Project Report: Evaluation of Using a Web-Based 3D City Model in Urban Planning

A Web-Based Visualization Platform Using PostgreSQL/PostGIS and CesiumJS

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Abstract

This project addresses the critical challenge of integrating 2D cadastral data (ALKIS) with 3D city models (CityGML) to support advanced urban planning applications in the Untertürkheim district of Stuttgart, Germany. The fragmentation of spatial information across disparate systems necessitates significant manual intervention, hindering holistic urban planning. This research develops a comprehensive methodology for seamless integration using a linked-schema database approach built on PostgreSQL/PostGIS, automated semantic mapping between ALKIS and CityGML features, and a web-based visualization system powered by CesiumJS.

The methodology tackles four key challenges: semantic heterogeneity, performance optimization for interactive 3D applications, synchronization of updates between source datasets, and effective visualization for diverse stakeholders. Implementation results successfully demonstrate the integration of cadastral parcels with 3D building models, allowing urban planners to simultaneously analyze property boundaries, ownership, and 3D spatial relationships. Performance evaluation confirmed acceptable query response times and visualization frame rates for complex urban scenes. The resulting system effectively supports key urban planning tasks, including site analysis, impact assessment, and the visualization of planning regulations. This work contributes to the field by establishing automated synchronization workflows, developing standardized semantic mapping, and demonstrating the effectiveness of open-source platforms for integrated spatial data management.

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Chapter 1

Introduction

1.1 Background on Spatial Databases and 3D City Models

The evolution of Geographic Information Systems (GIS) has fundamentally transformed urban planning, moving from traditional 2D representations to sophisticated 3D models that capture the multidimensional complexity of modern cities. While 2D spatial data remains essential, it often lacks the necessary depth for accurately representing contemporary urban environments (Biljecki et al., 2016). The integration of 3D spatial data into robust databases has opened new avenues for urban planning, emergency response, and infrastructure management (Kolbe et al., 2005).

PostgreSQL with its PostGIS extension has become the de facto standard for open-source spatial databases, offering capabilities that rival proprietary alternatives (Steiniger & Hunter, 2013). PostGIS supports 2D and 3D geometries, topology, and advanced spatial analysis, making it ideal for managing complex urban datasets.

Parallel to this, 3D city modeling has become a critical field. The CityGML standard, introduced by the OGC in 2008, provides a standardized framework for 3D urban modeling (Gröger et al., 2012). Key features of CityGML include:

- **Levels of Detail (LOD):** Multi-scale representations, from basic blocks (LOD1) to detailed architectural models (LOD3).
- **Semantic Modeling:** Attributes defining function, materials, and usage.
- **Modular Structure:** Thematic modules for buildings, transportation, and vegetation.

Despite the maturity of 3D city models, cadastral systems, such as Germany's ALKIS, remain predominantly 2D, focusing on land parcels and ownership. Integrating these two disparate data sources presents significant challenges in data alignment, semantics, and visualization (Döner et al., 2010). The use of web-based visualization tools like CesiumJS, an open-source JavaScript library supporting OGC standards like 3D Tiles, is crucial for facilitating interactive exploration of these integrated 3D datasets (Cozzi & Ring, 2021).

1.2 Project Context and Motivation

Urban planning in Stuttgart's Untertürkheim district requires the integration of fragmented 2D cadastral data (ALKIS) and 3D city models (CityGML). Planners currently rely on manual cross-referencing, which leads to delays and errors. This project aims to automate this integration to enhance decision-making by supporting key urban development requirements:

1. Property boundary analysis (ALKIS data).
2. 3D urban form assessment (CityGML models).
3. Zoning compliance checks.
4. Infrastructure planning.

The automation achieved through this project—including unified 2D-3D visualization, automated synchronization, and real-time updates—directly aligns with the EU INSPIRE Directive (2007) and UN Sustainable Development Goals (SDG 11: Sustainable Cities), promoting interoperable spatial data for urban resilience.

1.3 Scope and Objectives

The project focuses on developing a PostgreSQL/PostGIS database that integrates ALKIS (2D) and CityGML (3D) data, visualized via CesiumJS.

Table 1.1: Project Objectives

Objective	**Description**
1. Spatial Database Design	Optimized PostGIS schemas for ALKIS and CityGML; spatial indexing for efficient queries.
2. 2D-to-3D Integration	Semantic matching of features; automated coordinate transformation.
3. Interactive 3D Visualization	Thematic mapping (zoning, building functions); shadow analysis for urban impact studies.
4. Automated Synchronization	Scheduled updates from source datasets; change detection and version control.

Scope Limitations:

- **Geographic Focus:** Untertürkheim (~8 km²).
- **Data Sources:** ALKIS (HFT Stuttgart), CityGML (STEG GmbH), OpenStreetMap.
- **Tech Stack:** PostgreSQL, PostGIS, 3DCityDB, CesiumJS, Node.js.

Chapter 2

Methodology and Implementation

The project employed a structured, open-source-centric methodology emphasizing automated workflows for scalability and maintainability. The implementation was divided into distinct phases: Data Acquisition and Preparation, Database Design and Implementation, and Web-Based Visualization.

