AGILE: GIScience Series, 6, 3, 2025. https://doi.org/10.5194/agile-giss-6-3-2025
Proceedings of the 28th AGILE Conference on Geographic Information Science, 10–13 June 2025.
Eds.: Auriol Degbelo, Serena Coetzee, Carsten Keßler, Monika Sester, Sabine Timpf, Lars Bernard
This contribution underwent peer review based on a full paper submission.

3D Land Use Planning: Making Future Cities Measurable with Ontology-Driven Representations of Planning Regulations

Ayda Grisiute [1], Martin Raubal [1], and Pieter Herthogs [2]

[1]Institute of Cartography and Geoinformation, ETH Zurich, Zurich, Switzerland
[2]Singapore-ETH Centre, Future Cities Lab Global Programme, CREATE Campus, Singapore

Correspondence: Ayda Grisiute (agrisiute@ethz.ch)

Abstract. This study addresses the challenge of evaluating Singapore's long-term urban strategy by quantifying the impact of planning regulations, a task often hampered by fragmented data and siloed tools. To overcome these limitations, we developed a data-driven workflow using Semantic Web Technologies (SWT). Central to this workflow are two ontologies: OntoPlanningRegulations, which captures a subset of Singapore's planning rules, and OntoBuildableSpace, which defines measurable 3D spaces within urban plots. These ontologies integrate diverse regulatory data into a structured Knowledge Graph (KG), connecting regulations to 3D urban models. This approach bridges document-based urban policies and advanced urban analytics, offering an automated methodology to generate 3D master plans. In doing so, it provides valuable information on the cumulative impacts of regulations on the future urban form of the city.

Submission Type. Model, dataset, analysis

BoK Concepts. [DM] Data Modeling, Storage and Exploitation

Keywords. spatial policy model, urban planning regulations, applied ontology

1 Introduction

The city master plan reflects one of the city's modalities, translating its long-term strategy for future urban development into actionable spatial guidelines and rules (Grisiute et al., 2023). In Singapore, this strategy is structured through interconnected guidelines and rules that govern various spatial characteristics, including the allowable Gross Floor Area (GFA) limits for specific uses of land on a plot (Urban Redevelopment Authority, 2019a). The allowable GFA is a common parameter in urban models and simulations that inform development strategies, including planning guidelines (Indrajit et al., 2020).

However, the long-term urban development strategy of the city embedded in urban regulatory data is rarely quantitatively evaluated once established. This is due to data fragmentation, siloed tools, and inconsistent formats, which hinder interoperability and integrated analyses at scale (Jehling and Hecht, 2022; Kandt and Batty, 2021). Unlike dynamic urban data sources (e.g., traffic data), regulations change infrequently, and are often treated as the final output of planning efforts, a set of static boundary conditions to ensure acceptable outcomes within those constraints. For example, regulatory constraints on allowable GFA, building height, and setbacks determine a solution space for future urban developments, but no method systematically evaluates the combined impact of planning regulations on allowed 3D spaces. However, rapid hypothesis testing over longer time frames (such as those governed by regulatory data) is vital to address modern urban challenges (Kandt and Batty, 2021).

As a result, there is a growing need for a comprehensive and automated approach to analyze the effects of urban planning regulations on the future urban form. This requires two key elements: 1) an interoperable system that integrates heterogeneous urban data from diverse sources - Semantic Web Technologies (SWT) offer promising applications in urban planning context (von Richthofen et al., 2022), and 2) innovative methods and metrics must be developed to quantify the effects of planning regulations (Grisiute et al., 2023).

This study aims to evaluate whether the permitted urban form in Singapore accommodates long-term urban development goals and to enable data-driven hypothesis testing for planning strategies. Building on the parametric spatial policy model introduced by Grisiute et al. (2023) to generate allowable GFAs in Singapore, we further formalize this approach by developing two new ontologies: **OntoPlanningRegulations**, capturing Singapore's urban planning rules, and **OntoBuildableSpace**, defining measurable 3D space characteristics. This work builds on existing related ontologies such as OntoZoning (Silvennoinen et al., 2023),

Table 1. Comparison of Features and Regulations addressed in this study. Note that these represent a subset of the broader set of planning regulations in Singapore.

Feature / Regulations	MP	SBP	DCP	UDG	ConA	CenA	LHA	HCP	PB	Mon
Spatial resolution										
Plot part (XXS)					✓					✓
Building (XS)		✓			✓					✓
Plot (S)	✓									
Street block (M)		✓			✓					
District (L)			✓							
City region (XL)					✓			✓		
Available formats										
GIS layer	✓	✓	✓		✓	✓	✓	✓		✓
PDF document	✓	✓	✓	✓						
Online text			✓		✓					
3D diagrams			✓		✓					
JPEG image									✓	
Regulated LoD1 features										
Partywall		✓		✓	✓		✓			
Absolute Height	✓		✓	✓			✓			
Number of Storeys	✓	✓	✓	✓	✓		✓			
Setback	✓		✓	✓						
Road buffer			✓		✓					
Site coverage	✓		✓	✓						
Gross Plot Ratio	✓		✓	✓						
Building edge			✓		✓					
Land Use	✓		✓			✓				
Gross Floor Area			✓							

MP - Master Plan (plot data), SBP - Street Block Plans, DCP - Development Control Plans, UDG - Urban Design Guidelines, ConA - Conservation Areas, CenA - Central Area, LHA - Landed Housing Areas, HCP - Height Control Plan, PB - Planning Boundaries, and Mon - Monuments.

which integrates SWT with regulatory land use and zoning data, and OntoCityGML (Chadzynski et al., 2021), which supports semantic 3D city models for advanced urban analytics. Together, these ontologies support parametric policy analysis by connecting planning regulations and 3D urban models.

Formalizing planning regulations supports advanced analysis and inference of contradictions, overlaps, and usage patterns. Integrated into our proposed workflow, these regulations produce a geospatial artifact that opens up new possibilities for urban analysis. This approach allows for the extraction of quantifiable urban metrics, such as permissible GFAs, and provides a framework to evaluate the regulatory impacts on a city's future urban development. Together, these advances inform us about the structure, function, and long-term consequences of urban regulations.

2 Background

This section examines efforts to measure the impact of urban planning regulations, focusing on Singapore. It emphasizes the importance of the allowable GFA metric in data-driven analyses and introduces relevant semantic tools to manage and represent regulatory data.

2.1 Assessing Urban Planning Regulations and Their Impacts

Urban form regulations shape future cities, encapsulating long-term objectives with lasting impacts. A classic example is New York City's 1916 zoning ordinance, which introduced height and setback rules that not only redefined the skyline but also influenced urban design for decades (Lehavi, 2018). Contemporary studies illustrate the diverse ways in which urban planning regulations are evaluated in various contexts: defining mixed-use typologies (Shi et al., 2022), assessing resilience to sea level rise (Phua et al., 2024), analyzing impacts of urban form on CO_2 emissions (Bliznina, 2023), estimating densification potential (Walczak, 2021), examining how neighboring countries' regulations affect variations in regional built form (Jehling and Hecht, 2022), and assessing sustainability across cities (Cortinovis et al., 2019).

Although the mentioned studies assess the effects of urban planning regulations using urban metrics such as allowable GFAs in specific contexts, the broader concept of "plannedness", the degree to which urban spaces are structured through regulations, remains largely qualitative. Debray et al. (2023) introduced the concept of the "Intensity of Plannedness" (IoP), characterizing urban spaces on a spectrum from self-organizing systems to highly top-down planned environments. This concept aligns with

