Zonology: An Ontology-Based Framework for Harmonizing Zoning Semantics Across Multi-Jurisdictional Greater Toronto Area (GTA) Planning Systems

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Abstract

Zoning regulations in the Greater Toronto Area (GTA) are governed by a decentralized system in which 25 municipalities independently define land use permissions, development standards, and zoning classifications. Although operating under a shared provincial framework, these municipalities employ inconsistent zoning terminologies and abbreviation systems, resulting in significant semantic fragmentation. This lack of standardization introduces inefficiencies in development approvals, increases reliance on manual interpretation, and limits the effectiveness of digital planning tools such as GIS and automated compliance systems. This study introduces Zonology, an ontology-based framework designed to harmonize zoning semantics across multi-jurisdictional planning systems while preserving municipal autonomy. Developed using the Linked Open Terms (LOT) methodology and implemented in OWL, the framework establishes formal relationships between zoning designations, permitted land uses, and development standards. A proof-of-concept case study aligning the City of Toronto and the City of Markham demonstrates the ability to integrate over 60 zoning categories and 150 land uses within a unified semantic structure. Results show high precision and recall in competency question queries, confirming the model's effectiveness in enabling cross-jurisdictional interpretation. Zonology provides a scalable foundation for interoperable urban planning, supporting digital permitting, data-driven decision-making, and Artificial Intelligence (AI) assisted governance.

1. Introduction

Urban development in the Greater Toronto Area (GTA) operates within a highly decentralized regulatory environment in which 25 municipalities independently administer zoning by-laws. Zoning regulations form the legal backbone of land use planning by defining permitted uses, density limits, built form parameters, performance standards, and development controls. Although municipalities operate under the same provincial Planning Act framework, the semantic structure, terminology, and categorization of zoning designations vary substantially across jurisdictions (Hodge & Gordon, 2013). This structural heterogeneity creates a fragmented regulatory landscape in one of Canada's fastest-growing metropolitan regions.

Zoning by-laws are traditionally written as text-based legal instruments supplemented by schedules and static maps. While these documents provide detailed regulatory control, they are primarily designed for human interpretation rather than machine processing. Each municipality has historically developed its own abbreviation systems, definitional hierarchies, exception mechanisms, and overlay structures. As a result, zoning categorize that appear similar across municipalities often encode different regulatory permissions and constraints. Conversely, identical land uses may be categorized under entirely different zoning abbreviations depending on jurisdiction.

For example, the designation "R2" in the City of Toronto and "R2-S" in the City of Markham differ in their permitted land uses, minimum lot frontage, building typologies, and performance standards. These distinctions are not merely nominal but reflect substantive regulatory divergence. For planners, engineers, developers, and municipal reviewers operating across municipal boundaries, such inconsistencies require repeated manual interpretation of by-law text and cross-referencing of definitions. This interpretive burden increases soft costs, introduces ambiguity, and prolongs the feasibility assessment phase of development projects (Pomeroy, 2020).

The implications of zoning fragmentation extend beyond administrative inconvenience. The GTA is currently experiencing significant population growth and intensification pressures. Provincial housing targets aim to deliver 1.5 million new homes by 2031, necessitating accelerated development approvals and improved planning efficiency. While financial and construction constraints are often cited as barriers to housing delivery, delays associated with regulatory interpretation and inter-municipal inconsistency remain under-examined structural challenges. In practice, development feasibility studies, zoning by-law amendments, and site plan approvals all depend on accurate interpretation of permitted uses and quantitative standards. When zoning semantics are inconsistent and non-standardized, digital tools such as GIS platforms and automated compliance systems cannot reliably support these processes.

At the same time, urban planning is undergoing rapid digital transformation. Geographic information systems (GIS), digital twins, automated code checking systems, and Artificial Intelligence (AI) assisted decision-support tools increasingly rely on structured, machine-readable regulatory data. However, most municipal zoning by-laws are distributed as static PDFs or loosely structured GIS layers without formal semantic representation. This lack of machine-readable zoning data limits interoperability between jurisdictions and constrains integration with advanced computational tools. The absence of a harmonized semantic framework therefore represents a critical barrier to data-driven urban governance.

Ontology engineering offers a structured solution to such semantic fragmentation. Ontologies provide formal, machine-readable representations of domain knowledge through explicit class hierarchies, properties, and logical constraints (Gruber, 1993). In the context of urban planning, ontology-based models have demonstrated potential for representing land use regulations, aligning heterogeneous datasets, and enabling semantic interoperability (Silvennoinen et al., 2023). However, most existing efforts focus on modeling zoning within a single jurisdiction rather than aligning multiple independently developed zoning systems.

