

Semantic 3D City Models as a Catalyst for Circular Construction Practices

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Abstract. Rapid global urbanization and escalating environmental challenges demand innovative strategies to reduce waste and enhance resource efficiency. As a major resource consumer, the construction industry requires a transformative shift toward sustainable practices through improved material stock assessments and efficient management of construction and demolition waste (CDW). Semantic 3D city models, utilizing the CityGML standard, provide a structured framework for capturing and analyzing building-related data across various levels of detail (LOD). This paper demonstrates how semantic 3D models could empower stakeholders to perform rapid stock inventories, assess reuse potential, and plan waste-minimizing demolition or renovation scenarios, through a sample system architecture for a Web GIS application built on open-access LOD2 CityGML data enriched with material-specific, recyclability, and life-cycle metadata. This framework underscores the role of semantic information in bridging geometric data and circular-economy decision support, supporting more resilient and resource-efficient urban development.

Keywords: Circular Economy · Construction and Demolition Waste · CityGML

1 Introduction

1.1 Construction and Demolition Waste in Circular Economy

The growing pressure to make the urban environment more sustainable has led to an increased focus on the principles of circular economy in the construction sector. Circular economy prioritizes the reuse, recycling and recovery of materials in order to minimize waste and reduce resource consumption [1]. The construction industry, responsible for more than 30% of global waste generation and significant resource extraction, faces critical challenges in managing construction and demolition waste (CDW) due to its volume, diversity, and complex handling requirements [2, 3]. Effective CDW management is pivotal for reducing environmental impacts, such as landfill overuse and greenhouse gas emissions, while also yielding economic benefits through material recovery and cost savings. By adopting circular economy practices, cities can mitigate environmental footprints, optimize resource use, and foster resilient urban infrastructure [4, 5].

Digital technologies are emerging as facilitative tools in this process. The semantic 3D city model, especially CityGML, has become a prominent standard to model, analyze,

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and manage urban environments digitally [6]. By holding geometric as well as semantic attributes of buildings, meticulous material stock assessments can be conducted, which is essential for proper the management of CDWs [7]. Such specifics are useful for decisions on recycling, reuse plans, and environmentally friendly practices that align urban growth with circular economy endeavors.

The aim of this paper is to demonstrate how semantic 3D city models, especially a CityGML-based model, can serve as a catalyst for circular construction practices. The objective is to illustrate how a system architecture of such a Web GIS application possibly could be structured to support urban stakeholders in visualizing, querying, and evaluating building materials at scale. The proposed system emphasizes interoperability, real-time visualization, and semantic querying through a modular architecture, and a user-friendly frontend interface. This prototype can help assess reuse potential, map recyclable elements, and inform material recovery strategies for urban renovation or demolition projects.

By providing detailed semantic information in 3D models, CityGML-based models enable stakeholders to identify recyclable materials and effectively make plans for material reuse optimization. It highlights the dual benefit of semantic enrichment: to improve the accuracy of material inventories and to facilitate interdisciplinary cooperation between urban planners, geospatial analysts and sustainability experts. In this respect, this paper aims to lay the foundation for analyzing how advanced digital models can fill the gap between conceptual models of the circular economy and practical application in urban building and demolition processes.

This paper is organized into four chapters. In Sect. 1, we introduce the concepts of circular economy in construction and demolition waste, define the scope and objectives of our study, and emphasize the value of semantic 3D urban models in facilitating the assessment and management of material stocks. Section 2 explores CityGML as a semantic information holder and explains its structure, the concept of levels of detail and its benefits in providing detailed material properties for effective circular economy applications. In Sect. 3, we present the sample architecture of a web portal for material management showing how geospatial data is used, and visualized by an interactive front-end to facilitate decision-making in sustainable urban development. Finally, the last section summarizes the key conclusions, discusses limitations, and indicates future research directions to further improve the integration of semantic 3D models into circular construction practices.

2 CityGML as a Semantic Information Holder

CityGML is a standard data model and exchange format for 3D urban models, which integrates geometric and semantic information [8]. Its structure is organized into core modules and thematic modules that define together the spatial and non-spatial characteristics of urban objects [9]. One of the most important aspects of CityGML is the concept of level of detail (LOD) [10]. LODs provide a formal framework for representing urban models at varying granularities, ranging from simple block models (LOD1) to detailed models of architectural elements and material characteristics (LOD3).