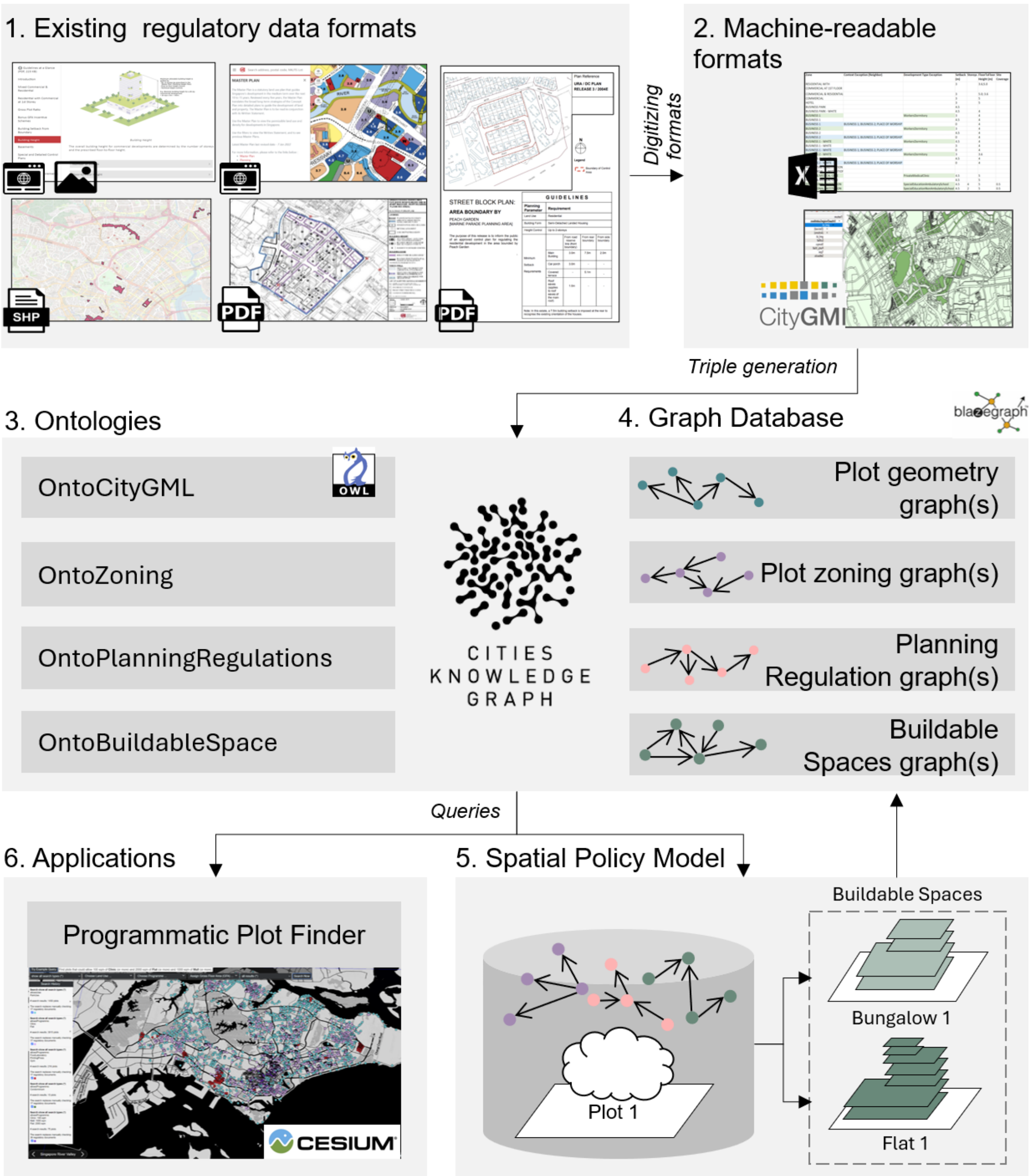


Figure 1. The workflow diagram described in the Methodology section. The workflow involves: (1) digitizing regulatory data into machine-readable formats (top), as described by Grisiute et al. (2023); (2) developing and integrating new ontologies to instantiate Singapore's regulatory data into the Cities Knowledge Graph (middle); and (3) enhancing the spatial policy model by Grisiute et al. (2023) to generate allowable GFAs across Singapore and demonstrate dataset application in planning tasks (bottom).

Lefebvre's notion of *space dominance*, which emphasizes how collective planning measures such as urban ordinances, codes, and norms transform space into a controlled and regulated construct (Lefebvre, 1992). However, more planning regulations do not necessarily indicate restrictiveness. For example, Singapore's bonus incentive schemes that allow an additional 10% GFA aim to enhance development flexibility rather than impose limitations. Therefore, the IoP should be seen as a measure of planning effort rather than an indicator of restrictiveness. This concept is particularly relevant in cities like Singapore, where top-down planning practices dominate, and understanding the cumulative impact of regulations is critical to various aspects of urban management, such as efficient resource allocation or government's provision of equitable urban environments.

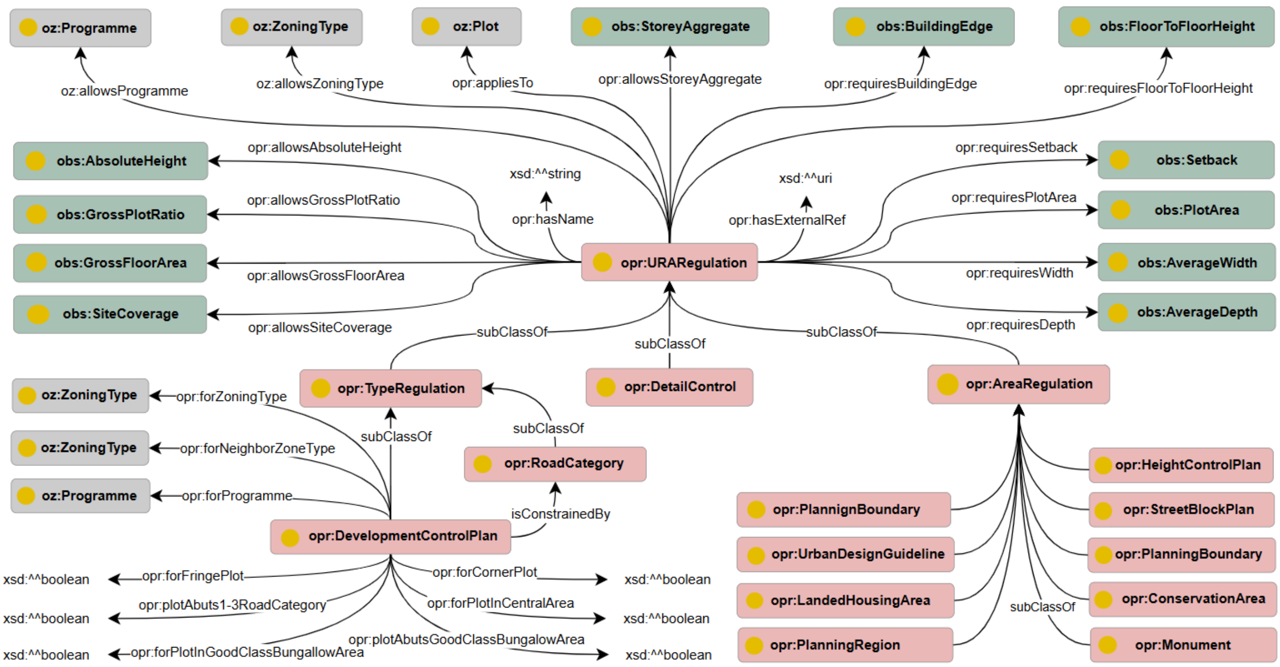


Figure 2. Concept map of the OntoPlanningRegulations ontology (opr), illustrating key classes, and integration with external ontologies such as OntoBuildableSpace (obs) and OntoZoning (oz). Detailed ontology classes, objects, and data properties available for download as an OWL file following the steps described in Section 7.

2.2 Planning Regulations and Data Integration Challenges in Singapore

In Singapore, as in many other cities, the intended urban form is shaped by interconnected planning documents, such as the Concept Plan, Master Plan, Development Plans, and Street Block Plans (Urban Redevelopment Authority, 2019b). Table 1 lists planning regulations used in this study, structured by their original spatial resolution, data formats, and built-form features that they regulate at Level of Detail (LoD) 1.

The regulations span multiple spatial scales, from national-level frameworks to street block-level details. When overlapped in space, the boundaries of planning regulations create unique planning conditions that require planners to synthesize regulatory information of different granularities. For example, a Planning Boundary (a district-sized spatial unit of governance) can simultaneously contain hundreds of plots featuring various types of zoning that each allow a multitude of land uses, as well as contain multiple Street Block Plans (a regulation governing plots or plot parts along designated streets), with the final allowable land use density depending on interactions between overlapping regulations (if any). We use LoD as a meta-structure for regulation modeling to support compatibility with international standards for city data exchange, such as CityGML[1]. Moreover, LoD1 represents the typical built-form resolution required for many urban models and simulations.

[1] https://www.ogc.org/publications/standard/citygml/

A significant challenge during data integration is the diverse and inconsistent data formats across regulations. This hinders digitization and integrated analysis, thereby limiting their utility for data-driven policy decisions. For example, the Master Plan is available as GIS layers and a written statement, Development Control Plans as text with interpretable diagrams, Urban Design Guidelines as PDF maps with online text, and Street Block Plans range from geo-referenced PDFs to low-quality JPEGs of hand-drawn maps. This heterogeneity complicates efforts to harmonize regulatory data and hinders the ability to conduct comprehensive analyses at scale, a challenge likely shared by cities globally due to diverse regulatory frameworks and standards. The digitized versions of these regulation formats, as described by Grisiute et al. (2023), form the basis of this study.

Finally, the table shows how the included regulations in Singapore control critical aspects such as zoning, land use, building height, setbacks, and densities. It highlights the unique parameters that can be adjusted in planning regulations to modify the urban form, which we also model in our workflow.

2.3 The Role of Allowable GFA in Urban Planning Decisions

Gross Floor Area (GFA) is a common metric that underpins regulatory data analyses and urban simulations, linking planning regulations and urban models. By quantifying the total envisioned space for a particular purpose, GFA informs critical decisions on resource allocation, including mobility, energy infrastructure, and building stock (Bliznina, 2023; Shi et al., 2021; Kang et al., 2024; Walczak, 2021). Its widespread utility in urban planning and decision-making processes is highlighted by the ability to distinguish between the GFA of actual buildings and the allowable or permissible GFA that could potentially be built on a plot (Grisiute et al., 2023).

In Singapore, GFA is defined as "the total area of covered floor space measured between the centerline of party walls, including the thickness of external walls but excluding voids" (Urban Redevelopment Authority, 2019a). Unlike related measures such as the Gross Plot Ratio (GPR) or the Floor Area Ratio (FAR), which focus on the relationship between the plot size and the building area and emphasize the overall density of the development, GFA provides a greater programmatic specificity. Specifically, it means that interactions between regulations can result in multiple allowable GFAs for different land uses or specific programs on the same plot. In addition, GFA operates in conjunction with controls on setbacks, party walls, and building heights, collectively shaping the permitted built form. Therefore, this study focuses on allowable GFA as a more granular and detailed regulatory unit.

2.4 Leveraging Semantic Web Technologies for Urban Regulation Modeling

Semantic Web Technologies (SWTs) provide a domain-agnostic framework for structuring information, enabling efficient knowledge representation and processing. Central to SWTs are ontologies (Mizen et al., 2005) and Knowledge Graphs (KGs) (Akroyd et al., 2021). Ontologies define key terms and relationships within a domain of interest and are used to organize information into semantic triples (subject, predicate, object). These triples form KGs, labeled (and often directed) graphs. When stored in accessible triple stores, KGs facilitate the discovery and interpretation of complex interactions embedded within the labeled graph data structure (Kuhn et al., 2014). In the context of urban planning regulations, these tools offer an interoperable framework that integrates diverse urban data sources, linking zoning regulations, land use policies, and built-form guidelines into a cohesive system.

Research at the intersection of urban regulations and SWTs has produced several ontologies for specific purposes. For example, Iwaniak et al. (2016) developed an ontology for semantic annotation of land use regulations in HTML documents. Zoning-focused ontologies, such as those suggested by Chichkova et al. (2020) and Silvennoinen et al. (2023), link parcels to land use and legal documents, but lack 3D spatial detail. The Urban Morphology Ontology (UMO) (Berta et al., 2016) models urban fabrics, including buildings, streets, and land uses, but does not specifically address the impact of regulations on these spatial features. Similarly, the Building Topology Ontology (BOT) (Rasmussen et al., 2020) links building components to zones, but lacks connections to planning regulations. Although Kaczmarek (2023) automates the extraction of urban metrics from regulatory data, a similar approach to our work, it does not support the generation of permissible spaces. These ontologies vary in their ability to describe allowed 3D spaces and link to regulatory data, revealing a gap in integrating urban regulations with detailed spatial models.