This paper introduces Zonology, an ontology-based framework designed to harmonize zoning abbreviations, land use permissions, and development standards across GTA municipalities. Rather than replacing municipal by-laws or imposing standardized terminology, Zonology functions as an interoperable semantic translation layer. It preserves municipal autonomy while enabling consistent cross-jurisdictional interpretation. By formalizing zoning semantics using OWL-based representation and description-logic reasoning, the framework supports automated querying, equivalence mapping, and integration with geospatial systems.

Through a proof-of-concept case study involving the City of Toronto and the City of Markham, Ontario, Canada; this research demonstrates that zoning fragmentation can be systematically addressed using ontology engineering. The approach advances semantic interoperability in urban planning and provides foundational infrastructure for digital permitting systems, automated compliance workflows, and regionally coordinated planning analytics.

2. Related Work and Research Gap

Ontology engineering has emerged as a foundational methodology for knowledge representation and semantic interoperability across heterogeneous domains. An ontology formally specifies a shared conceptualization of a domain through explicit classes, relationships, constraints, and axioms (Gruber, 1993). Within the semantic web paradigm, ontologies enable machine-readable data integration, reasoning, and automated querying, supporting interoperability across distributed information systems.

In the geospatial domain, ontology-based models have been widely applied to address conceptual mismatches between datasets, support spatial data integration, and enable cross-platform interoperability. GIS traditionally manage spatial data effectively but often lack formal semantic representation of regulatory or conceptual structures. As a result, inconsistencies in terminology and classification schemes across jurisdictions limit meaningful data exchange and automated reasoning.

Urban planning and land-use regulation present particularly complex semantic challenges. Zoning by-laws are structured as hierarchical regulatory systems combining land-use classifications, performance standards, development controls, exception overlays, and textual provisions. These components are often interdependent and context sensitive. Several studies have attempted to formalize aspects of land-use planning using semantic technologies. For example, ontology-based frameworks have been developed to represent building regulations, land-use categories, and planning constraints within specific jurisdictions. The OntoZoning ontology developed for Singapore demonstrates that zoning rules can be represented in a machine-readable format, enabling semantic querying of permitted uses and regulatory standards (Silvennoinen, et al., 2023).

Other urban ontologies, such as those focused on infrastructure modeling, land administration, or smart city governance, provide structured vocabularies for representing physical and administrative systems. In addition to OntoZoning, several urban and infrastructure ontologies have been explored in the literature for their potential applicability to land use and regulatory modeling. The LBCS-OWL2 ontology provides a standardized classification of land uses based on activity, function, and structure, supporting consistent categorization across datasets (Montenegro et al., 2012). The iCity Ontology Suite offers a comprehensive framework for integrating urban data, including land use, infrastructure, and governance components, although it lacks detailed regulatory logic (Katsumi & Fox, 2019). OntoURBAN focuses on representing urban planning concepts and relationships, particularly in the context of smart city applications, but does not explicitly model zoning rules or development standards (Calderón & Ortiz, 2015). Similarly, CityGML Utility Network ADE (Becker et al., 2013) and LandInfra (ISO TC211, 2016) emphasize physical infrastructure and land administration, providing valuable representations of spatial and engineering systems but limited support for regulatory semantics. However, these ontologies often emphasize spatial entities (e.g., parcels, utilities, buildings) rather than the regulatory semantics that govern development permissions. In many cases, zoning is treated as an attribute of spatial units rather than as a complex rule-based construct requiring explicit logical modeling.

Furthermore, most existing ontology implementations are designed for single-jurisdiction environments. They formalize regulatory semantics within a unified planning framework, where zoning terminology and definitions are internally consistent. While this approach is effective for centralized regulatory systems, it does not address federated governance contexts such as the GTA, where multiple municipalities independently develop and maintain their own zoning by-laws.

In federated metropolitan regions, semantic fragmentation arises from historical, administrative, and political autonomy. Municipalities adopt unique abbreviation systems, definitional hierarchies, and exception mechanisms. Even when regulatory objectives are similar, terminological divergence prevents straightforward equivalence mapping. For example, residential density categories may be structured differently across municipalities, with varying thresholds for permitted uses, frontage requirements, or floor space indices. Without a formal alignment framework, cross-jurisdiction comparison requires manual interpretation.

