and manage urban systems within a unified digital ecosystem (Batty, 2018; Ketzler et al., 2020; Shahat et al., 2021; Deren et al., 2021). Despite their growing adoption across diverse application domains, significant challenges remain in integrating heterogeneous datasets, ensuring interoperability, and establishing sustainable implementation pathways for municipalities (Ferré-Bigorra et al., 2022). Consequently, there is broad consensus that interoperable geospatial information constitutes the essential foundation for Urban Digital Twins, providing the data, semantic models, and infrastructure upon which higher-level urban analytics, simulation, and decision-support services can be built (Gil, 2020).

Recent advances in geospatial data acquisition and 3D modelling have significantly expanded the technological foundation for Urban Digital Twins. UAV photogrammetry has enabled rapid and cost-effective acquisition of very high-resolution urban geospatial data (Colomina and Molina, 2014; Nex and Remondino, 2014), while recent developments in 3D city modelling have considerably improved the semantic representation and interoperability of urban environments through standards such as CityGML 3.0 (Kutzner et al., 2020). More recently, neural rendering techniques represented by 3D Gaussian Splatting (3DGS) have introduced highly photorealistic 3D scene reconstruction with real-time rendering capabilities (Kerbl et al., 2023). Together, these technological advances enable municipalities to derive multiple complementary 3D representations from common geospatial datasets. Semantic city models, semantic meshes, and neural rendering models can coexist within a unified geospatial environment, providing complementary semantic, geometric, and visualization capabilities for future Urban Digital Twin applications.

Despite these technological advances, many municipalities, particularly those in developing countries, still face significant challenges in establishing the geospatial foundation required for Urban Digital Twin implementation. Although orthophotos, cadastral maps, GIS databases, and thematic geospatial information are often available, these resources are commonly managed independently, maintained by different agencies, and implemented using heterogeneous data models and software platforms (Rajabifard et al., 2002; Williamson et al., 2010). Consequently, the availability of geospatial datasets alone does not necessarily indicate that a municipality is prepared to support future Urban Digital Twin applications.

A research gap therefore exists between conventional geospatial data management and operational Urban Digital Twin implementation. Existing studies have extensively investigated


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individual technological components, including UAV mapping, semantic city modelling, spatial data infrastructures, semantic meshes, neural rendering, and Urban Digital Twin platforms. However, comparatively little attention has been devoted to evaluating how municipalities progressively establish the geospatial foundation required to integrate these complementary technologies within a unified operational environment. Consequently, municipalities lack a practical framework for assessing whether their existing geospatial capabilities are sufficiently prepared to support future Urban Digital Twin implementation.

To address this gap, this paper introduces a Municipal Digital Twin Readiness Framework that evaluates the readiness of municipal geospatial capabilities and infrastructure to support future Urban Digital Twin implementation. The framework is implemented through a four-stage workflow comprising geospatial data acquisition, multi-representation 3D urban modelling, geospatial infrastructure development, and operational 3D geoportal implementation. Municipal readiness is evaluated using five cumulative readiness levels presented in Section 2.3.

The proposed framework is demonstrated through its implementation in Cimahi City, Indonesia, where UAV-derived geospatial datasets are progressively transformed into an interoperable municipal geospatial environment supporting multiple 3D urban representations and operational web-based geospatial services. The principal contributions of this research are threefold: (1) the introduction of a Municipal Digital Twin Readiness Framework focusing on the geospatial dimension of Urban Digital Twins; (2) an operational workflow for generating and integrating multi-representation 3D urban models from common UAV-derived geospatial datasets; and (3) a city-scale implementation demonstrating how interoperable geospatial foundations can support future Urban Digital Twin development through an operational 3D geoportal.

## 2. Geospatial Foundation for Municipal Digital Twin Readiness

The implementation of an Urban Digital Twin (UDT) requires more than the availability of geospatial datasets or 3D city models. It depends on the establishment of an interoperable geospatial foundation that supports the acquisition, integration, management, and dissemination of heterogeneous spatial information. This section reviews the geospatial foundations of UDT, discusses the complementary roles of multiple 3D representations, and introduces the proposed Municipal Digital Twin Readiness Framework.