The semantic enrichment provided by CityGML is particularly useful for applications in the circular economy. By associating detailed material properties and construction elements with their geometric counterparts, CityGML makes it possible to conduct comprehensive material stock analyses. Within CityGML, building components such as walls, roofs, windows, and doors can be enhanced with semantic attributes describing their material attributes [7]. This is facilitated by utilizing predefined attribute classes and, if required, Application Domain Extensions (ADEs) through which additional domain-specific information can be added [11]. Material attributes such as thermal conductivity, recyclability, or life expectancy can be appended to the data. This capability is important in CDW management. This information allows planners and engineers to assess the extent of material recycling, reduce waste and the environmental impact of construction activities.

Besides, the standardization through CityGML also increases data interoperability across disciplines and platforms which helps promote cooperation among urban planners, environmental scientists, and policy makers. CityGML is a semantic information source that not only provides transparency and access to urban data but also enables innovative solutions for circular construction practice.

3 Use Case: Web Portal for Material Management

Recent advancements in web technologies, data formats, and increased internet speed have significantly enhanced Web GIS solutions, positioning them as primary interfaces between geospatial data and end-users. While traditional GIS systems have predominantly provided solutions based on two-dimensional (2D) datasets, contemporary developments have enabled more realistic and detailed visualizations using three-dimensional (3D) data. Specifically, the growing importance of CityGML standards and the adoption of urban digital twins have underscored the critical role that 3D geospatial data plays in sustainable urban development and management. Yao et al. highlight how CityGML significantly extends analytical capabilities beyond conventional 2D GIS by enabling realistic simulations, detailed visualizations, and comprehensive spatial analyses [12, 13].

The number of cities utilizing CityGML datasets, particularly at LOD 2, has been increasing. Planners, engineers, managers, and administrators, increasingly rely on web-based GIS platforms designed to leverage geometric and semantic information for informed decision-making. Examples include the Hamburg Geoportal, the Berlin Economy Overview Map, or the Helsinki's Energy and Climate Atlas [14–16]. Such platforms offer interactive visualization, advanced querying functions, and enhanced accessibility for diverse stakeholders involved in urban material management and circular economy initiatives. On this background, this paper proposes a system architecture, illustrated by the modern Web GIS architecture depicted in Fig. 1, for effectively publishing CityGML data in a web environment.

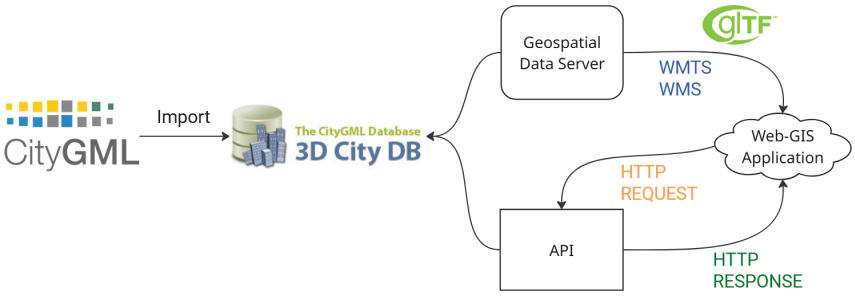

Fig. 1. System Architecture of a conceptual Web GIS Portal. *Source: authors*

3.1 Data Processing

Before being utilized in web applications or machine and deep-learning analyses, raw geospatial data require extensive preprocessing. Depending on data types and target applications, preprocessing tasks may vary significantly. CityGML data produced through surveying must undergo validation processes using dedicated tools such as FZKViewer [17].

CityGML's raw XML-based format is generally not efficient for direct use in interactive web applications. Therefore, the data must be converted into formats compatible with browser-based visualization technologies such as WebGL. Among the most suitable standards for this purpose is the Graphics Library Transmission Format (glTF), developed by the Khronos Group. glTF provides a compact, self-contained format optimized for real-time online rendering, enabling rapid data loading and reduced computational demands [18]. The core of glTF comprises a JSON file that describes the structure and composition of 3D models, combined with binary blocks containing vertex, index, and animation data in raw byte arrays [19]. Using the 3DCityDB, CityGML data can be efficiently exported into glTF format, establishing a secure and streamlined data processing pipeline from raw data to visualization-ready datasets [13] (Fig. 2).