Efforts to automate building permit compliance checks using SWTs offer valuable insights for modeling urban form regulations. They demonstrate how principles such as formal rule definition, semantic integration, and automated reasoning can streamline complex city-wide regulations. However, these efforts focus primarily on systematic data management and process efficiency (Noardo et al., 2022), rather than scenario testing, urban analysis, and long-term impact assessments. For example, IfcOWL focuses on the management of 3D building data, with limited applicability to planning regulations (Pauwels and Terkaj, 2016), OntoBPR allows semi-automated compliance checks (Zentgraf et al., 2023), while the Ontology for Building Permit Authorities (OBPA) structures administrative workflows and stakeholder roles (Fauth and Seiß, 2023). Finally, the *ACCORD project* that aims to digitize building permit and compliance processes using BIM and other data sources while also handling country-specific regulatory variations (Hettiarachchi et al., 2025). Although focused on building permits, these methodologies can directly inform efforts to model urban form regulations by enabling compliance checks at the planning level and integrating building permit processes with broader urban development tasks.

3 Methods

The Methods section outlines the workflow for semantically modeling Singapore's urban planning regulations to enable automated urban analytics (see Figure 1). It details the development of two new ontologies, OntoPlanningRegulations and OntoBuildableSpace, which formalize regulatory concepts and their interactions to define buildable spaces, and explains how a dataset of particular metrics can be generated for the entire Singapore.

3.1 OntoPlanningRegulations Ontology

This section describes the development of an ontology to represent a subset of Singapore's built-form regulations, using data from the Urban Redevelopment Authority (URA) and Singapore's open data registry[2]. Building on previous work by Grisiute et al. (2023), who digitized urban form regulations into structured spreadsheets and GIS layers (see Sections 2.2 and 7), the ontology organizes its key terms and their interrelationships using SWTs. The initial development of the ontology includes the definition

[2]https://data.gov.sg/

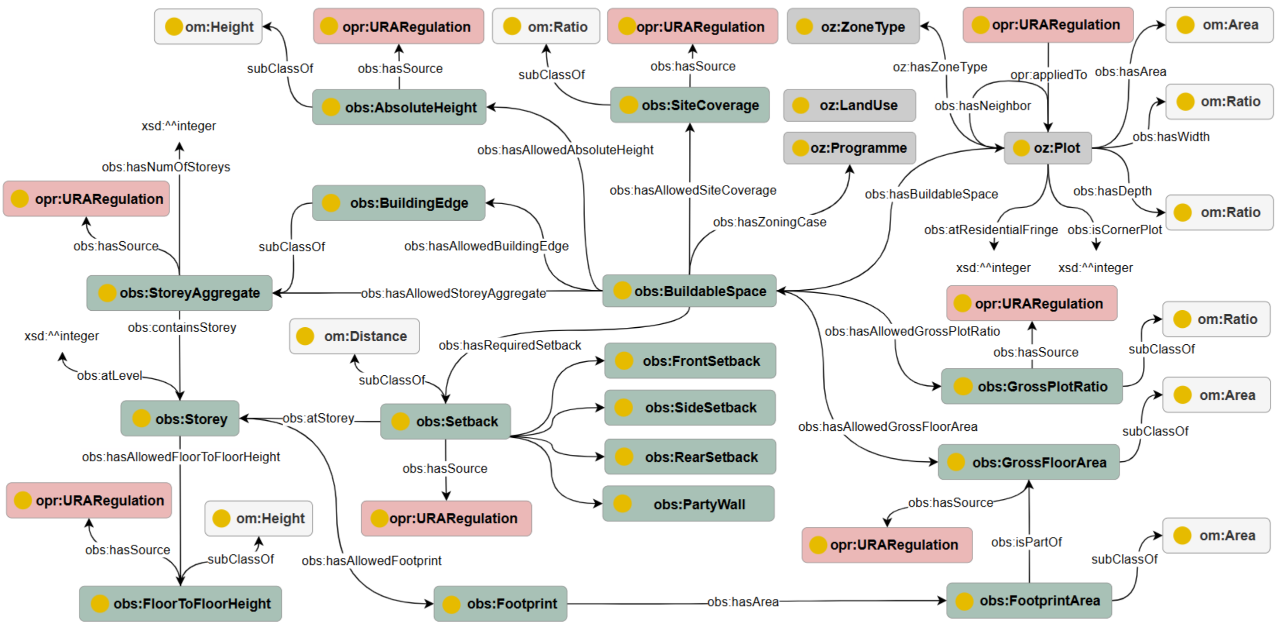


Figure 3. Concept map of the OntoBuildableSpace ontology (obs), illustrating its key terms, relationships, and integration with external ontologies such as OntoPlanningRegulations (opr), OntoZoning (oz), and Units of Measure Ontology (om). Detailed ontology classes, objects, and data properties are available for download as an OWL file following the steps described in Section 7.

of competency questions for a comprehensive representation of the domain, supported by a concept network map (see Figure 2). Key modeling decisions are summarized below, with detailed ontology classes, objects, and data properties available for download as an OWL file following the steps described in Section 7.

- **CQ1.** What types of planning regulations exist in Singapore?
- **CQ2.** What types of planning regulations apply to a plot?
- **CQ3.** Which regulations have the greatest impact based on the number of plots they affect?
- **CQ4.** What is the average allowable number of storeys specified across all URA regulations applicable to a specific plot?
- **CQ5.** Which plots are governed by an identical set of development control regulations?

Ontology Classes. We defined built-form regulations from the URA website as classes (e.g., *StreetBlockPlan*, *UrbanDesignGuideline*, *DevelopmentControlPlan*, *HeightControlPlan*) under a parent *URARegulation* class. A *RoadCategory* class was introduced to address regulatory exceptions related to different types of roads. A *DetailControl* was introduced to capture rules requiring human assessment, often labeled "Subject to Detail Control" in URA regulations. Based on a distinction made by Grisiute et al. (2023), we defined two more abstract regulatory classes: *TypeRegulation* which applies to plots based on their type (e.g., zoning type) and *AreaRegulation* which is characterized by a geospatial boundary it governs. It should be noted that Singapore's Master Plan regulations were formalized separately in the OntoZoning ontology (Silvennoinen et al., 2023).

Object Properties. Relationships between regulations and urban terms were modeled in terms of allowances (e.g., *allowsGrossFloorArea*) and requirements (e.g., *requiresSetback*) complying with the existing regulatory language. The *appliesTo* property connects regulations to *oz:Plot*, as defined in **OntoZoning**. Additional concepts of OntoZoning were incorporated, including *oz:ZoningType*, which we used to associate development control plans with the zoning types they govern (e.g., *oz:Commercial*, *oz:Hotel*, *oz:EducationalInstitution*). To support more specific regulatory exceptions, we used *oz:Program* that captures more detailed land uses (e.g., *oz:Bar*, *oz:Clinic*, *oz:Nightclub*) nested within broader OntoZoning categories such as *oz: CommercialOrHotelUse*. Finally, *hasExternalRef* connects regulations to online resources for additional information and validation.

Data Properties. We pay special attention to *DevelopmentControlPlan* regulations due to many exceptions linked to specific conditions. We formalized such conditions as Boolean properties. For example, *forFringePlot* and *forCornerPlot* indicate regulation applicability to residential fringe or corner plots, while *isConstrainedBy* links regulations to road categories to define applicable road buffers. Although alternative modeling approaches, such as the use of SHACL[3] rules, could be explored, we adopted a pragmatic approach given the already high complexity of the regulatory data.

[3] https://www.w3.org/TR/shacl/

3.2 OntoBuildableSpace Ontology

This section describes the development of an ontology to represent buildable spaces as determined by planning regulations. In this ontology, we define the term *buildable space* as a 3D volume allowed by the cumulative effects of planning regulations. This concept introduces a type of modal space that has not been explicitly defined in existing literature. For example, previous reviews on the classification of space within spatial sciences, such as Zlatanova et al. (2020), provide a comprehensive list of spatial types but do not consider a buildable space influenced by planning regulations. Since regulations consist of various exceptions related to local conditions (e.g., neighboring road types) or zoning constraints, they can result in unique sets of planning regulations and multiple buildable spaces. For example, plots with a *oz:Residential* zoning type would have an instance of a *BuildableSpace* for every residential type (e.g. *oz:Condominium*, *oz:Flat*, or *oz:Terrace*) possible on that plot, as planning regulations for each type of residential development may vary.

We developed the ontology using the same methodology as before, using competency questions and a concept network map (see Figure 3). Key modeling decisions are summarized below, with detailed ontology classes, objects, and data properties available for download as an OWL file following the steps described in Section 7.

- **CQ6.** What is the setback at the first storey of a specific allowable Buildable Space?
- **CQ7.** Which plots have buildable spaces that require a PartyWall?
- **CQ8.** Which URA regulation is linked to the most instances of Buildable Space?
- **CQ9.** Which plot has the largest Buildable Space (by GFA) for a Student Hostel programme?
- **CQ10.** How do the GPR values in Singapore differ from the calculated allowable GFA for residential plots?

Ontology Classes. We introduced the *BuildableSpace* term to represent 3D spaces defined by regulations related to built-form features (e.g., *AbsoluteHeight*, *FloorToFloorHeight*, *Setback*). We modeled the terms of *Footprint* and *FootprintArea* to represent the 2D outcomes of the planning regulations. To model height regulations commonly expressed in terms of storeys, we introduced the *StoreyAggregate* term. The *Storey* class was introduced to capture regulations governing setbacks on specific floors. For example, podium-based building typologies emerge from different setback rules applied at certain levels, shaping a series of footprints. Integrating floor-specific footprints with height regulations extends buildable space representation to 3D. This approach supports detailed simulations for wind comfort, heat island effects, daylight access, and noise dispersion, and enables the extraction of complex urban metrics such as the sky view factor.