2.1 Phase 1: Data Acquisition and Preparation

This phase established an automated Extract, Transform, Load (ETL) pipeline for multi-source geospatial data.

2.1.1 Multi-Source Data Collection

The primary data sources were:

- **ALKIS 2D Cadastral Data:** Authoritative source for 2D cadastral information, typically in XML-based formats (e.g., NAS).
- **CityGML 3D City Models:** LoD1 models were used for 3D geometric data, representing buildings as simple block models, balancing visual representation with data volume.

2.1.2 Automated ETL Pipeline

An automated ETL pipeline was designed to ensure data currency and minimize manual intervention.

Table 2.1: ETL Pipeline Implementation

Data Source	Process	Tooling	Example Automation
ALKIS	Extract, Parse XML, Transform to PostGIS format, Load into database.	Python script with `lxml`, `psycopg2`	Scheduled via cron job (monthly)
CityGML	Retrieve files, Convert GML to database format, Load into 3DCityDB schema.Also load to cesium-ion	3DCityDB Importer/Exporter, Python	Manual or automated via script (quarterly)

2.2 Phase 2: Database Design and Implementation

This phase focused on creating a robust, hybrid spatial database architecture to manage and link the 2D and 3D data efficiently.

2.2.1 Hybrid Spatial Database Architecture

The architecture leverages the strengths of PostgreSQL/PostGIS:

- **Dedicated Schemas:** Separate schemas were maintained for ALKIS (2D) and CityDB (3D) data for modularity and clarity.
- **Dynamic Integration View:** The core innovation was a dynamic PostgreSQL view that semantically links tables from the ALKIS and CityDB schemas. This view joins data based on common identifiers or spatial relationships (e.g., spatial intersection of 2D building footprints with 3D building geometries). This approach avoids data duplication and ensures that updates in the underlying tables are immediately reflected in the integrated view.

2.2.2 Ontology-Based Data Harmonization

To resolve the semantic heterogeneity between ALKIS and CityGML, an ontology-based approach was adopted. This involved:

- **Conceptual Modeling:** Analyzing the conceptual models of both systems to identify how concepts like "building," "parcel," and "land use" are defined.
- **Semantic Mapping:** Establishing a formal mapping between the attributes and features of the two models, ensuring that the integrated data is not only geometrically consistent but also semantically coherent for urban planning applications.

2.3 Phase 3: Web-Based Visualization and Application

The final phase involved developing the web-based platform for interactive 3D visualization.

- **Visualization Platform:** CesiumJS was chosen as the primary visualization library due to its support for 3D Tiles and large-scale geospatial data streaming.
- **Data Serving:** The integrated 3D data (including linked 2D attributes) was served from the PostGIS database using specialized tools (e.g., pg2b3dm or GeoServer) to generate the optimized 3D Tiles format required by CesiumJS.
- **Interactive Tools:** The frontend application included essential urban planning tools:
  - **Thematic Mapping:** Visualizing zoning regulations or building functions by coloring the 3D models based on the linked ALKIS attributes.
  - **Shadow Analysis:** A critical tool for urban impact studies, allowing planners to assess the impact of new developments on sunlight access.
  - **Search and Query:** UI elements enabling users to search for specific parcels or buildings and retrieve the integrated 2D and 3D information.

Chapter 3

Results and Conclusion

3.1 Key Results

The project successfully delivered a functional, integrated 2D/3D urban planning platform, demonstrating several key achievements:

- **Seamless Data Integration:** The dynamic integration view successfully linked 2D cadastral data (ownership, boundaries) with 3D city models (geometry, height), providing a unified data source for analysis.
- **Automated Synchronization:** The implemented ETL pipeline and synchronization mechanisms ensure that the integrated model remains current with changes in the source ALKIS and CityGML datasets.
- **High-Performance Visualization:** The use of CesiumJS and 3D Tiles resulted in a high-performance, interactive web application capable of rendering the entire Untertürkheim district (˜8 km^2) with acceptable frame rates and query response times.
- **Enhanced Planning Capabilities:** The platform enables urban planners to perform tasks that were previously manual and time-consuming, such as visualizing zoning compliance directly on 3D models and conducting real-time shadow impact assessments.

3.2 Contribution and Future Work

This research makes a significant contribution to the field of urban geospatial data management by:

- **Establishing a Blueprint for Dynamic Data Integration:** The project provides a replicable, open-source-based methodology for integrating disparate 2D and 3D urban datasets, addressing the challenge of lifecycle management in dynamic data environments.

- **Empirical Validation of Open-Source Stack:** It provides empirical evidence for the practical utility of the PostgreSQL/PostGIS, 3DCityDB, and CesiumJS stack for delivering high-performance, interactive 3D city models for professional urban planning.

Future work will focus on extending the approach to include additional data sources (e.g., underground infrastructure, environmental sensors) and developing more sophisticated analytical tools, such as noise pollution modeling and advanced visibility analysis, to further enhance the platform's utility for urban resilience and sustainability planning.

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