### 2.1 Geospatial Foundations for Urban Digital Twins

Recent UDT initiatives consistently identify interoperable geospatial information as the foundation supporting urban monitoring, analysis, visualization, and decision-making. UDTs are commonly defined as integrated digital representations of urban environments that combine geospatial information, physical assets, sensing technologies, and analytical capabilities to support planning and decision-making (Weil and Longchamp, 2022; OGC, 2024). The IEC Technology Report further describes UDTs as an evolution of City Information Modelling (CIM), integrating geospatial information, BIM, sensing technologies, and digital platforms within a common information environment (IEC, 2021). This systems perspective is consistent with recent reviews that characterize UDTs as integrated information ecosystems rather than standalone 3D visualization platforms (Lehtola et al., 2022). Recent research further demonstrates that transforming geospatial data into operational UDTs requires systematic workflows that integrate spatial data acquisition, processing, procedural modelling, and interactive visualization within a unified digital environment (Somanath et al., 2024). This capability is supported by the ongoing evolution of conventional Spatial Data Infrastructures (SDIs) towards interoperable geospatial data spaces that enable standardized data exchange across organizations and application domains (Kotsev et al., 2020).

Municipal implementation experiences reinforce this perspective. Röttcher (2026) reports that the City of Cape Town progressively established orthophotos, airborne LiDAR, multi-resolution 3D city models, and interoperable geospatial services before deploying Urban Digital Twin applications. Similarly, the Busan Urban Digital Twin integrates UAV-derived geospatial data, semantic city models, and web-based visualization within an operational municipal platform (Jeong et al., 2026). These examples demonstrate that interoperable geospatial infrastructures are prerequisites for Urban Digital Twin implementation rather than merely supporting technologies.

### 2.2 Multi-representation 3D Urban Models

Recent advances in 3D urban modelling have produced multiple complementary representations of the same urban environment. Semantic city models provide explicit object semantics, hierarchical relationships, and standardized information structures for interoperability and spatial analysis. CityGML 3.0 further strengthens these capabilities through improved semantic consistency, support for dynamic objects, and enhanced interoperability (Kutzner et al., 2020). Beyond their role in urban information modelling, semantic city models have also become valuable open reference datasets for developing and benchmarking novel 3D reconstruction methods, highlighting their importance as a bridge between structured urban information and data-driven reconstruction approaches (Wysocki et al., 2024). Conversely, semantic meshes preserve detailed surface geometry with semantic surface classification, making them suitable for high-fidelity visualization and urban scene understanding (Gao et al., 2021). More recently, 3DGS has introduced highly photorealistic scene reconstruction with real-time rendering performance, enabling immersive visualization while providing limited explicit semantics and topology (Kerbl et al., 2023).

These representations exhibit complementary rather than competing characteristics. Semantic city models excel in semantic interoperability, semantic meshes preserve detailed geometric structures, while 3DGS delivers highly realistic visualization. Recent studies have also investigated approaches for integrating semantic city models, semantic meshes, and neural rendering models within a common urban modelling framework (Suwardhi et al., 2026). Building upon this perspective, the present research adopts a multi-representation 3D urban modelling approach in which multiple representations are generated from common UAV-derived geospatial datasets and managed within a unified municipal geospatial infrastructure.

Table 1 summarizes the principal characteristics of the three complementary 3D urban representations adopted in this study. Rather than competing with one another, each representation provides distinct capabilities for different municipal applications, ranging from semantic information management to high-fidelity visualization

Table 1. Comparison of complementary 3D urban representations.

| Representation | Core Capability | Typical Applications |
|---|---|---|
| **Semantic City Model** | Rich semantics & interoperability | Urban information management, municipal administration, asset management, spatial analysis |
| **Semantic Mesh** | High geometric fidelity with semantic surfaces | Urban analysis, environmental simulation, visibility analysis, scene understanding, high-fidelity visualization |
| **3D Gaussian Splatting** | Photorealistic scene representation | Immersive visualization, VR/AR, virtual inspection, Digital Twin visualization |

### 2.3 Municipal Digital Twin Readiness Framework

Although significant progress has been achieved in Urban Digital Twin architectures and 3D urban modelling, existing studies primarily focus on technological components or implementation platforms. Recent research has also introduced levels of integration to distinguish different stages of Urban Digital Twin development (Jeddoub, 2026). Comparatively little attention has been devoted to evaluating whether municipalities possess the geospatial capabilities required to operationalize these technologies. To address this gap, this research proposes a Municipal Digital Twin Readiness Framework that evaluates the progressive development of municipal geospatial capabilities instead of organizational or institutional maturity.