Object Properties. The *hasBuildableSpace* property links *oz:Plot* (as defined in **OntoZoning**) to one or more buildable spaces, while the *forZoningCase* property connects buildable spaces to specific OntoZoning *oz:Programme* classes (e.g., *oz:Bungalow*, *oz:Flat*, *oz:Condominium*). The *hasSource* property traces individual built-form feature (e.g., setback, height, GPR) values back to their originating regulation. The relationships between plots, buildable spaces, and built-form features were modeled similarly to those in the OntoPlanningRegulations ontology, in terms of allowances (e.g., *hasAllowedGrossFloorArea*) and requirements (e.g., *hasRequiredSetback*).

Data Properties. To address regulations for specific storeys, we introduced the *atLevel* data property, specifying the governed floor level in line with regulatory terminology. Although the total number of storeys can be inferred from *Storey* instances, the *numberOfStoreys* property was kept for simplicity. Since many regulations depend on plot characteristics, we formalized attributes such as *isCornerPlot* and *isAtResidentialFringe* as Boolean properties to indicate relative plot positions, although they could be modeled as different plot subclasses. We introduced the *hasRoadType* property for plots zoned as *oz:Road* to capture road category classifications, necessary to express regulatory exceptions related to road types.

3.3 From Concept Maps to OWL Implementation

This ontology integrates established standards instead of modeling units of measure or geometric properties. The Units of Measure Ontology (OM) (Rijgersberg et al., 2013) is used to represent quantities described in planning regulations (e.g., height, plot width, road buffer), while the GeoSPARQL ontology (Consortium, 2024) is used to model spatial features (e.g., footprints). As mentioned in the previous sections, we reused the existing OntoZoning ontology classes, as it already represents Singapore's Master Plan. We demonstrate how OntoPlanningRegulations, OntoBuildableSpace, and OntoZoning function as complementary ontologies, each with a distinct scope, while enhancing expressivity through integration.

The concept maps for the OntoPlanningRegulations and OntoBuildableSpace ontologies formed the basis for their implementation in the Web Ontology Language (OWL)[4]. The resulting OWL files, developed using Protége[5], are available for download following the steps described in Section 7. Consistency was ensured using Protege's HermiT reasoner, and accuracy was validated with the Debugger plugin.

[4]https://www.w3.org/TR/owl-ref/
[5]https://protege.stanford.edu/

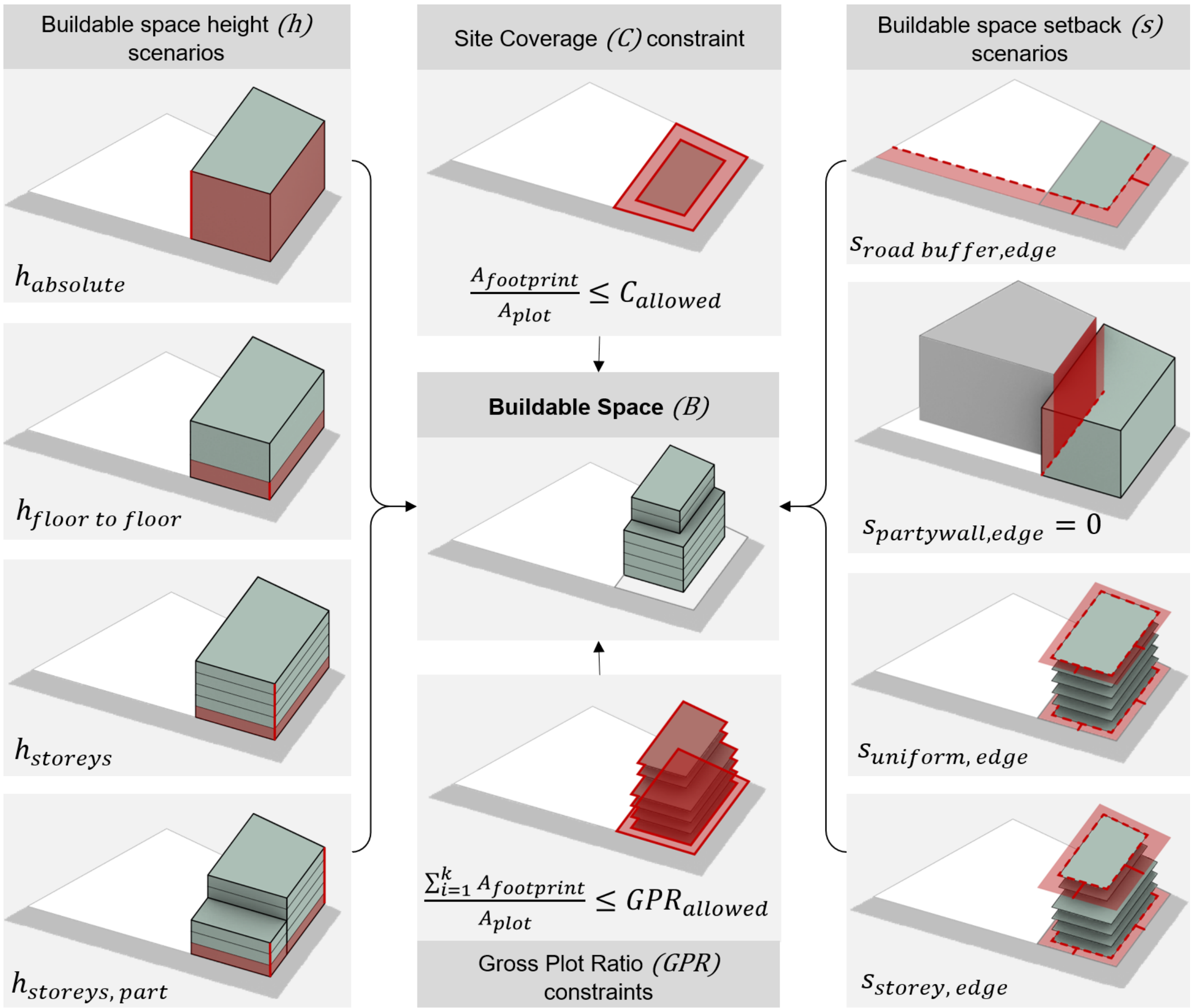


Figure 4. Visualization of key regulatory scenarios that shape buildable spaces in the discussed GFA dataset estimation workflow.

3.4 Generating a KG for Singapore's Planning Regulations

We developed an automated workflow that converts unstructured regulatory documents into semantic triples in the RDFS[6] notation, forming a KG, stored in a local triple store. This workflow relies on intermediate digitized versions of Singapore's planning regulations, as detailed in Grisiute et al. (2023). In brief, area-based regulation geometries were downloaded directly from the URA data registry and transformed into semantic triples using the OntoCityGML ontology and the methods described by Chadzynski et al. (2021). More complex regulations, such as Street Block Plans, Urban Design Guidelines, and Development Control Plans, required manual digitization and interpretation due to their multimodal nature (e.g. GIS layers, online text, and visual diagrams). As plot data, we used Singapore's Master Plan 2019 (Urban Redevelopment Authority, 2019b), which includes zoning types and allowable GPR values for individual plots. The masterplan was formalized as RDF data using the OntoCityGML ontology and the methods described by Chadzynski et al. (2021).

To link planning regulations and plots in the KG, we enriched the plot data by adding key attributes necessary for assessing the applicability of the regulations. Specifically, using heuristic algorithms, we derived key plot properties, such as whether a plot is a corner plot, located on a residential fringe, or its average width and depth. These attributes, encoded as semantic triples in RDFS, were instantiated in the triple store alongside the regulatory data. These heuristics should be regarded as placeholders for more accurate definitions by domain experts. For example, to estimate the average plot width, we measured the width at consistent intervals along the longer edge of its minimum bounding rectangle and calculated the average. However, domain experts might use alternative methods to determine the width of the plot.

We also precomputed the *appliesTo* relationships between planning regulations and plots to improve efficiency, as these relationships are unlikely to change and computationally expensive to generate during runtime. For area-based regulations, spatial overlaps were evaluated,

[6] https://www.w3.org/TR/rdf12-schema/

Table 2. Singapore's regulatory KG overview - linked number of plots for each planning regulation in the generated KG. *n - number of planning regulation instances.

Planning Reg.	Reg. count	Linked MP Plots	Area
			km^2
MP	113,664	113,664	782.228
SBP	92	3,412	1.074
DCP	113	101,646	328.990
UDG	378	818	2.065
ConA	248	7,402	5.018
CenA	1	7,710	18.986
LHA	215	58,132	26.425
HCP	931	9,994	18.662
PB	55	113,663	782.220
Mon	123	79	2.130

MP - Master Plan (plot data), SBP - Street Block Plans, DCP - Development Control Plans, UDG - Urban Design Guidelines, ConA - Conservation Areas, CenA - Central Area, LHA - Landed Housing Areas, Mon - Monument, HCP - Height Control Plan, PB - Planning Boundaries.

while type-based regulations were evaluated using zoning-related conditions, including location (e.g., landed housing areas, the central area), geometric attributes (e.g., size, width, or depth), and contextual factors (e.g., proximity to specific plot types). These precomputed relationships were encoded in RDFS and instantiated in the triple store.

3.5 Expanding and Automating Allowable GFA Calculations for Whole Singapore

This section details our workflow for generating a semantic dataset of allowable GFA using regulatory ontologies. Based on the approach described by Grisiute et al. (2023), which introduced a method for GFA calculation, our work expands its scope and functionality in two ways. First, we scaled the implementation to cover all of Singapore, instead of a single city area. Second, our model interacts directly with the KG rather than relying on individually digitized regulatory files, simplifying data integration.

In summary, the automated workflow consists of four steps. First, the plot and regulatory data were retrieved from the KG and pre-processed. Next, for each plot, we determined the allowed number of storeys and setbacks for every unique set of applicable regulations, including program-specific regulatory exceptions. The footprints for each permitted storey, determined after applying setback requirements, are further adjusted for site coverage and GPR constraints. Finally, the allowable GFAs are calculated by aggregating the refined footprints for each permissible programme. Figure 4 illustrates the key urban characteristics, governed by the planning regulations used in the allowable calculation of the GFA. Although this section offers a concise overview, for a more detailed explanation of the computational model and its implementation, see Grisiute et al. (2023) and Section 7.