The literature on regulatory digitization increasingly emphasizes the importance of machine-readable legal frameworks for enabling automated compliance checking and AI-assisted governance (Gruber, 1993; McGuinness & Van Harmelen., 2004). However, most digitization efforts focus on document accessibility rather than semantic harmonization. Converting zoning by-laws into searchable PDFs or GIS layers improves access but does not resolve structural inconsistencies between jurisdictions. Semantic alignment requires explicit modeling of

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equivalence relationships, hierarchical mappings, and shared conceptual constructs.

Within the Canadian context, limited research has addressed zoning harmonization at the metropolitan scale (Hodge & Gordon, 2013; Pomeroy, 2020; Slack and Bird, 2013). Planning scholarship has documented the administrative and political challenges associated with inter-municipal coordination (Hodge & Gordon, 2013; Pomeroy, 2020), yet technical solutions for semantic interoperability remain underdeveloped. Existing studies recognize that regulatory fragmentation contributes to inefficiencies in development approvals but stop short of proposing formal computational frameworks to address the issue.

Accordingly, the primary research gap can be identified in three dimensions as follows:

- First, while urban ontologies exist, (Silvennoinen et al., 2023) few focus explicitly on the semantic alignment of zoning abbreviations and regulatory constructs across independent municipalities.
- Second, existing ontology implementations rarely distinguish clearly between spatial entities (zones as mapped areas) and regulatory entities (zoning designations as rule sets), limiting their capacity for cross-jurisdiction harmonization.
- Third, there is an absence of a scalable, interoperable ontology framework tailored to multi-municipal metropolitan regions characterized by heterogeneous zoning taxonomies.

This paper addresses these gaps by introducing Zonology, a cross-jurisdictional zoning ontology designed to align regulatory semantics without altering municipal autonomy. By separating spatial geometries from regulatory constructs and modeling equivalence relationships explicitly within an OWL-based framework, Zonology advances semantic interoperability in federated urban governance systems. Through this contribution, the study bridges urban planning scholarship and knowledge engineering, positioning ontology development as a structural solution to regulatory fragmentation in rapidly growing metropolitan regions.

3. METHODOLOGY

The development of Zonology followed a structured ontology engineering process based on the Linked Open Terms (LOT) methodology as presented in Table 1. LOT integrates best practices from established ontology development frameworks and organizes the workflow into five principal stages: specification, conceptualization, implementation, and evaluation. This structured approach ensures methodological transparency, reproducibility, and logical consistency.

3.1 Ontology Specification

The specification phase focused on defining the scope, goals, and requirements of the ontology. Domain knowledge was acquired through a systematic review of zoning by-laws, official plans, and policy documents from selected municipalities within the Greater Toronto Area (GTA). The City of Toronto and the City of Markham were selected as proof-of-concept case studies due to their contrasting zoning taxonomies and regulatory structures.

An Ontology Requirements Specification Document (ORSD) was developed to formalize the scope, stakeholders, and system requirements. Functional requirements were defined through competency questions representing real-world planning workflows, such as identifying permitted land uses, determining development standards, and evaluating cross-municipal equivalencies (Grüninger & Fox, 1995). In addition, non-functional requirements including clarity, consistency, extensibility, usability, and coverage were established to ensure the robustness of the ontology (Raad & Cruz, 2015).

Phases	Primary Purpose	Key Activities
1. Ontology Specification	Define scope, goals, and requirements	• Acquire domain knowledge (zoning by-laws, OPs, policy docs) • Create ORSD (scope, stakeholders, requirements) • Formulate competency questions (CQs) • Identify functional & non-functional requirements
2. Ontology Conceptualization	Structure knowledge model	• Use hybrid top down & bottom-up modeling • Identify core zoning terms & class hierarchy • Define object & data properties • Align terminology with real-world planning workflows
3.Ontology Refinement & Alignment	Refine and standardize conceptual model	• Standardize terms and fix naming inconsistencies. • Reuse elements from existing ontologies and refine structure. • Prepare for OWL-DL compliance and finalize properties.
4. Ontology Implementation	Build ontology in OWL	• Implement in OWL 2 with Protégé • Encode concepts as classes & properties • Add constraints, axioms, & reasoning support • Enable cross-municipal linkage between Toronto & Markham
5. Ontology Evaluation	Validate quality, usability, and reasoning	• Perform DL reasoning checks (consistency, inference) • Test against competency questions (CQ validation) • Apply to real-world case studies/scenarios • Gather feedback from planners & stakeholders

Table 1. The proposed framework to develop Zonology.