Figure 1. Readiness Framework.

The proposed framework comprises five cumulative readiness levels (Figure 1): (1) Geospatial Data Readiness, (2) 3D Urban Model Readiness, (3) Geospatial Infrastructure Readiness, (4) Operational Geoportal Readiness, and (5) Municipal Digital Twin Readiness. Unlike conventional Urban Digital Twin maturity models, the proposed framework focuses specifically on the geospatial dimension, providing a technology-independent mechanism for evaluating whether municipalities have established the geospatial foundation required to support future Urban Digital Twin implementation.

Unlike existing Urban Digital Twin frameworks that primarily emphasize system architecture and platform integration, the proposed framework evaluates the progressive establishment of municipal geospatial capabilities required to support future Urban Digital Twin implementation.

## 3. Methodology

The proposed Municipal Digital Twin Readiness Framework was implemented in Cimahi City through a progressive workflow that transforms existing municipal geospatial resources into an operational multi-representation geospatial infrastructure. The proposed methodology demonstrates how municipal geospatial capabilities are progressively established through four implementation stages, namely geospatial data acquisition, multi-representation 3D urban modelling, geospatial infrastructure development, and operational 3D geoportal deployment.

### 3.1 Study Area and Available Geospatial Resources

The proposed Municipal Digital Twin Readiness Framework was implemented in Cimahi City, West Java, Indonesia, representing a medium-sized municipality that has progressively developed various geospatial resources to support municipal planning and urban management. This study investigates how existing municipal geospatial resources can be progressively transformed into an interoperable geospatial foundation supporting future Urban Digital Twin implementation. Figure 2 illustrates the location of the study area together with the principal municipal geospatial resources available for implementing the proposed framework. These resources constitute the initial geospatial foundation from which the subsequent multi-representation 3D urban models and municipal geospatial infrastructure are developed.

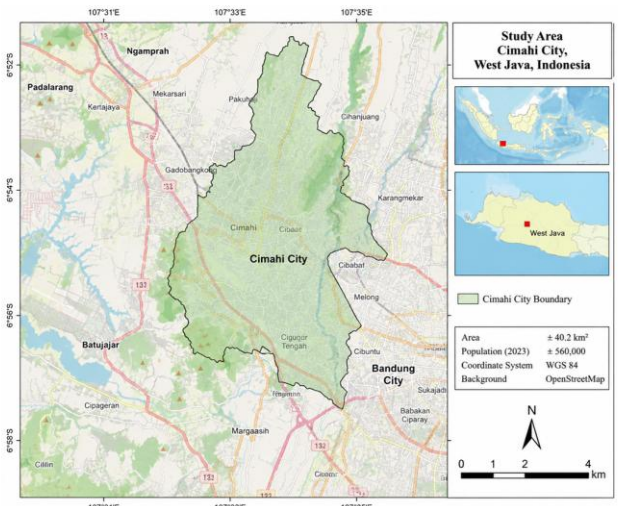


Figure 2. Location of the Cimahi City study area and available municipal geospatial resources.

The available geospatial resources comprise UAV photogrammetric imagery, orthophotos, digital terrain models (DTMs), digital surface models (DSMs), cadastral datasets, road networks, building footprints, and thematic GIS layers maintained by different municipal agencies. Although these datasets provide complementary geometric and semantic information, they were originally developed using different acquisition methods, data models, and software environments. Consequently, they present a realistic municipal scenario for evaluating the proposed Municipal Digital Twin Readiness Framework.

The proposed methodology progressively integrates these heterogeneous datasets into a unified municipal geospatial infrastructure through multi-representation 3D urban modelling, interoperable spatial data management, and operational webbased geospatial services.

### 3.2 Stage 1 – Geospatial Data Acquisition and Processing

The first stage establishes the geospatial foundation through a UAV photogrammetric survey and the integration of existing municipal geospatial datasets. Figure 3 presents the UAV photogrammetric field campaign conducted to acquire the very high-resolution aerial imagery used as the primary data source for generating orthophotos, DSMs, DTMs, and dense point clouds. Existing cadastral maps, transportation networks, administrative boundaries, and thematic GIS layers complement these products by providing structured municipal information.