3.2 Backend Infrastructure

Backend systems in Web GIS applications serve as intermediaries between data storage layers and frontend visualization platforms, primarily through Application Programming Interfaces (APIs) and geospatial data servers. Although modern tech stacks often conceptualize backend systems purely as APIs, handling geospatial data requires specialized data servers that comply with standards set by organizations such as the Open Geospatial Consortium (OGC). Standardized communication protocols, like Web Mapping Service (WMS), allow backend systems to deliver geospatial data consistently to various frontend clients, including both web and desktop GIS applications, ensuring sustainability and broad interoperability [20].

Additionally, APIs manage critical functions such as user authentication and authorization. APIs enable user-specific data access, ensuring that data security and privacy regulations are strictly adhered to, particularly important in circular economy contexts.

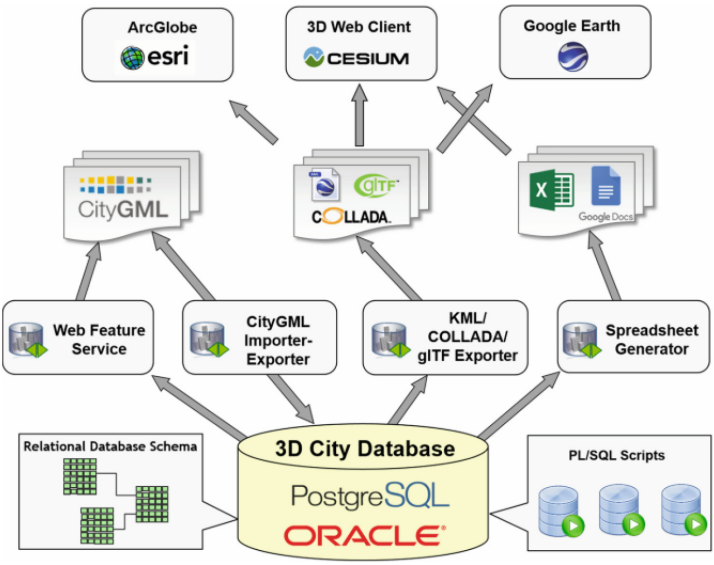

Fig. 2. Key components of the 3DCityDB Software Suite. *Source: Yao et al.* [12]

A common approach for backend implementation involves using Python-based frameworks, which offer extensive libraries for geospatial data handling. When integrated with databases like 3DCityDB, Python frameworks can securely manage SQL interactions via libraries such as SQLAlchemy, facilitating efficient database processing capabilities directly accessible to frontend users [12].

For serving large-scale 3D datasets, scalable geospatial servers are essential. One prominent example is Cesium Ion, an online platform offering streamlined handling of 3D data formats compatible with web and game-engine applications [21]. Although its free tier has limitations, Cesium Ion is ideal for proof-of-concept (POC) projects due to minimal initial backend investment. Larger projects, however, might require deploying a dedicated, scalable 3D Tiles server. Literature such as Yao et al. [12] and Liu [22] provide valuable insights into implementing on-premise tile servers, highlighting the importance of careful backend design to ensure smooth frontend interactions and efficient data transfer.

3.3 Frontend Design Considerations

Frontend interfaces are the primary points of interaction between geospatial data and end-users, enabling visualization, filtering, and analysis functionalities. Given the broad application scope of GIS, designing Web GIS interfaces tailored to specific user profiles through user experience (UX) and user interface (UI) design principles has become a standard practice. A common pattern includes the implementation of side panels (left and right) to facilitate intuitive information navigation, especially effective in map-centered applications. Two primary approaches exist for frontend implementation:

Fully Customized Development. This involves building a bespoke frontend architecture from scratch, allowing full control over interface design and functionalities. A popular technology choice for 3D visualization in this scenario is Cesium.js, an open-source library enabling streaming and rendering of extensive heterogeneous geospatial datasets through its 3D tiles specification. While this offers comprehensive flexibility, it demands substantial time, human resources, and financial investment, which might not be feasible for limited-resource scenarios.

Framework-Based Rapid Development. Alternatively, projects can leverage existing open-source frameworks designed specifically for Web GIS, such as the TOSCA initiated by HafenCity University Digital City Science [23]. The TOSCA is an open source and full stack application for WEB GIS solution. TOSCA backend system utilizes Python Django API, a Postgre database and GeoServer, a geospatial data server solution [23–25]. The frontend of TOSCA uses Vue-3 Js web framework and the Maplibre GL mapping library based on WebGL. Including its underlying subsystems, the entire codebase of the TOSCA infrastructure is accessible as open source. Furthermore, the system infrastructure is suitable for publishing both 2D and 3D data. By using established documentation, project-specific functionalities can be quickly integrated, significantly reducing initial development effort and facilitating early stakeholder testing and feedback (Fig. 3).