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3.2 Ontology Conceptualization

The conceptualization phase translated the extracted domain knowledge into a structured and formal knowledge model. A hybrid modeling approach was adopted, combining top-down abstraction of planning concepts with bottom-up analysis of real-world zoning data (Noy & McGuinness, 2001).

Core zoning terms were identified and organized into a hierarchical class structure, forming the foundation of the ontology. Key classes such as *ZoningDesignation*, *LandUse*, *BuildingType*, *DevelopmentStandard*, *Municipality*, and *Authority* were defined to represent the regulatory and planning framework. Object and data properties were introduced to capture relationships between these classes, including permitted land uses, building regulations, and administrative control. Terminology was aligned with real-world planning workflows to ensure that the ontology reflects practical zoning interpretation and application. This approach supports semantic clarity and interoperability across heterogeneous municipal systems (Guarino et al., 2009).

3.3 Ontology Refinement and Alignment

Following conceptualization, the ontology underwent a refinement and alignment phase to improve consistency, clarity, and interoperability. Terminology was standardized and naming inconsistencies were resolved to ensure uniformity across the ontology.Elements from existing urban and infrastructure ontologies were selectively reused and integrated to enhance the structure and completeness of the model. This reuse aligns with best practices in ontology engineering, where existing knowledge structures are leveraged to improve efficiency and interoperability (Kuhn et al., 2014; Silvennoinen et al., 2023).The ontology was then prepared for OWL-DL compliance by refining class definitions, object properties, and logical constraints. OWL-DL ensures a balance between expressiveness and computational reasoning capability, enabling reliable automated inference.

3.4 Ontology Implementation

The ontology was implemented in OWL 2 using the Protégé platform. OWL was selected due to its strong support for formal logic representation, description-logic reasoning, and compatibility with semantic web technologies (McGuinness & van Harmelen, 2004). Concepts were encoded as classes and properties, and logical constraints and axioms were introduced to support reasoning capabilities. Zoning designations were modeled as subclasses with defined property restrictions, enabling formal representation of regulatory conditions. Cross-municipal linkages between Toronto and Markham were explicitly incorporated to support semantic alignment. Description-logic reasoners were applied to validate class hierarchies, detect inconsistencies, and infer implicit relationships, ensuring that the ontology is logically coherent and structurally sound (Baader et al., 2003).

3.5 Ontology Evaluation

The evaluation phase assessed the quality, usability, and reasoning performance of the ontology. Competency questions were translated into SPARQL queries and used to test the ontology's ability to retrieve relevant planning information, including permitted land uses, development standards, and cross-municipal equivalencies. Logical validation was performed using description-logic reasoning to confirm global consistency, ensure the absence of domain and range violations, and verify correct inference of relationships (Baader et al., 2003).

In addition, the ontology was evaluated against non-functional requirements such as clarity, extensibility, usability, and coverage (Raad & Cruz, 2015). The model was further applied to real-world case studies to demonstrate practical applicability. Finally, feedback from planners and stakeholders was incorporated to refine the ontology and ensure alignment with real-world planning practices. This evaluation confirms that Zonology provides a scalable and reliable framework for harmonizing zoning information across municipalities.

4. Results And Discussion

The Toronto–Markham case study demonstrates the practical feasibility of cross-jurisdictional zoning harmonization through ontology engineering. Within the proof-of-concept implementation, more than 60 zoning designations and over 150 permitted land uses were aligned within a unified semantic hierarchy. These designations encompassed residential, mixed-use, employment, industrial, and special-purpose categories, each modelled with explicit regulatory relationships and quantitative standards.

4.1 Structural Alignment Outcomes

The ontology successfully established formal semantic relationships between zoning designations that were functionally equivalent but terminologically distinct. Equivalence was not inferred based solely on naming similarity; instead, it was derived from shared regulatory characteristics, including permitted land uses, development standards, and building typologies. For example, residential categories in Toronto and Markham were mapped through shared restrictions such as:

- Permitted dwelling types
- Maximum floor space index
- Minimum lot frontage
- Height limitations

This structured equivalence mapping enabled the ontology to recognize functional similarity even where abbreviations differed. As a result, cross-municipal comparisons that previously required manual interpretation were automated through semantic inference.