Photogrammetric processing includes image orientation and dense image matching to generate the primary geometric datasets. In parallel, orthophoto imagery is analysed using machine learning and deep learning techniques to derive semantic information. General land-cover classes are obtained through semantic segmentation, while buildings and vegetation are extracted using dedicated deep learning models, including the Segment Anything Model (SAM) and customized convolutional neural network (CNN)-based approaches. The outputs of this stage consist of integrated geometric and semantic geospatial datasets that serve as inputs for subsequent 3D urban modelling.


Figure 3. UAV photogrammetric field campaign for acquiring very high-resolution imagery.

### 3.3 Stage 2 – Multi-representation 3D Urban Modelling

The second stage transforms the geometric and semantic datasets generated in Stage 1 into multiple complementary 3D urban representations. The proposed methodology generates several interoperable representations from a common geospatial foundation to support different municipal applications.

Figure 4 summarizes the automated multi-representation 3D urban modelling pipeline proposed in this study. Photogrammetric processing first generates the primary geometric products, including orthophotos, dense point clouds, DSMs, and DTMs, while AI-based semantic segmentation extracts land-cover information, building footprints, and vegetation objects. These geometric and semantic datasets are subsequently integrated to reconstruct three complementary urban representations, namely semantic city models, semantic meshes, and photorealistic 3DGS. Semantic correspondence is then established among these representations, enabling them to coexist within a unified municipal geospatial environment.

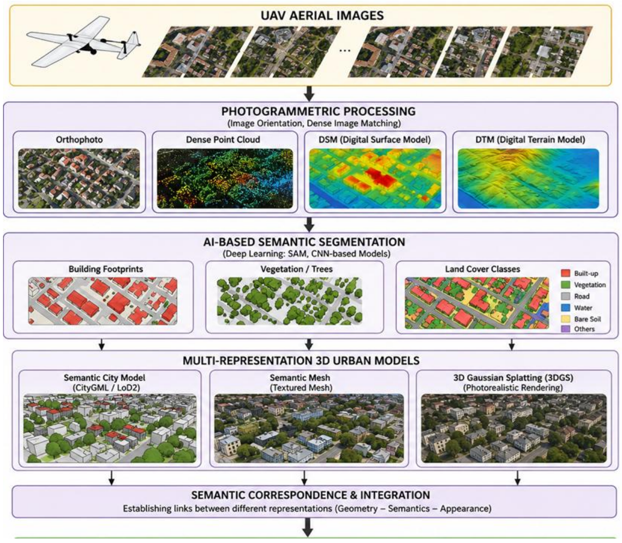


Figure 4. Generation of semantic city models, semantic meshes, and 3DGS from common UAV-derived geospatial datasets.

The resulting multi-representation models provide complementary capabilities for municipal applications. Semantic city models support information management and interoperability, semantic meshes preserve detailed geometry for analysis and simulation, while 3DGS enables immersive photorealistic visualization.

Unlike conventional workflows that produce a single 3D city model, the proposed pipeline enables multiple interoperable representations to be generated from the same geospatial foundation, providing greater flexibility for diverse municipal applications.

### 3.4 Stage 3 – Geospatial Infrastructure Development

The third stage integrates heterogeneous geospatial resources into an interoperable municipal geospatial infrastructure. 3D models and supporting datasets are organized within open geospatial databases and published through standardized web services to enable efficient storage, retrieval, and interoperability.

The infrastructure adopts open-source technologies, including PostgreSQL/PostGIS for spatial database management, GeoServer for OGC-compliant web services, 3DCityDB for semantic city model management, and associated middleware supporting multi-representation data integration. The proposed infrastructure provides a unified environment capable of supporting semantic, geometric, and photorealistic urban representations.

### 3.5 Stage 4 – Operational 3D Geoportal

The final stage operationalizes the integrated geospatial infrastructure through a web-based 3D geoportal implemented using the UrbanScope platform. The geoportal provides interactive visualization, navigation, information retrieval, and exploration of multiple 3D representations within a unified user environment.

