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Evaluating Urban Data Models for Parking Regulation Compliance: A Requirement-Driven Approach

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Abstract

Parking facilities play a vital role in urban planning and traffic management. However, regulatory assessments remain largely manual, building-centric, and focused on the initial lifecycle phase, with limited support for operational parking facilities or city-scale analysis. This study identifies legal and technical requirements from the Bavarian Garage and Parking Space Ordinance (GaStellV) and technical design standards for ramps, driveways, and pedestrian paths, and formalises them into a UML-based regulatory conceptual model for automated compliance checking. Representative urban data models, including CityGML, IFC, OpenDRIVE, and XPlanung, are then evaluated based on their ability to represent the identified regulatory concepts, considering semantic representation, and geometric as well as topological modelling capabilities. The evaluation shows that while each model excels within its application domain, none independently represents the complete set of regulatory requirements. Among the evaluated standards, CityGML 3.0 provides the most comprehensive foundation for city-scale automated compliance checking. Consequently, the regulatory conceptual model is mapped to and extends the CityGML 3.0 conceptual model using generic attributes together with the Building and Transportation modules. The approach demonstrates the feasibility of automatic, semantic, city-scale parking regulation checking.

1. Introduction

Parking provision and regulation influence car ownership and travel behaviour, creating governance challenges that require coherent and effective parking management strategies (Kirschner and Lanzendorf, 2020). While current research often focuses on accessibility, traffic management, and parking policies (Christiansen et al., 2017; Marsden, 2006), ensuring compliance with regulatory requirements is equally critical, but remains underexplored.

Regulation compliance checks are typically conducted during the building permit phase (Amor and Dimyadi, 2021). However, this aspect is often underdeveloped in the context of parking facilities (Klementschitz et al., 2007). Manual reviews are prone to errors and inefficiencies. The digitization of these processes aims to automate regulatory checks by translating regulations into machine-readable formats. Although this approach has been widely explored for building regulations (e.g. Eastman et al., 2009), it has not been sufficiently adapted to parking-specific requirements. A systematic comparison of urban data models with respect to representing parking regulations at the city scale is currently lacking.

To address this challenge, this study follows a four-step methodology. First, parking regulations are analysed and formalized into a UML-based conceptual model representing regulatory entities, attributes, and relationships. Second, the ability of existing urban data models, including IFC, OpenDRIVE, CityGML, and XPlanung, to represent these requirements is evaluated. Third, the approach is demonstrated through an extension of the CityGML 3.0 data model. Fourth, the approach is validated using high-resolution street-space data from Ingolstadt, Germany. Through this approach, the research aims to assist government officials in verifying compliance through improved digital representations.

The remainder of this paper is organised as follows. Section 2 reviews related work on parking facility evaluation and automated compliance checking. Section 3 presents the legal framework and formalises the regulatory requirements into a UML-based conceptual model. Section 4 evaluates representative urban data models against these requirements. Section 5 introduces the proposed CityGML 3.0 extension, while Section 6 presents a proof of concept. Finally, Section 7 concludes the paper and outlines future work.

2. Related Work

Compliance checking ensures that buildings and facilities adhere to regulatory standards, promoting sustainability and safety (Dimyadi and Amor, 2013). Traditionally, this process has been manual, labour-intensive, and error-prone, leading to delays and increasing costs (Eirinaki et al., 2018; Malsane et al., 2015). Over the past forty years, efforts to digitise and automate compliance checking have accelerated, driven by advancements in building models and algorithms (Amor and Dimyadi, 2021).

Several national and international initiatives have promoted the digitalisation of building permit processes and automated compliance checking. Representative examples include the CORENET programme in Singapore and the European initiatives CHEK and EU4DBP, supporting interoperable digital building permit workflows (CORENET X, 2024; CHEK, 2022; EU4DBP, 2022). Automated code compliance checking provides computational support for assessing building projects (Altıntaş and Ilal, 2021). Further developments include semantic models for fire regulations (Malsane et al., 2015) and BIM-based compliance workflows (Ciribini et al., 2016). However, these initiatives primarily focus on building permit assessment rather than city-scale parking regulation compliance.