4 Results

This section demonstrates the utility of the proposed workflow for semantically modeling and analyzing Singapore's urban planning regulations. We present key findings in three areas: (1) the ontology-based regulatory KG, (2) the coverage and accuracy of the generated allowable GFA dataset, and (3) illustrative example tool showcasing the workflow's potential for urban analysis at scale.

4.1 Overview of Singapore's Regulatory Knowledge Graph

This subsection provides an overview of the regulatory KG developed for Singapore. Table 2 highlights the extensive coverage of the KG, linking more than 113,000 plots to more than 2,000 regulatory instances. Among these, Development Control Plans have the broadest impact, affecting the largest number of plots and underscoring their critical role in shaping Singapore's urban landscape. In contrast, Street Block Plans apply to smaller areas, reflecting their more targeted regulatory scope.

We present two example queries that demonstrate how KG can be explored to answer different questions about urban planning regulations in Singapore. While this dataset enables numerous other analyses not discussed here, we leave further explorations to the reader.

Query 1. *How many regulations are linked to each plot?*

To quantify *Intensity of Plannedness* introduced in Section 2, this query examines the number of regulations associated with individual plots. Figure 5 highlights the results, showcasing areas with greater regulatory complexity, which can inform policy adjustments to balance regulatory effort between districts, for example. These areas correspond primarily to residential areas, reflecting Singapore's distinctive urban challenge: achieving high-density housing within a geographically constrained area. Interestingly, the Orchard Road district, a renowned shopping area, exhibits a significantly higher *Intensity of Plannedness*. This can be attributed to its higher density and the diverse mix of landuses. Therefore, manually assessing regulations for mixed-use developments can be labor intensive. As densification and mixed use strategies, such as the 15-minute city concept (Moreno et al., 2021), gain more attention, the need for automated and digitized planning processes becomes increasingly relevant.

Query 2. *Which regulations have the greatest impact based on the number of plots they affect?*

An analysis of individual regulations reveals their varying levels of impact. Table 3 highlights the most influential regulations, such as the Development Control Plan for the *oz:Flat* program, which is linked to more than 84,000 plots. This outcome is not surprising, given the number of zoning types that permit this program. Instances of the same regulation for a given program may appear multiple times in the table, as they might address different ex-

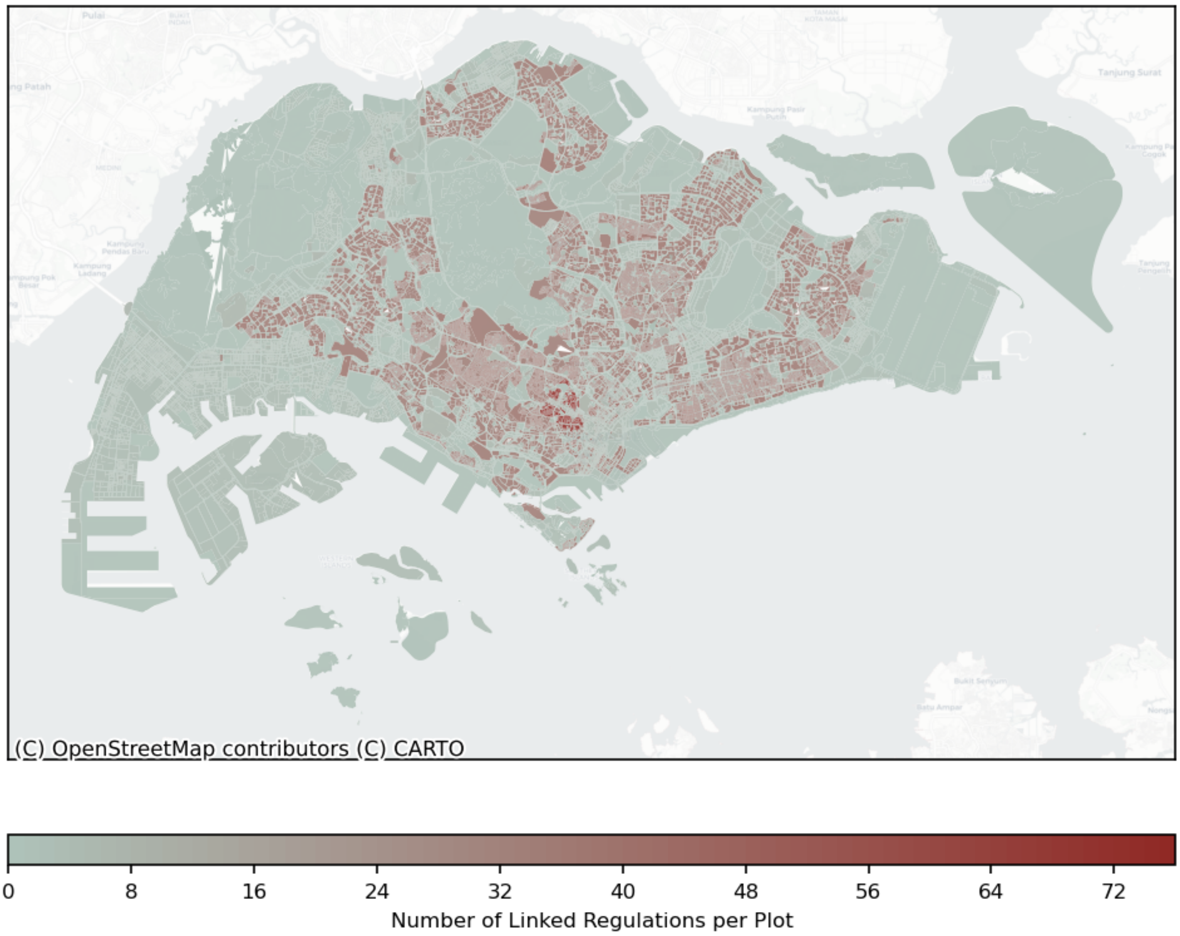


Figure 5. Visualization of the *Intensity of Plannedness* (Debray et al., 2023), showing the number of regulations linked to individual plots and hence highlighting areas with higher regulatory complexity. These areas correspond primarily to residential areas across the city state.

ceptions, such as plot's location in a good-class bungalow area. Our query identified that five regulation instances were not linked to any plots, which could be due to modeling errors, improperly established spatial relationships in the workflow, or the regulations being inapplicable at this particular time.

4.2 Allowable Gross Floor Area dataset

This study provides an overview of the generated allowable GFA dataset and its utility as a modal urban indicator for large-scale regulatory analysis. By integrating ontologies and urban indicator analytics, we effectively estimated the buildable space capacity across Singapore plots. Table 4 summarizes the dataset, detailing the allowable GFA estimates by zoning type and their coverage in relation to available GPR values.

We estimated the GFA values for 73.70% of the total plots ($n = 83,770$), after excluding certain categories where the GFA estimate was not meaningful or applicable, including roads, reserve sites, open spaces, specialized zones (e.g., ports, airports), or plots with conservation or detailed control status ($n = 22,627$). For the plots included in the GFA calculation, the model achieved high coverage, with 7,267 plots (6.4%) lacking GFA estimates due to the complexity of the zoning or the irregularities of the data. Furthermore, $n = 77,822$ plots (92.9% of all plots for which GFAs were estimated) had multiple allowable GFA values. Specifically, almost every plot in the allowable GFAs dataset has more than one buildable space, reflecting a higher granularity of the dataset compared to existing plot data with available GPR values. The dataset exhibits strong coverage across multiple zoning types, including several business zones ($77.45 - 100\%$), residential (89.3%) and educational institution (91.26%) zones. The lower coverage in commercial zones is likely due to plots located in conservation areas, such as *Chinatown* neighborhood.

We present two example queries that illustrate how the generated dataset and its additional granularity support regulatory analysis, urban policy design, and the assessment of cumulative regulatory impacts at scale. Beyond these specific applications, the dataset provides numerous opportunities for further exploration, which we encourage the readers to investigate.

Table 3. Planning regulations with most significant impact based on the number of plots they affect. The identical rows occurring in the table indicate that there are several distinct instances of regulations associated with a particular programme. These instances differ based on specific boolean properties of the regulation, such as whether they apply to plots that abut Good Class Bungalow areas or to plots situated within landed housing areas.

Reg. Type	Programme	Zone Types	MP Plots	Area km^2
DCP	Flat	Business1 White, Business2 White, Commercial And Residential, Residential, Residential Or Institution, Residential With Commercial At 1st Storey, White, Business Park White	84,171	141.906
DCP	Bungalow	Residential, Residential With Commercial At 1st Storey	84,171	132.225
DCP	Good Class Bungalow	Residential, Residential With Commercial At 1st Storey	82,053	132.225
DCP	Semi-Detached House	Residential, Residential With Commercial At 1st Storey	82,053	132.225
DCP	Terrace Type1	Residential, Residential With Commercial At 1st Storey	82,053	132.225
DCP	Terrace Type2	Residential, Residential With Commercial At 1st Storey	82,053	132.225
DCP	Condominium	Business1 White, Business2 White, Residential, Residential Or Institution, White, Business Park White	80,431	134.574
DCP	Bungalow	Residential, Residential With Commercial At 1st Storey	55,823	18.967
DCP	Semi-Detached House	Residential, Residential With Commercial At 1st Storey	55,823	18.967
DCP	Terrace Type1	Residential, Residential With Commercial At 1st Storey	15,599	65.267

DCP - Development Control Plans, MP - Masterplan (plot data)

Query 3. *What is the difference between allowable GFAs and GFAs based only on GPR?*

This query compares GFAs derived from GPR values with those generated by our workflow. Our model, which incorporates additional regulatory constraints, is inherently more conservative in its estimates of allowed density, exceeding GPR-based GFA values in only approximately 1,800 plots (1.58% of the total). This highlights the limitations of GPR-only datasets, which require manually cross-referencing other planning regulations for accuracy, emphasizing the efficiency of our workflow in automating time-intensive tasks.