Beyond visualization, the geoportal demonstrates the operational integration of municipal geospatial resources, enabling planners and municipal stakeholders to access semantic city models, semantic meshes, and neural rendering models according to different application requirements. The successful deployment of the geoportal corresponds to Operational Geoportal Readiness.

Figure 5 presents the proposed municipal geospatial infrastructure architecture. The architecture integrates opensource geospatial technologies through standardized interfaces, enabling heterogeneous datasets and multiple 3D representations to be managed within a unified operational environment.

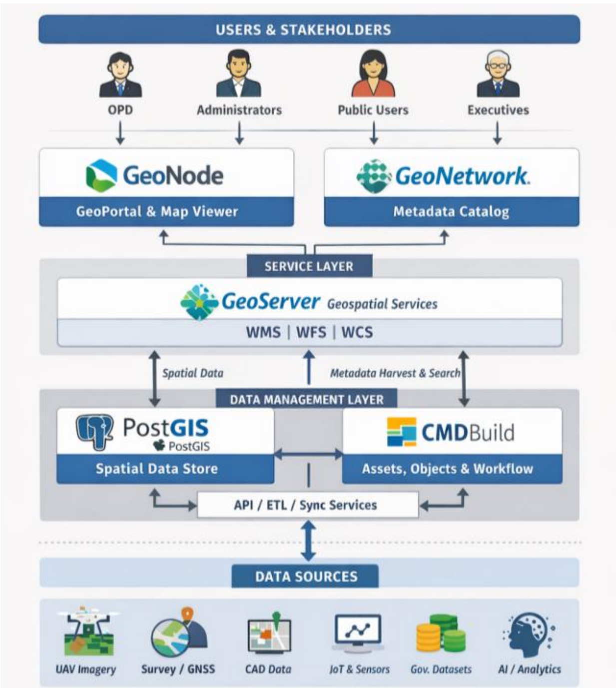


Figure 5. Municipal Geospatial Infrastructure Architecture

## 4. Results and Discussion

The proposed Municipal Digital Twin Readiness Framework was implemented in Cimahi City to evaluate how existing municipal geospatial resources can be progressively transformed into an operational geospatial foundation for Urban Digital Twins. Following the four implementation stages described in the previous section, this chapter presents the resulting geospatial products, multi-representation 3D urban models, municipal geospatial infrastructure, and operational geoportal. The implementation results are subsequently discussed in relation to the five Municipal Digital Twin Readiness levels to demonstrate how each stage contributes to the progressive development of municipal geospatial capabilities.

### 4.1 Geospatial Data Readiness

The first implementation stage successfully established the geospatial foundation required for subsequent multi-representation 3D urban modelling. A UAV photogrammetric survey was conducted to acquire very high-resolution aerial imagery covering the entire Cimahi City study area. The acquired imagery was processed using a standard photogrammetric workflow to generate orthophotos, dense point clouds, digital surface models (DSMs), and digital terrain models (DTMs), which collectively provide the primary geometric datasets for municipal mapping.

In parallel, the generated orthophotos were analysed using machine learning and deep learning techniques to derive semantic information required for urban modelling. General land-cover classes were obtained through semantic segmentation, while buildings and vegetation objects were extracted using dedicated deep learning approaches, including the Segment Anything Model (SAM) and customized convolutional neural network (CNN)-based models. These semantic datasets were subsequently converted into vector representations and integrated with the photogrammetric products to establish a consistent geospatial database for 3D reconstruction.

Figure 6 presents examples of the principal geospatial datasets generated during this stage, including the orthophoto, and DSM results. Together, these datasets provide complementary geometric and semantic information that serves as the common geospatial foundation for the subsequent generation of multiple 3D urban representations.

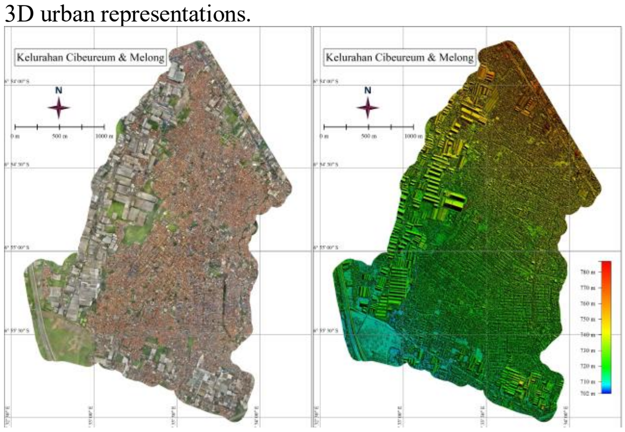


Figure 6. Geospatial datasets generated from the UAV photogrammetric survey, including (a) orthophoto, and (b) digital surface model (DSM).