A major challenge in compliance checking is translating legal texts into machine-readable representations (Amor and Dimyadi, 2021). Zhang and El-Gohary developed a rule-based semantic natural language processing (NLP) approach to convert regulations into logical clauses for automated reasoning (Zhang and El-Gohary, 2016). Lee et al. (2016) proposed a logic-based approach that translates the Korean Building Code into a computer-executable format by categorising building objects and attributes and storing logical rules in the KBimCode meta-database (Lee et al., 2016).

BIM has been the primary focus of building compliance checking because of its detailed representation of building components (Ciribini et al., 2016; Dimyadi and Amor, 2013;

Lee et al., 2016; Malsane et al., 2015). In contrast, semantic 3D city models such as CityGML support city-scale representation and the integration of multiple urban domains. Although these models cannot perform compliance checking directly, they can represent regulatory information and support compliance workflows. Guler and Yomralioglu (2021) proposed a framework integrating 3D property ownership, digital building permits, and CityGML/IFC models to improve urban planning and compliance checking. Saeidian et al. (2023) developed a CityGML 3.0 Application Domain Extension (ADE) for underground assets, linking legal and physical information.

Zahid et al. (2024) integrated urban planning regulations into semantic 3D city models based on CityGML to enhance urban simulations. Beil (2025) compared several standardised urban data models regarding their representation of street space, including parking facilities, but did not address parking regulation compliance.

Only a limited number of studies have specifically addressed automated compliance checking for parking regulations. Temel (2022) proposed a BIM-based approach that automatically verifies the number and dimensions of parking spaces from IFC models against municipal requirements. Similarly, Wu (2021) incorporated parking regulations into BIM–3D city model workflows for automated building permit checking. However, these studies focus on building permit assessment rather than evaluating existing parking facilities at the urban scale.

Furthermore, existing approaches often rely on non-standardised data models and do not systematically evaluate the capabilities of standardised urban data models for representing parking regulations. This motivates the requirement-driven evaluation presented in this study to assess their suitability for automated city-scale parking regulation compliance.

3. Requirement Identification and Formalization Framework

This section defines the requirements for a data model capable of representing urban parking regulations. The requirements are derived from a systematic extraction of legal and technical constraints and are formalised into a regulatory conceptual model that serves as the benchmark for evaluating existing urban data models.

3.1 Regulatory Framework Exemplified by the City of Ingolstadt, Bavaria

The legal framework governing parking facilities in Bavaria comprises federal, state, and municipal legislation. At the federal level, the German Road Traffic Act (StVG) (Bundesministerium der Justiz, 2024a) and the German Road Traffic Regulations (StVO) establish the general legal framework governing road traffic (Bundesministerium der Justiz, 2024b). At the state level, the Bavarian Building Code (BayBO) and the Bavarian Garage and Parking Slot Ordinance (GaStellV) define the technical requirements governing parking facilities (Freistaat Bayern, 2025; Freistaat Bayern, 1993). At the municipal level, the Garagen- und Stellplatzsatzung (GaStS) of the City of Ingolstadt introduces municipality-specific parking requirements (Stadt Ingolstadt, 2025).

Although the legal framework consists of several legislative levels, this study focuses primarily on the Bavarian Garage and Parking Slot Ordinance (GaStellV). The reason is that GaStellV contains the detailed and measurable technical requirements necessary for automated regulation checking, including parking dimensions, circulation areas, ramp geometry, garage classification, clearance heights, and parking demand. In contrast, higher-level regulations such as the Road Traffic Act (StVG), the Road Traffic Regulations (StVO), and the Bavarian Building Code (BayBO) establish the legal framework and planning obligations but generally do not specify the detailed geometric and semantic parameters required for machine-interpretable assessment. Consequently, these regulations provide the legislative context for this research, whereas GaStellV serves as the primary source for deriving the regulatory conceptual model. Municipality-specific provisions from the Ingolstadt Garagen- und Stellplatzsatzung (GaStS) are considered only where they introduce additional parking demand requirements relevant to the selected case study. Where municipality-specific parking demand requirements apply, the Ingolstadt Garagen- und Stellplatzsatzung (GaStS), particularly its Richtzahlenliste (parking space requirement table), is additionally considered to determine the required number of parking spaces according to building function. Based on this selection, only the legal provisions containing measurable geometric, semantic, and topological requirements were formalised and subsequently transformed into machine-interpretable concepts. Table 1 summarises the legal provisions selected for this study together with the regulatory concepts