Query 4. *What are the implications of a Height Control Plan change that increases the allowable building heights by one storey?*

To assess the impact of regulatory changes, we simulated an increase in allowable building height by one storey across all Height Control Plan regulations and reran our workflow. The analysis showed that of almost 10,000 affected plots, only 664 plots experienced an increase in GFA. On average, the increase in GFA per affected plot was 919.84 m^2, while 75% of the plots had an allowable increase in GFA less than 333.53 m^2. The total increase in GFA in Singapore was 610,774.89 m^2. This analysis demonstrates the utility of our workflow in efficiently quantifying the impacts of regulatory adjustments.

4.3 Programmatic Plot Finder

To demonstrate the practical applicability of this work, we developed the Programmatic Plot Finder (PPF) web application that automates site search based on Singapore's planning regulations as modeled in our ontologies. Specifically, OntoZoning, OntoBuildableSpace, and OntoPlanningRegulations and the generated allowable GFA dataset serve as the basis for this tool. This web application enables users to search for plots that meet specific criteria, such as combinations of land uses or programs (e.g., clinics, flats, and malls) and minimum allowable GFA requirements for each. Using regulatory data from our KG, the tool automates a previously manual process that potentially required more than 1.13 million verifications across 10 types of regulatory documents (as described in Table 3). The associated number of manual verifications depends on the query's specificity and the regulatory KG's completeness. The PPF showcases our KG's utility and exemplifies how automated, searchable representations of land-use and built-form regulations can transform urban planning tasks like site searches. Finally, our PPF is the first demonstrator of the Cities Knowledge Graph project and just one example of applications that could be developed on the basis of this KG. The PPF web application can be experienced here: https://ckg.sec.sg/3dwebclient/index.html?city=singaporeEPSG4326.

5 Discussion

This study presents an SWT-driven workflow for urban planning in Singapore, which addresses built-form regulatory data fragmentation and enables advanced analytics of the envisioned urban form of the city, as shaped by its land use planning regulations. We developed two new ontologies, OntoPlanningRegulations and OntoBuildableSpace, to formalize planning rules and their impact on buildable spaces. These are integrated into a KG that combines regulatory and plot data, providing a unified data source for analyzing planning regulations.

Table 4. Descriptive statistics of the allowable GFA dataset compared to Singapore's Master Plan 2019. The "delta" column represents the difference between the available GFAs based on GPR values and the GFA estimated by our model. The "excluded" column indicates plots located in conservation areas or in zoning types that are omitted by our workflow.

Zone									**MP Plots**
	Plot Count	**with GPR**	**%**	**with GFA**	**%**	**excluded**	**delta**	**GFA >1**	**GFAs / Plot**
Agriculture**	241					241			
Beach Area*	37					37			
Business 1	1,510	1,507	99.8	1,473	97.55	1	-2.25 (↓)	1,476	2.00
Business 1 - White	45	38	84.44	43	95.56	0	+11.12 (↑)	43	4.00
Business 2	5,995	5,908	98.55	5,850	97.58	0	-0.97 (↓)	5,933	2.00
Business 2 - White	14	14	100	14	100	0		14	4.00
Business Park	204	160	78.43	158	77.45	1	-0.98 (↓)	198	2.00
Business Park - White	12	11	91.67	11	91.67	1		11	4.55
Cemetery*	18					18			
Civic & Community Institution***	638			498	78.06	126	78.06 (↑)	498	5.96
Commercial	6,005	2,155	35.89	868	14.45	4,770	-21.44 (↓)	1,153	2.00
Commercial & Residential	914	737	80.63	537	58.75	347	-21.88 (↓)	288	1.59
Commercial / Institution	533	533	100	0	0	533	-100 (↓)	0	
Educational Institution***	618			564	91.26	40	91.26 (↑)	567	5.00
Health & Medical Care	196	2	1.02	7	3.57	9	2.55 (↑)	182	3.00
Hotel	291	248	85.22	165	56.7	92	-28.52 (↓)	0	1.00
Open Space*	774					774			
Park*	1,450					1,450			
Place of Worship***	647			327	50.54	102	50.54 (↑)	0	1.00
Port / Airport**	49					49			
Rapid Transit**	68					68			
Reserve Site**	683					683			
Residential	79,227	18,987	23.97	70,750	89.3	2,681	65.33 (↑)	66,092	2.86
Residential / Institution	963	963	100	56	5.82	905	-94.18 (↓)	0	1.00
Residential with Commercial at 1st Storey	2,826	2,254	79.76	2,056	72.75	621	-7.01 (↓)	756	1.44
Road*	6,745					6,745			
Special Use**	62					62			
Sports & Recreation	245	0	0	2	0.82	17	0.82 (↑)	220	2.00
Transport Facilities	352	0	0	327	92.9	23	92.9 (↑)	327	2.00
Utility**	1,068					1,068			
Waterbody*	1,064					1,064			
White	170	124	72.94	64	37.65	99	-35.29 (↓)	64	4.38
Total	113,664	33,641	29.60	83,770	73.70	22,627	44.10 (↑)	77,822	2.73

*Zoning types that typically imply unbuilt space. **Zoning type that do not have openly public urban planning regulations. ***Zoning types that do not have directly available GPR values but which can be derived based on assessing Development Control Plans.

This workflow was used to generate a city-wide dataset of allowable GFAs, quantifying regulatory impacts on urban form. We integrated these datasets into a web-based tool, the Programmatic Plot Finder (PPF), which demonstrates how urban development professionals could interact with our regulatory data KG, and how it could streamline site search, an essential urban development task. The components of the workflow are visually summarized in Figure 1. By consolidating fragmented data and offering tools to evaluate planning outcomes, this approach enhances transparency and supports data-driven decision making for sustainable urban development.

Next, we discuss these contributions in detail. First, we enhanced planning regulations by making implicit knowledge explicit, improving their machine readability and interoperability. The regulation ontology and the generated KG serve as a centralized regulatory database, addressing data fragmentation and integrating diverse regulatory information into a unified workflow. Second, we digitized the regulations, enabling the generation of key

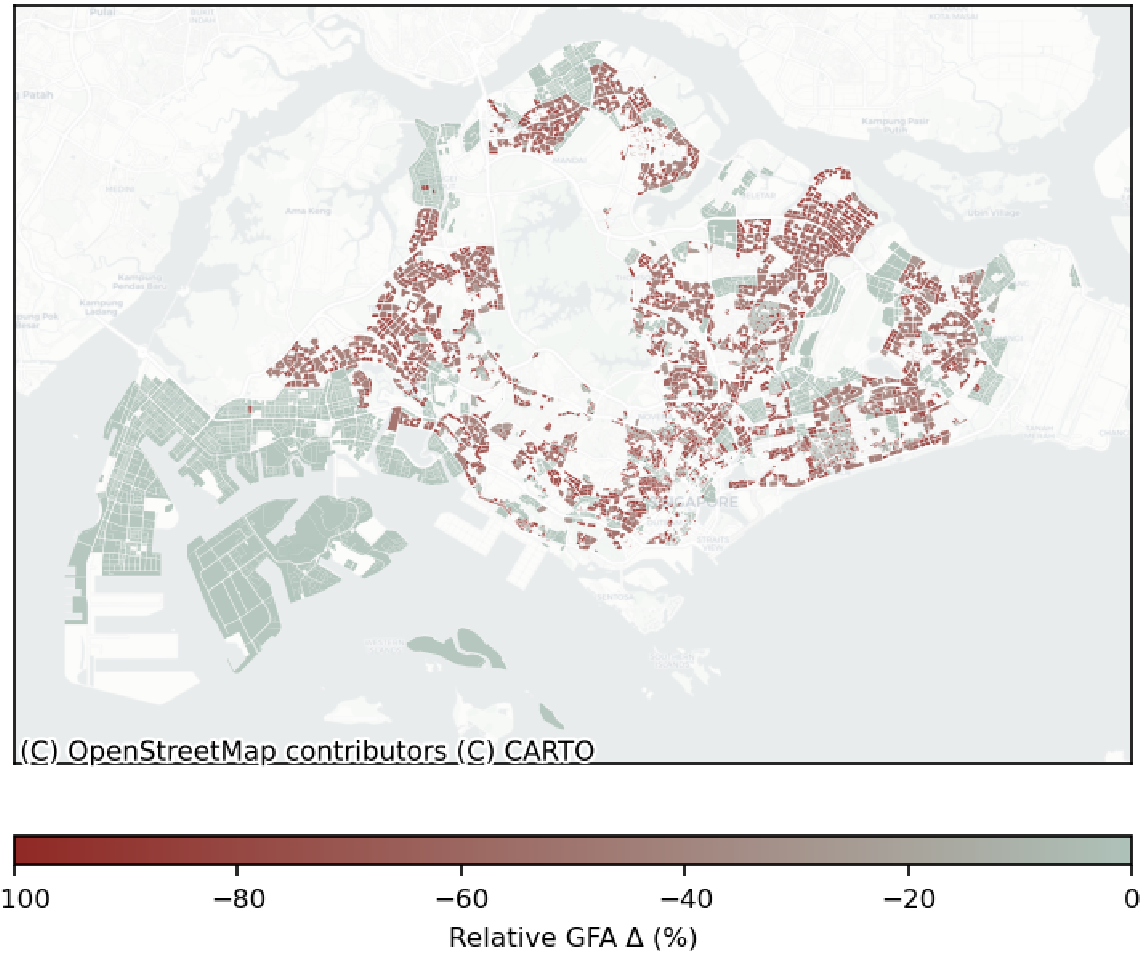
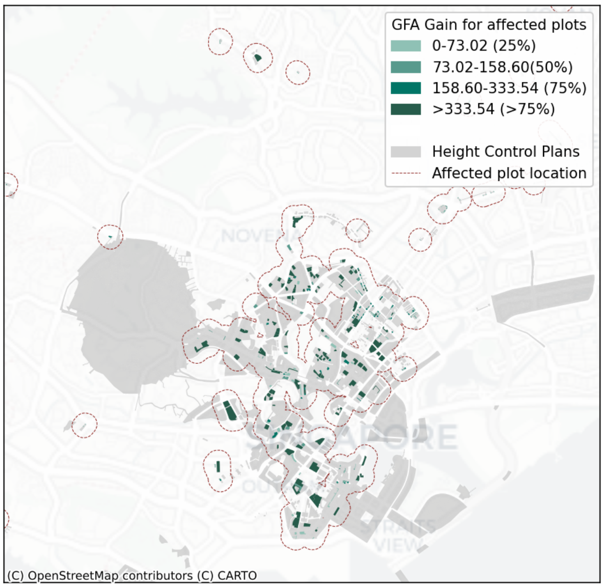