The implementation demonstrates that Cimahi City has successfully established Level 1 (Geospatial Data Readiness) of the proposed Municipal Digital Twin Readiness Framework. Level 1 readiness is characterized by the integration of consistent geometric and semantic geospatial information that directly supports automated multi-representation 3D urban modelling.

### 4.2 Multi-representation 3D Urban Model Readiness

Building upon the geometric and semantic datasets established in the previous stage, the proposed workflow automatically generated multiple complementary 3D urban representations from a common geospatial foundation. Unlike conventional approaches that typically produce a single 3D city model, the proposed methodology integrates photogrammetric products and AI-derived semantic information to generate semantic city models, semantic meshes, and photorealistic 3DGS models simultaneously.

Semantic city models were generated through automated reconstruction using the extracted building footprints, terrain information, and semantic attributes. Building models were


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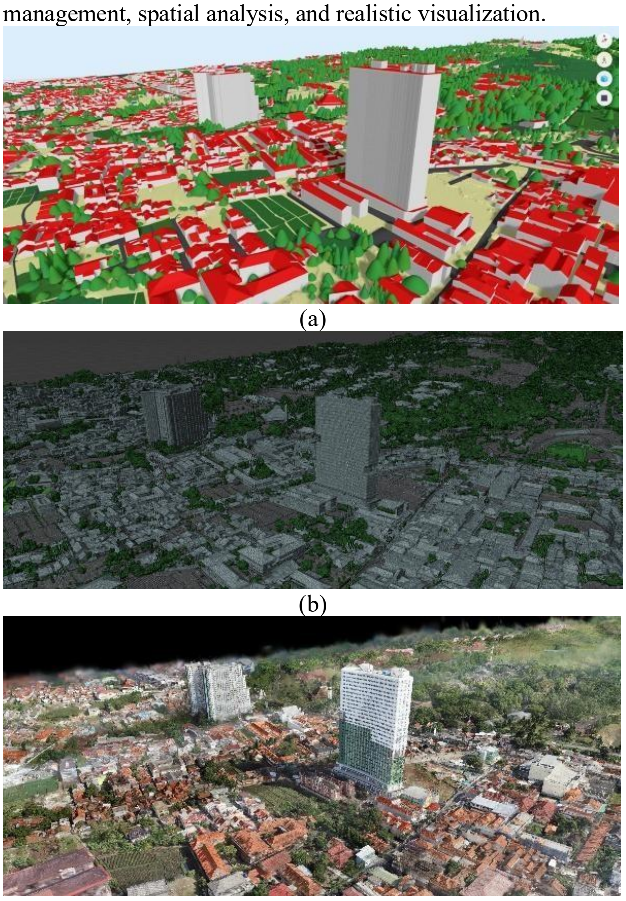
produced at both LoD1 and LoD2 to support different levels of geometric detail, while vegetation objects were represented as semantic LoD2 tree models. In parallel, semantic meshes preserved detailed surface geometry for high-fidelity visualization and spatial analysis, whereas image-based 3DGS provided photorealistic scene reconstruction for immersive visualization. Although these representations differ in their data structures and intended applications, they originate from the same UAV-derived geospatial datasets, ensuring geometric consistency and enabling semantic correspondence among them.

Figure 7 illustrates representative outputs of the proposed multi-representation workflow, including semantic city models, semantic meshes, and 3DGS generated from the same study area. The figure demonstrates that different 3D representations can coexist within a unified municipal geospatial environment while preserving their individual strengths for information management, spatial analysis, and realistic visualization.



(a)

(b)

(c)

Figure 7. Examples of multi-representation 3D urban models generated from the same UAV-derived geospatial datasets, including (a) semantic city model (LoD1/LoD2), (b) semantic mesh, and (c) 3DGS.