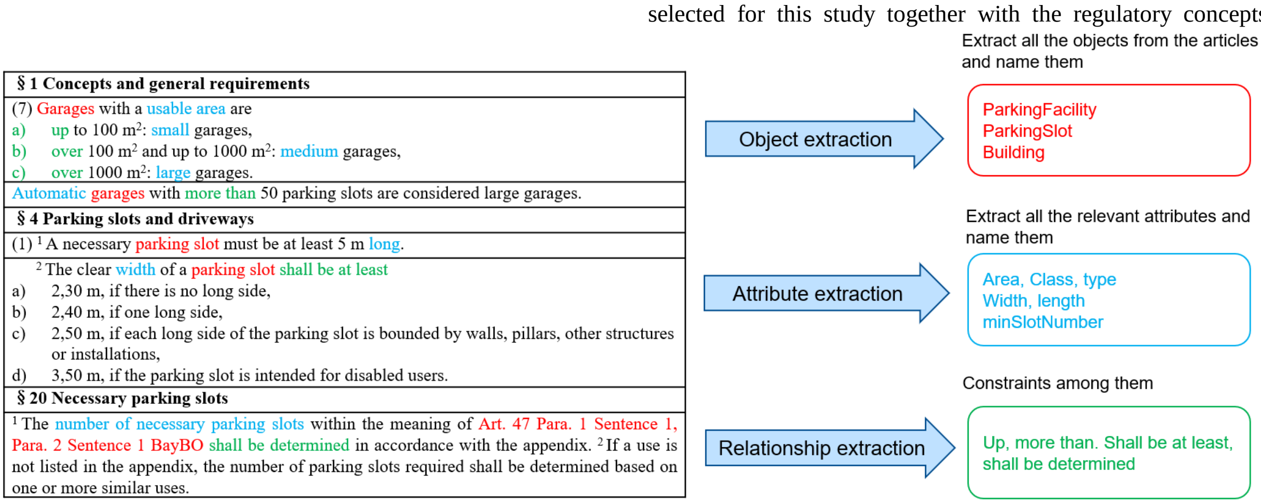

Figure 1. Workflow for extracting machine-interpretable regulatory concepts from selected provisions of the Bavarian Garage and Parking Slot Ordinance (GaStellV) (Chu, 2024).

extracted for automated compliance checking.

To support automated regulation checking, the selected legal provisions undergo a systematic formalisation process that transforms natural-language legislation into machine-interpretable concepts. Rather than directly mapping legal text to a particular urban data model, the proposed methodology

Source	*Object(s)*	*Rule*
§1	ParkingFacility	Threshold
§2	EntranceExit	Minimum
§3	Ramp	Threshold
§4	ParkingSlot, Driveway	Geometric
§5	ParkingFacility	Minimum
§20	Building	Formula
GaStS	Building	Lookup

Table 1. Legal provisions selected for this study and the corresponding regulatory concepts extracted to support automated parking regulation compliance checking.

introduces an intermediate conceptual layer that separates legal semantics from implementation-specific representations. This intermediate representation enables a consistent evaluation of multiple urban data models like IFC or CityGML and provides the foundation for developing model extensions where necessary. The formalisation process consists of four consecutive steps (Chu, 2024):

1. Selection of legal provisions. Legal articles relevant to parking assessment are identified based on whether their requirements can be represented through measurable geometric, semantic, or topological information.
2. Knowledge extraction. Each selected article is manually analysed to identify its regulatory components.
3. Conceptual modelling. The extracted regulatory concepts are organised into a UML conceptual model.
4. Rule formalisation. Natural-language constraints are translated into machine-interpretable logical rules suitable for automated compliance checking.