Figure 6. Comparison of allowable GFAs generated by the workflow with GFAs based solely on GPR values, highlighting the relative delta across plots. Negative values (red) indicate that allowable GFAs from our workflow are more conservative (lower) than GPR-based GFAs, and primarily correspond with residential developments across Singapore. The positive values (pale green) indicate that our GFA exceeds GPR-based GFA and primarily correspond to industrial areas.

urban metrics, such as allowable GFAs, with traceability to their originating regulations. This traceability is relevant for using the generated datasets in urban analytics or more sociopolitical evaluations, for example, assessing the efficiency of civic trust in city planning regulations, such as the distribution of design control ("plannedness") or potential blind spots in planning processes. Integrating these metrics into urban models allows scenario testing, bridges generative workflows with legal frameworks, and moves beyond simplified urban models, especially regarding land use (and program) granularity. Third, the KG's graph structure links regulations, plots, and buildable spaces, clarifying how specific rules shape urban form and reveal nuanced interactions that are at present synthesized manually by planners, but inaccessible afterward. Our approach leveraged SWTs to automate regulatory assessments, transforming manual verifications into a streamlined querying, as illustrated with the PPF tool. This enables comprehensive evaluations beyond individual plot-level assessments, a critical gap in current planning workflows.

Finally, our approach has broader implications beyond the evaluation of planning regulations in isolation. By formalizing planning rules and linking them to spatial data, we can integrate regulatory analysis with urban development processes, such as building permit compliance checks. Furthermore, structured representations of planning regulations can enrich the multiverse of urban digital twins with a regulatory city modality (Argota Sánchez-Vaquerizo, 2025). Although developed for Singapore, many insights from the CKG can be transferred. While regulations vary by country, the presented ontologies offer novel conceptualizations that can be adapted elsewhere. Specifically, our modeling of different types of planning regulations (based on area and type) and their means of application (as requirements and allowances) introduces new building blocks for formalizing urban regulatory systems. Furthermore, our approach supports universally relevant urban tasks, such as site search in the PPF demonstrator.



Overview metric	Value
Total GFA Gain (sqm)	610,774.89
Number of Affected Plots	664
Average GFA Gain per Plot (sqm)	919.84
Average Plot Size (sqm)	1599.6

Figure 7. A zoom-in visualization and an overview of plots impacted by a regulatory change in Height Control Plans allowing an additional storey, showing the spatial distribution and magnitude of GFA gains.

Our workflow has several limitations that highlight opportunities for future improvement. First, converting planning regulations into machine-readable formats requires substantial manual and interpretive efforts. This underscores the need for capacity-building initiatives to equip planners and policymakers with relevant SWT-related skills. Second, while multiple regulatory data streams have been modeled and integrated, additional validation with planning authorities is essential to refine the ontologies and validate our assumptions. Third, the incremental development of OntoPlanningRegulations, OntoBuildableSpace, and OntoZoning revealed limitations, such as missed opportunities to model properties (*isCornerPlot* or *atResidentialFringe*) as plot subclasses due to OntoZoning's initial focus on zoning types. These challenges highlight the need for iteration and refactoring as a critical step to improve the quality of ontologies. Finally, incorporating additional regulations, such as the maximum building depth, is necessary to further refine the generation of buildable spaces.

6 Conclusions and Future Outlooks

This study introduces a workflow to formalize and analyze urban planning regulations in Singapore. By developing two new ontologies, OntoPlanningRegulations and OntoBuildableSpace, we organize complex regulatory data into a KG. This approach enables the quantification and evaluation of regulatory impacts on urban form, providing a more precise interpretation of the city's envisioned built form as defined by its planning rules.

Although the workflow demonstrates potential, challenges remain in digitizing complex regulatory data, particularly the manual effort and interpretation required to standardize diverse formats. Future work should focus on the integration and refinement of the OntoZoning, OntoPlanningRegulations, and OntoBuildableSpace ontologies through a detailed validation by relevant planning authorities.

7 Data and Software Availability

Research data supporting this publication are available in zenodo via the following DOIs: ontologies in RDF notation (https://doi.org/10.5281/zenodo.14585554), input data (https://doi.org/10.5281/zenodo.14647555), generated data: (https://doi.org/10.5281/zenodo.14646814). The computational workflow supporting this publication is published on Github in the following repository: https://github.com/mie-lab/3d-landuse-planning. All data and code are licensed under the MIT License.

8 Funding information

This research was supported by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) program. Part of this research was conducted at the Chair of Geoinformation Engineering at the Swiss Federal Institute of Technology in Zurich (ETHZ). Part of this research was conducted at the Future Cities Lab Global at Singapore-ETH Centre. Future Cities Lab Global is supported and funded by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme and ETH Zurich (ETHZ), with additional contributions from the National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore and the Singapore University of Technology and Design (SUTD).

Declaration of Generative AI in writing

The authors declare that they have used Generative AI tools in the preparation of this manuscript to improve grammar, sentence structure, and LaTeX formatting. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

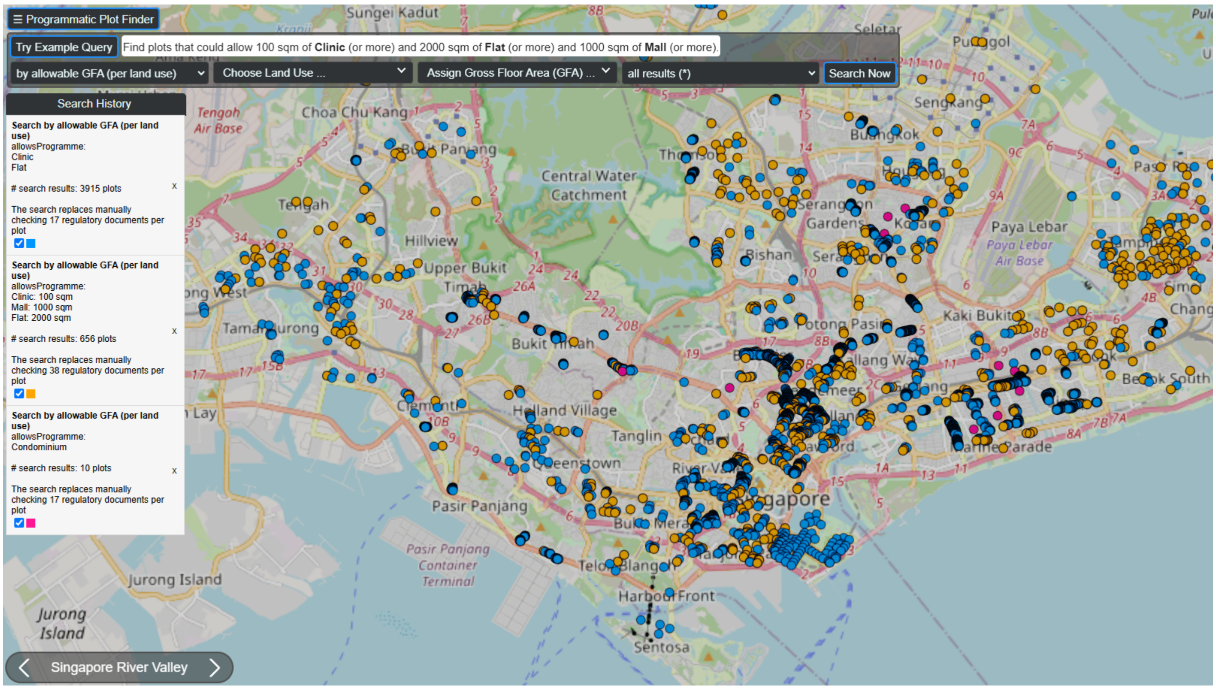


Figure 8. Interface of the Programmatic Plot Finder (PPF) web app, showcasing its functionality for automated site search and evaluation based on Singapore's URA regulations. Users can query plots by specific land use combinations, programs, and minimum allowable GFA requirements, leveraging data modeled in the Cities Knowledge Graph.

9 Acknowledgements

This work is part of the Cities Knowledge Graph (CKG) project, an Intra-CREATE collaborative project involving CARES (Cambridge Centre for Advanced Research and Education in Singapore), which is University of Cambridge's presence in Singapore, and the Singapore-ETH Centre, which was established collaboratively between ETH Zurich and the National Research Foundation Singapore. We acknowledge contributions of the CKG team, in particular Shiying Li, Arkadiusz Chadzynski, Heidi Silvennoinen, Chenyi Cai, and Markus Kraft. The authors express their gratitude to the officers of Singapore's Urban Redevelopment Authority and Smart Nation Singapore who provided valuable feedback.

Author contributions. **Ayda Grisiute**: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - Original Draft; **Martin Raubal**: Funding acquisition, Supervision, Writing - Review & Editing; **Pieter Herthogs**: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing - Review & Editing.

Competing interests. The authors declare that there are no competing interests.

References

Akroyd, J., Mosbach, S., Bhave, A., and Kraft, M.: Universal Digital Twin - A Dynamic Knowledge Graph, Data-Centric Engineering, 2, e14, https://doi.org/https://doi.org/10.1017/dce.2021.10, zSCC: 0000002 tex.ids= akroyd_2021_UniversalDigitalTwin publisher: Cambridge University Press, 2021.

Argota Sánchez-Vaquerizo, J.: Urban Digital Twins and metaverses towards city multiplicities: uniting or dividing urban experiences?, Ethics and Information Technology, 27, 4, https://doi.org/10.1007/s10676-024-09812-3, 2025.