The implementation confirms that a common geospatial foundation can support the automated generation of multiple interoperable 3D representations rather than a single city model. This capability establishes Level 2 (Multi-representation 3D Urban Model Readiness) within the proposed Municipal Digital Twin Readiness Framework and provides the basis for supporting diverse municipal applications through representation-specific strengths.

### 4.3 Municipal Geospatial Infrastructure Readiness

The third implementation stage focused on establishing an interoperable municipal geospatial infrastructure capable of managing and disseminating multiple urban datasets generated in the previous stages. The proposed framework integrates geometric, semantic, and administrative information within a unified Spatial Data Infrastructure (SDI), thereby enabling efficient data management, interoperability, and long-term maintenance.

The implemented infrastructure adopts a modular architecture based primarily on open-source technologies. PostGIS serves as the central spatial database for storing two-dimensional and 3D geospatial information, while GeoServer publishes standardized OGC web services to facilitate data dissemination and interoperability. Metadata management is supported through GeoNode, and municipal asset information is administered using CMDBuild, allowing spatial objects to be linked with corresponding municipal information. This architecture provides a scalable environment in which heterogeneous datasets can be managed through standardized interfaces without requiring modifications to the underlying data models.

Unlike conventional municipal GIS implementations that primarily function as data repositories, the proposed infrastructure establishes an interoperable geospatial ecosystem capable of supporting multiple 3D representations simultaneously. This implementation demonstrates the achievement of Level 3 (Municipal Geospatial Infrastructure Readiness) by providing a standardized platform for data integration, management, dissemination, and future system expansion.

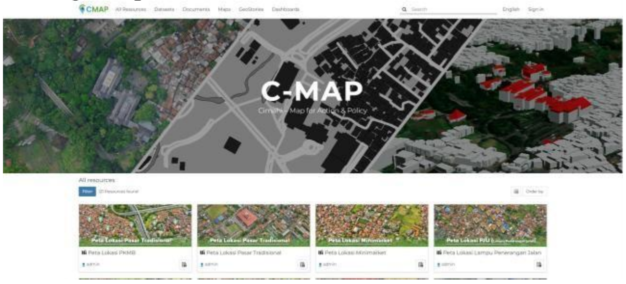
### 4.4 Operational Municipal 3D Geoportal Readiness

The fourth implementation stage focused on deploying the integrated geospatial resources through an operational web-based 3D geoportal. While the previous stage established the municipal geospatial infrastructure, this stage demonstrates how the infrastructure can be utilized to provide accessible, interactive, and interoperable geospatial services for municipal stakeholders.

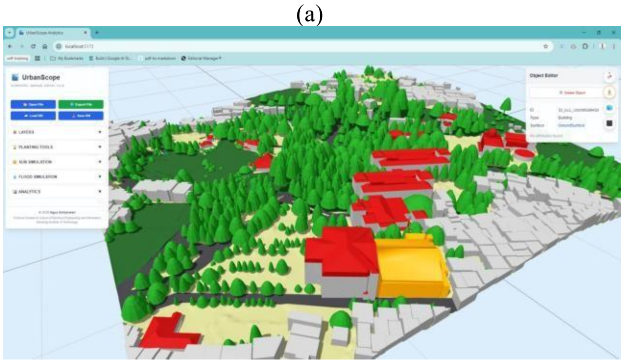
The developed platform integrates two-dimensional geospatial information, semantic city models, semantic meshes, and photorealistic 3DGS within the UrbanScope environment. Through a web browser, users can explore the study area interactively, visualize multiple 3D representations, and access semantic information associated with buildings, vegetation, terrain, and other municipal assets. The platform also consumes standardized OGC web services published by the municipal geospatial infrastructure, ensuring that data remain synchronized and centrally managed.

Figure 8 presents the operational Municipal Geoportal (C-MAP) together with the UrbanScope interface developed for Cimahi City. The figure demonstrates how heterogeneous geospatial datasets are presented through an integrated web environment, enabling users to seamlessly navigate between conventional map services and immersive 3D visualization.

Beyond visualization, the operational geoportal provides a practical environment for disseminating municipal geospatial information, supporting urban planning, infrastructure management, and public information services. By integrating standardized geospatial services with multiple 3D representations, the platform establishes Level 4 (Operational Municipal 3D Geoportal Readiness) within the proposed Municipal Digital Twin Readiness Framework.