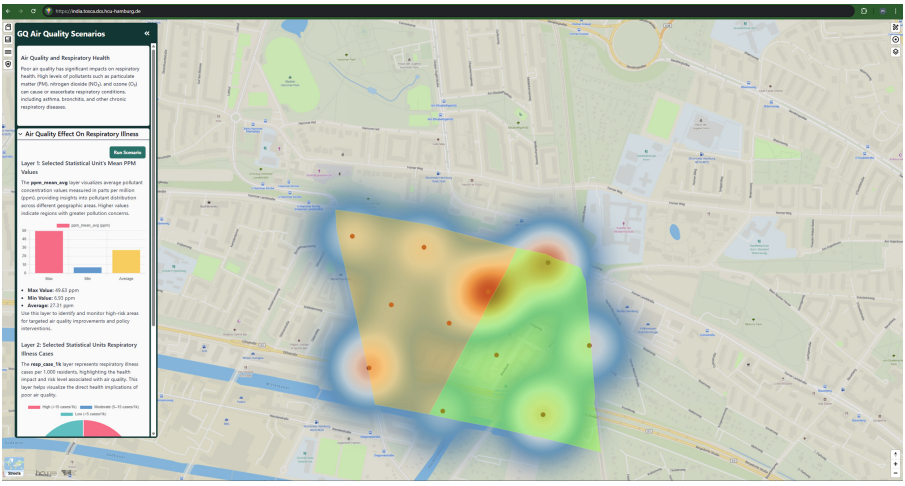

Fig. 3. TOSCA for public health use case. *Source: authors* [26]

Regardless of whether a fully customized frontend or a framework-based approach is employed, the effectiveness of a Web GIS application in supporting circular construction practices largely depends on its interface design and functional responsiveness. Figure 1 illustrates the shared conceptual foundation underlying both development strategies. Central to this foundation is the prioritization of user-centered design, where interface components such as side panels and interactive map elements must be tailored to the specific analytical needs of end-users. Filtering functionalities represent a core component of such platforms. Both attribute-based filtering (e.g., by material type, construction

year, or reuse potential) and spatial filtering are fundamental for enabling users to extract relevant subsets of the building stock. In addition, the integration of essential geospatial processing functions such as buffer, dissolve, and intersection can enhance the platform's analytical capabilities, supporting scenario-based analyses of demolition, renovation, and resource recovery. These foundational functions enable stakeholders to derive actionable insights from complex urban datasets and are critical for the implementation of circular economy strategies in the built environment.

When geospatial data is produced and published according to standardized formats, the integration of new scenarios into existing Web GIS systems is significantly facilitated. In particular, adopting a framework-based development approach allows for the seamless inclusion of additional use cases as requirements evolve. For example, the Digital City Science team at HafenCity University has developed the AGORA Web GIS platform for the LIG (Hamburg Real Estate and Land Property Management Authority) using the TOSCA base system [26, 27]. This platform supports urban planning workflows compatible with German geospatial standards such as ALKIS and XPlanung and enables experts to identify the most suitable land parcels [28] (Fig. 4).

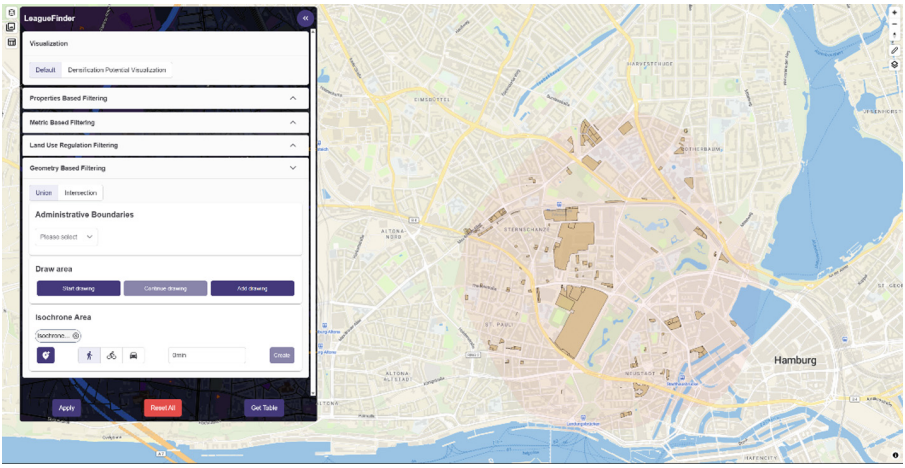

Fig. 4. AGORA property (include general real estate and exclude roads) and geometry (15 min concept) based filtering. *Source: authors* [27]