Berta, M., Caneparo, L., Montuori, A., and Rolfo, D.: Semantic urban modelling: Knowledge representation of urban space, Environment and Planning B: Planning and Design, 43, 610–639, https://doi.org/10.1177/0265813515609820, 2016.

Bliznina, N.: A Narrative Literature Review: What Is the Ideal Density for Environmentally Sustainable Urban Growth?, Housing Policy Debate, 33, 1167–1186, https://doi.org/10.1080/10511482.2021.1950801, 2023.

Chadzynski, A., Krdzavac, N., Farazi, F., Lim, M. Q., Li, S., Grisiute, A., Herthogs, P., von Richthofen, A., Cairns, S., and Kraft, M.: Semantic 3D City Database - an enabler for a dynamic geospatial knowledge graph, Pre-print Technical Report 273, University of Cambridge, Cambridge, https://como.ceb.cam.ac.uk/preprints/273/, 2021.

Chichkova, N., Begler, A., and Vlasov, V.: Modeling city land use with an ontology, in: Proceedings of the 13th International Conference on Theory and Practice of Electronic Governance, ICEGOV 2020, pp. 851–854, Association for Computing Machinery, New York, NY, USA, https://doi.org/10/ghv8bb, 2020.

Consortium, O. G.: OGC GeoSPARQL - A Geographic Query Language for RDF Data, Tech. rep., Open Geospatial Consortium, http://www.opengis.net/doc/IS/geosparql/1.1, 2024.

Cortinovis, C., Haase, D., Zanon, B., and Geneletti, D.: Is urban spatial development on the right track? Comparing strategies and trends in the European Union, Landscape and Urban Planning, 181, 22–37, https://doi.org/10.1016/j.landurbplan.2018.09.007, 2019.

Debray, H., Kraff, N. J., Zhu, X. X., and Taubenböck, H.: Planned, unplanned, or in-between? A concept of the intensity of plannedness and its empirical relation to the built urban landscape across the globe, Landscape and Urban Planning, 233, 104 711, https://doi.org/10.1016/j.landurbplan.2023.104711, 2023.

Fauth, J. and Seiß, S.: Ontology for building permit authorities (OBPA) for advanced building permit processes, Advanced Engineering Informatics, 58, 102 216, https://doi.org/10.1016/j.aei.2023.102216, 2023.

Grisiute, A., Silvennoinen, H., Li, S., Chadzynski, A., Raubal, M., Kraft, M., Von Richthofen, A., and Herthogs, P.: A Semantic Spatial Policy Model to Automatically Calculate Allowable Gross Floor Areas in Singapore, in: Computer-Aided Architectural Design. INTERCONNECTIONS: Co-computing Beyond Boundaries, edited by Turrin, M., Andriotis, C., and Rafiee, A., vol. 1819, pp. 455–469, Springer Nature Switzerland, Cham, https://doi.org/10.1007/978-3-031-37189-9_30, series Title: Communications in Computer and Information Science, 2023.

Hettiarachchi, H., Dridi, A., Gaber, M. M., Parsafard, P., Bocaneala, N., Breitenfelder, K., Costa, G., Hedblom, M., Juganaru-Mathieu, M., Mecharnia, T., Park, S., Tan, H., Tawil, A.-R. H., and Vakaj, E.: CODE-ACCORD: A Corpus of building regulatory data for rule generation towards automatic compliance checking, Scientific Data, 12, 170, https://doi.org/10.1038/s41597-024-04320-x, 2025.

Indrajit, A., Van Loenen, B., Ploeger, H., and Van Oosterom, P.: Developing a spatial planning information package in ISO 19152 land administration domain model, Land Use Policy, 98, 104 111, https://doi.org/10.1016/j.landusepol.2019.104111, 2020.

Iwaniak, A., Kaczmarek, I., Łukowicz, J., Strzelecki, M., Coetzee, S., and Paluszyński, W.: Semantic Metadata for Heterogeneous Spatial Planning Documents, in: ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. IV-4-W1, pp. 27–36, Copernicus GmbH, https://doi.org/10/gcc632, 2016.

Jehling, M. and Hecht, R.: Do land policies make a difference? A data-driven approach to trace effects on urban form in France and Germany, Environment and Planning B: Urban Analytics and City Science, 49, 114–130, https://doi.org/10.1177/2399808321995818, 2022.

Kaczmarek, I.: Transforming text into knowledge graph: Extracting and structuring information from spatial development plans, Open Geosciences, 15, 20220 513, https://doi.org/10.1515/geo-2022-0513, 2023.

Kandt, J. and Batty, M.: Smart cities, big data and urban policy: Towards urban analytics for the long run, Cities, 109, 102 992, https://doi.org/10.1016/j.cities.2020.102992, 2021.

Kang, J., Cai, C., Herthogs, P., Fu, Y., and Waibel, C.: Investigation of the impact of urban planning regulations on distributed energy system performance, in: World Cities Summit 2024 Science of Cities Symposium Abstract Proceedings, pp. 25–26, Singapore-ETH Centre (SEC) / Future Cities Lab (FCL), World Cities Summit, https://www.worldcitiessummit.com.sg/programme/wcs-science-of-cities-symposium, 2024.

Kuhn, W., Kauppinen, T., and Janowicz, K.: Linked Data - A Paradigm Shift for Geographic Information Science, in: Geographic Information Science, edited by Duckham, M., Pebesma, E., Stewart, K., and Frank, A. U., vol. 8728, pp. 173–186, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-11593-1_12, series Title: Lecture Notes in Computer Science, 2014.

Lefebvre, H.: The Production of Space, Wiley, https://books.google.ch/books?id=SIXcnIoa4MwC, 1992.

Lehavi, A., ed.: One Hundred Years of Zoning and the Future of Cities, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-66869-7, 2018.

Mizen, H., Dolbear, C., and Hart, G.: Ontology Ontogeny: Understanding How an Ontology Is Created and Developed, in: GeoSpatial Semantics, vol. 3799, pp. 15–29, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/10.1007/11586180_2, series Title: Lecture Notes in Computer Science, 2005.

Moreno, C., Allam, Z., Chabaud, D., Gall, C., and Pratlong, F.: Introducing the "15-Minute City": Sustainability, Resilience and Place Identity in Future Post-Pandemic Cities, Smart Cities, 4, 93–111, https://doi.org/10.3390/smartcities4010006, 2021.

Noardo, F., Guler, D., Fauth, J., Malacarne, G., Mastrolembo Ventura, S., Azenha, M., Olsson, P.-O., and Senger, L.: Unveiling the actual progress of Digital Building Permit: Getting awareness through a critical state of the art review, Building and Environment, 213, 108 854, https://doi.org/10.1016/j.buildenv.2022.108854, 2022.

Pauwels, P. and Terkaj, W.: EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology, Automation in Construction, 63, 100–133, https://doi.org/10.1016/j.autcon.2015.12.003, 2016.

Phua, S. Z., Lee, K. F., Tsai, Y.-K., Ganguly, S., Yan, J., Mosbach, S., Ng, T., Moise, A., Horton, B. P., and Kraft, M.: Urban Vulnerability Assessment of Sea Level Rise in Singapore through the World Avatar, Applied Sciences, 14, 7815, https://doi.org/10.3390/app14177815, 2024.

Rasmussen, M. H., Lefrançois, M., Schneider, G. F., and Pauwels, P.: BOT: The building topology ontology of the W3C linked building data group, Semantic Web, 12, 143–161, https://doi.org/10.3233/SW-200385, 2020.

Rijgersberg, H., van Assem, M., and Top, J.: Ontology of units of measure and related concepts, Semantic Web, 4, 3–13, https://doi.org/10.3233/SW-2012-0069, 2013.

Shi, Z., Fonseca, J. A., and Schlueter, A.: Floor area density and land uses for efficient district cooling systems in high-density cities, Sustainable Cities and Society, 65, 102 601, https://doi.org/10.1016/j.scs.2020.102601, 2021.

Shi, Z., Silvennoinen, H., Chadzynski, A., von Richthofen, A., Kraft, M., Cairns, S., and Herthogs, P.: Defining archetypes of mixed-use developments using Google

Maps API data, Environment and Planning B: Urban Analytics and City Science, p. 23998083221141428, https://doi.org/10.1177/23998083221141428, publisher: SAGE Publications Ltd STM, 2022.

Silvennoinen, H., Chadzynski, A., Farazi, F., Grišiūtė, A., Shi, Z., von Richthofen, A., Cairns, S., Kraft, M., Raubal, M., and Herthogs, P.: A semantic web approach to land use regulations in urban planning: The OntoZoning ontology of zones, land uses and programmes for Singapore, Journal of Urban Management, p. S2226585623000067, https://doi.org/10.1016/j.jum.2023.02.002, 2023.

Urban Redevelopment Authority: Advisory Notes, Gross Floor Area, https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/gross-floor-area/GFA/Advisory-Notes, 2019a.

Urban Redevelopment Authority: Singapore Master Plan 2019, https://www.ura.gov.sg/Corporate/Planning/Master-Plan, 2019b.

von Richthofen, A., Herthogs, P., Kraft, M., and Cairns, S.: Semantic City Planning Systems (SCPS): A Literature Review, Journal of Planning Literature, p. 08854122211068526, https://doi.org/https://doi.org/10.1177/08854122211068526, 2022.

Walczak, M.: A multi-dimensional spatial policy model for large-scale multi-municipal Swiss contexts, Environment and Planning B: Urban Analytics and City Science, 48, 2675–2690, https://doi.org/10.1177/2399808320985854, 2021.

Zentgraf, S., Fauth, J., Hagedorn, P., Seiss, S., Smarsly, K., König, M., and Melzner, J.: OntoBPR: Ontology-based workflow and concept for building permit reviews, in: 30th EG-ICE: International Conference on Intelligent Computing in Engineering, 2023.

Zlatanova, S., Yan, J., Wang, Y., Diakité, A., Isikdag, U., Sithole, G., and Barton, J.: Spaces in Spatial Science and Urban Applications—State of the Art Review, ISPRS International Journal of Geo-Information, 9, 58, https://doi.org/10.3390/ijgi9010058, 2020.