(a)




(b)

Figure 8. (a) Operational Municipal Geoportal (C-MAP), and (b) UrbanScope interface for interactive visualization of multi-representation 3D urban models and municipal geospatial information.

### 4.5 Assessment of Municipal Digital Twin Readiness

The proposed Municipal Digital Twin Readiness Framework was applied to the Cimahi City case study to assess the municipality's readiness for Urban Digital Twin development. The framework assesses the availability of key capabilities grouped into five progressive readiness levels, ranging from geospatial data readiness to municipal digital twin readiness.

Table 2 summarizes the assessment results using the capability indicators defined for each readiness level. The assessment indicates that Cimahi City satisfies all capability indicators defined for Levels 1 to 4. The municipality possesses very high-resolution geospatial data, has developed multi-representation 3D urban models, established an interoperable geospatial infrastructure, and deployed an operational web-based 3D geoportal. These achievements demonstrate that Cimahi has established the essential geospatial foundation required for future Urban Digital Twin implementation.

The assessment also shows that none of the Level 5 capability indicators are currently fulfilled. Although the municipality has established a comprehensive geospatial ecosystem, capabilities such as dynamic data integration, real-time monitoring, urban simulation, and decision support have not yet been implemented. Consequently, Cimahi has not yet reached full Municipal Digital Twin Readiness.

The proposed readiness levels are cumulative rather than independent. Each level builds upon the capabilities established in the preceding level, providing municipalities with a practical roadmap for progressively developing Urban Digital Twin capabilities. Instead of pursuing a complete digital twin implementation in a single stage, municipalities can use the framework to identify their current readiness level, recognize missing capabilities, and define realistic implementation priorities.

Table 2. Municipal Digital Twin Readiness Assessment of Cimahi City.

| Readiness Level | Capability Indicators | Cimahi |
|---|---|---|
| **Level 1 Geospatial Data Readiness** | Very high-resolution imagery | ✓ |
| | 3D surface data | ✓ |
| **Level 2 3D Urban Model Readiness** | Semantic 3D city model | ✓ |
| | Multi-representation 3D models | ✓ |
| **Level 3 Geospatial Infrastructure Readiness** | Spatial database | ✓ |
| | Standardized geospatial web services | ✓ |
| | Metadata management | ✓ |
| | Municipal asset management | ✓ |
| **Level 4 Operational Geoportal Readiness** | Operational web-based 3D geoportal | ✓ |
| | Interactive 3D visualization | ✓ |
| | Access to multi-representation urban models | ✓ |
| **Level 5 Municipal Digital Twin Readiness** | Dynamic data integration | ✗ |
| | Real-time monitoring | ✗ |
| | Urban simulation | ✗ |
| | Decision support | ✗ |

## 5. Conclusions

This study presented a municipal-scale framework for transforming UAV-derived geospatial data into an operational 3D geospatial infrastructure that supports Municipal Digital Twin Readiness.

The proposed framework integrates four sequential stages, namely geospatial data acquisition, automated semantic 3D urban modelling, spatial data infrastructure development, and operational 3D geoportal deployment. Unlike conventional workflows that treat these processes independently, the proposed approach explicitly links each stage to a corresponding level of Digital Twin Readiness, thereby providing a structured pathway for municipalities transitioning from conventional GIS environments toward future digital twin ecosystems.

The implementation in Cimahi City demonstrates that very high-resolution UAV mapping products can be systematically transformed into interoperable Semantic Mesh, CityGML models, integrated spatial databases, standardized web services, and an operational web-based 3D geoportal. The resulting infrastructure establishes a scalable geospatial ecosystem capable of supporting municipal planning, infrastructure management, and future digital twin applications.

The primary contribution of this research is the introduction of a Municipal Digital Twin Readiness Framework that bridges the gap between geospatial data production and operational digital twin implementation. The framework highlights the progressive development of geospatial capabilities required to support sustainable urban digital transformation.

Future work will extend the proposed framework through the incorporation of real-time sensor integration, Building Information Modelling (BIM), Internet of Things (IoT) data streams, and AI-driven urban analytics to enable fully operational digital twin environments.

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