Within the AGORA system, users can apply both attribute-based filters (e.g. zoning category, land use type) and spatial filters (e.g. drawn area of interest, administrative/statistical boundaries or isochrone-based catchment areas generated via a routing engine) to efficiently query and analyze land parcel data within the city of Hamburg.

The same modular filtering logic combining attribute and geometric constraints can be applied to other domains. For example, in the context of the circular economy use case, the same filtering mechanisms can be reused to produce relevant insights, provided that the underlying geospatial data is published in accordance with defined standards. As demonstrated in the AGORA system, such filters are not hard-coded but abstracted in a reusable manner, allowing them to be flexibly adapted to different application scenarios

with minimal front-end changes. Given these examples, we present a sample feature set for a Web GIS application for circular economy focus.

Exemplary Feature Set for a Circular Economy Web GIS Application
To support decision-makers in quickly performing analyses related to circular economy metrics, the proposed Web GIS solution should include:

- *Material Query & Filtering:* Query buildings by material type, quantity, and reuse/recycle potential.
- *Material Inventory Analysis:* Assess buildings based on recyclability, reuse potential, and sustainability scores.
- *Spatial Querying:* Filter buildings by attributes such as type, construction year, and materials.
- *Dashboard & Reporting:* Visualize key circular economy indicators, including recycling potentials and potential CO_2 savings.
- *Scenario Simulation:*Simulate building demolition and renovation scenarios, emphasizing material reuse.
- *Export & Sharing:*Provide options to export analysis results in standard formats (e.g., PDF, CSV) to facilitate stakeholder communication.

4 Conclusion and Future Work

In summary, this paper has demonstrated the potential of semantic 3D city models, particularly those based on CityGML, to act as a catalyst for circular construction practices. By integrating geometric and semantic information, CityGML provides a robust framework for accurately assessing material stocks and managing construction and demolition waste. This capability is critical in supporting the transition to a circular economy in urban environments, where efficient resource use is important. The detailed semantic enrichment in CityGML-based models enables experts to collaborate effectively, facilitating informed decisions regarding material reuse, recycling strategies, and sustainable demolition practices.

The system showcased how modern Web GIS solutions can bridge the gap between theoretical circular economy models and their real-world implementation. The system architecture, which includes backend infrastructure and user-friendly frontend interfaces, serves as an example of how digital tools can support experts in sustainable urban development.

Despite the advantages of CityGML-based semantic 3D city models in supporting circular construction, several limitations remain. First, the accuracy and completeness of these models heavily depend on the availability and quality of input data, which can vary significantly across different municipalities and regions. Inconsistencies in data collection methods, sensor precision, and classification standards can lead to discrepancies in material assessments and hinder interoperability. Additionally, while the web-based material management system presented in this paper facilitates visualization and decision-making, the complexity of ensuring real-time data updates and cross-platform compatibility remains an ongoing issue.

Looking ahead, several avenues for future work are apparent. First, further refinement of data processing workflows and the integration of more detailed semantic attributes

could enhance the accuracy and utility of material stock assessments. Expanding the use case to incorporate additional datasets from different cities or higher Levels of Detail (e.g., LOD3) would allow for more comprehensive analyses, despite the associated challenges in data acquisition and processing costs. Moreover, the development of standardized protocols for semantic enrichment across various urban contexts could foster greater interoperability and data sharing among municipalities, researchers, and industry practitioners.

Additionally, exploring the integration of other sustainability metrics—such as life cycle assessment (LCA) or carbon footprint estimation—into CityGML models could provide a more holistic view of urban environmental performance. These enhancements would not only support better planning decisions but also encourage wider adoption of circular economy practices. Ultimately, continued interdisciplinary research and collaboration are essential to advance these digital solutions, ensuring that they meet the evolving needs of sustainable urban development in the 21st century.

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