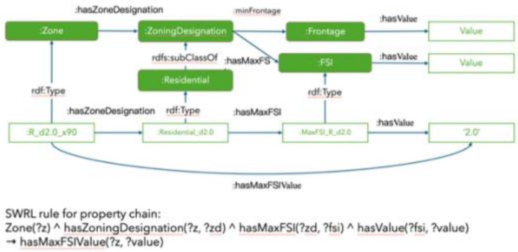

Figure 1. Mapping zoning abbreviations between municipalities (example: CL in Toronto and COM in Markham).

4.2 Logical Validation and Consistency Checking

Description-logic reasoning was applied to validate the internal coherence of the ontology. Reasoning tasks confirmed:

- **No unsatisfiable classes:** All zoning designations were logically consistent with defined restrictions.
- **Global consistency:** No contradictory axioms or conflicting property assertions were detected.
- **Property constraint stability:** Domain and range definitions for object properties were respected.
- **Hierarchy preservation:** Subclass relationships were correctly inferred without unintended class collapses.
- **Valid equivalence mappings:** owl:equivalent-Class assertions did not introduce logical inconsistencies.

These reasoning results demonstrate that the ontology structure supports formal logical integrity, ensuring reliability for computational querying and regulatory inference.

4.3 Competency Question Performance

Competency questions defined during the specification phase were operationalized through SPARQL queries. The ontology successfully retrieved structured responses for all primary query types, including:

- Retrieval of full zoning definitions from abbreviations (e.g., expanding “R2-S” to its regulatory structure)
- Identification of cross-municipal equivalent zoning categories
- Extraction of permitted land uses within a given designation
- Identification of permitted building types within residential or employment zones
- Retrieval of quantitative development standards (height, density, frontage).

Query execution confirmed that the ontology structure supports both direct retrieval and inferred results through reasoning. In cases where equivalence mappings were defined, inferred relationships allowed queries to return results that were not explicitly stated but logically entailed. Evaluation metrics indicated high precision and recall in competency question resolution. Retrieved results corresponded accurately to by-law provisions without omission of relevant regulatory attributes. Execution accuracy was high across standardized queries, demonstrating structural robustness of the model.

4.4 Scalability Validation

The modular design of the ontology allows additional municipalities to be incorporated without restructuring the core schema. Alignment bridges can be introduced incrementally, preserving existing class hierarchies while expanding coverage. The Toronto–Markham case study therefore demonstrates not only technical feasibility but also architectural scalability for broader GTA-wide implementation.

4.5 Discussion

Overall, the results confirm that zoning abbreviation inconsistencies are computationally addressable through formal semantic modeling. Zonology transforms fragmented regulatory text into a logically structured, machine-readable knowledge base capable of supporting automated reasoning, cross-jurisdiction alignment, and digital planning workflows. Zoning abbreviation inconsistencies represent structural interoperability barriers rather than mere linguistic variations. Fragmented taxonomies inhibit integration with GIS platforms, digital twins, automated compliance systems, and AI-assisted planning tools. By formalizing zoning semantics in OWL, Zonology introduces a shared conceptual vocabulary that supports machine-readable interpretation. The framework does not replace municipal autonomy but provides a semantic translation layer enabling consistent interpretation across jurisdictions. Scalability analysis suggests that the model can be extended to additional GTA municipalities through alignment bridges and modular ontology expansion.

5. Conclusion

This research presents Zonology, an ontology-based framework that addresses semantic fragmentation in zoning regulations across the Greater Toronto Area (GTA). The framework introduces a novel semantic translation layer that aligns zoning abbreviations, permitted land uses, and development standards while preserving municipal autonomy. By separating spatial entities from regulatory constructs and applying OWL-based equivalence mappings, Zonology enables consistent cross-jurisdictional interpretation. A proof-of-concept case study integrating over 60 zoning designations and 150 land uses across Toronto and Markham demonstrates high accuracy in competency question queries. This research demonstrates that ontology engineering can address structural zoning fragmentation in multi-jurisdictional urban systems. Zonology enhances consistency, reduces manual interpretation burdens, and enables interoperable digital planning workflows.

Future work will expand the model across all GTA municipalities and integrate spatial, temporal, and exception-based zoning rules. Future work includes:

- Integration with GeoSPARQL for spatial-semantic reasoning
- Exception modeling for site-specific overlays
- Temporal reasoning for evolving zoning regulations
- Expansion to all 25 GTA municipalities.

As governments pursue accelerated housing delivery and digital modernization, semantic harmonization of zoning data represents a foundational infrastructure for smart urban governance.

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