Figure 1 illustrates the knowledge extraction step of the proposed methodology. The legal provisions listed in Table 1 provide representative examples of measurable regulations that are systematically transformed into machine-interpretable concepts through object, attribute, and relationship extraction. **Object extraction** identifies the legal entities defined within the regulations. Examples include **ParkingFacility**, **ParkingSlot**, and **Building**, which subsequently become the primary classes of the conceptual model. **Attribute extraction** identifies the measurable properties associated with these entities, including **Area**, **Width**, **Length**, **Garage Type**, and **Minimum Number of Parking Slots**. These attributes represent the quantitative information required for automated regulation checking. **Relationship and constraint extraction** identifies the logical dependencies and quantitative conditions expressed within the legislation. Typical legal expressions include *shall be at least*, *up to*, *greater than*, and *shall be determined*. These textual constraints are subsequently transformed into formal logical expressions that can be evaluated automatically. For example, the expression *shall be at least* is represented using the mathematical operator (≥), while garage classifications based on usable area are converted into explicit threshold rules. This structured extraction preserves traceability between every identified concept and its originating legal article, ensuring transparency and facilitating future updates should the legislation evolve.

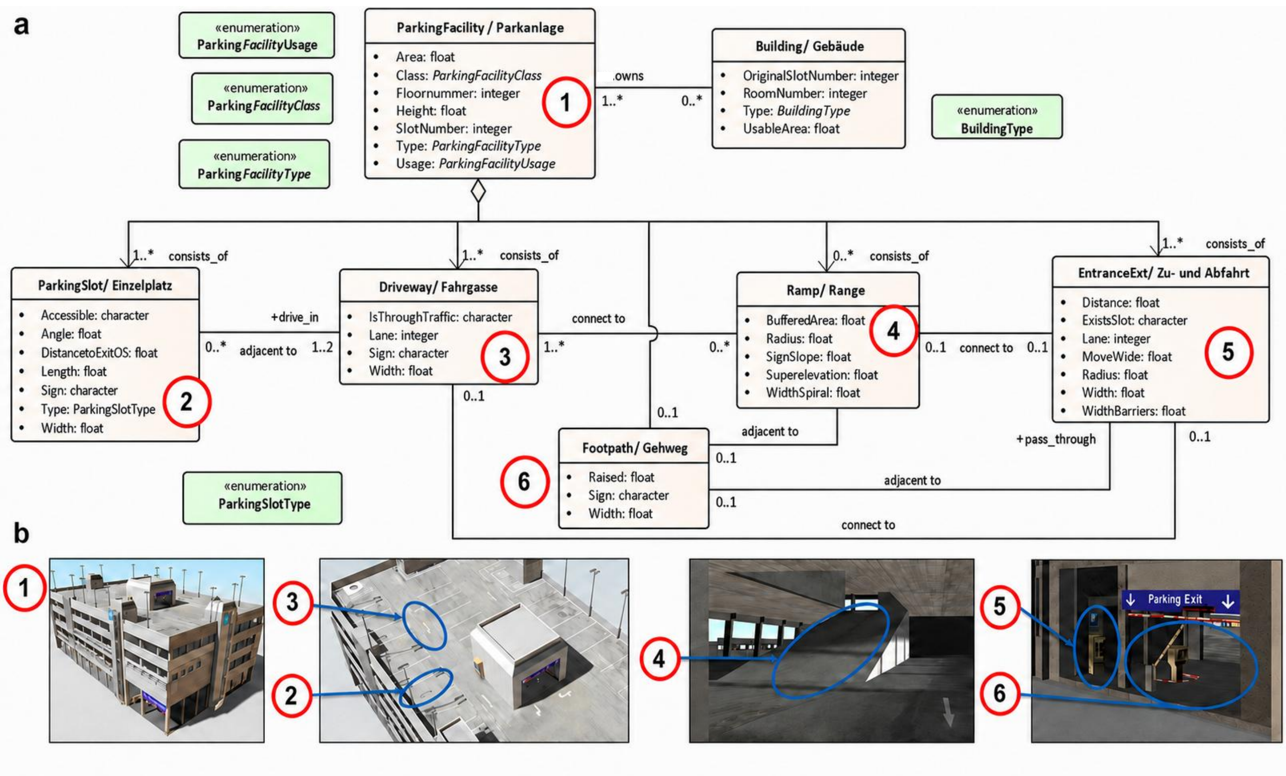

Figure 2. [a] The conceptual model developed from the selected regulation; [b] The explanation of the parking objects (Chu, 2024).

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3.2 The Conceptual Model of the Legal Requirements

Based on the legal provisions summarised in Table 1 and the regulatory concepts extracted through the workflow illustrated in Figure 1, a UML class diagram (Figure 2) was developed to organise the identified entities, attributes, relationships, and constraints into a platform-independent conceptual model for automated parking assessment (Chu, 2024). The ParkingFacility class represents parking structures or parking areas containing one or more parking slots. This class stores semantic properties including usable area, garage classification according to §1 GaStellV, minimum clearance height (§5 GaStellV), and usage type. The ParkingFacility is associated with the Building class through an *owns* relationship. This association is essential because the required parking capacity depends on building characteristics defined in §20 GaStellV and the Ingolstadt GaStS. Accordingly, the Building class stores attributes such as building function, usable floor area, room number, and existing parking capacity. The parking facility is further decomposed into five principal regulatory entities. The ParkingSlot class represents the primary assessment object and stores the geometric characteristics required for evaluating compliance with §4 GaStellV, including slot length, slot width, parking angle, and accessibility. Parking slots are connected to driveways through a *drive_in* relationship. This relationship identifies the driveway from which a vehicle can enter or leave a particular parking slot. The Driveway class models the internal vehicle circulation network and contains properties describing driveway width, lane configuration, and traffic characteristics. In this model, a driveway represents the internal vehicle-movement area that provides access to the parking slots and connects them to ramps and entrance or exit points. It is distinct from the EntranceExit, which connects the parking facility to the surrounding road network, and from the Ramp, which enables vehicle movement between different levels. The Ramp class represents level transitions within the parking facility and includes attributes such as longitudinal slope, curvature radius, superelevation, and transition areas. The EntranceExit class represents access points between the parking facility and the surrounding road network, storing entrance width, setback distance, barrier dimensions, and waiting areas. Finally, the Footpath class models pedestrian circulation areas adjacent to vehicle movement and includes attributes describing path width and elevation relative to the roadway. These regulatory entities are interconnected through topological, functional, and logical relationships, including *connects_to*, *adjacent_to*, *passes_through*, *drive_in*, and *owns*, thereby capturing both the spatial configuration and the legal dependencies specified by the Bavarian regulations. The *connects_to* relationship indicates functional circulation connectivity between two elements. The *adjacent_to* relationship indicates that two elements are located beside one another or share a boundary, without implying that movement occurs between or across them. In contrast, the *passes_through* relationship indicates that a circulation route traverses another element. The *drive_in* relationship specifically links a parking slot to the driveway from which a vehicle can enter or leave it. The own relationship expresses a semantic or administrative association rather than a spatial relationship. Explicit geometric properties are intentionally not included in Figure 2 because the UML diagram represents a platform-independent conceptual model rather than an implementation-specific spatial schema. At this conceptual level, spatial characteristics are expressed through measurable regulatory attributes, such as length, width, area, clearance height, slope, curvature radius, and setback distance. In a subsequent implementation, these values may either be stored directly or derived from the geometry representations supported by the evaluated data model.

The resulting conceptual model captures the complete set of measurable regulatory concepts required for automated parking assessment while remaining independent of any particular implementation standard. In the following section, this conceptual model serves as the benchmark for evaluating the capability of existing urban data models to represent the legal objects, attributes, spatial and functional relationships, and constraints required for automated compliance checking.

4. Evaluation of Standardized Urban Information Models

This section evaluates the capability of representative urban data models (CityGML, IFC, OpenDRIVE, and XPlanung) to satisfy the regulatory and technical requirements defined in Section 3. The evaluation assesses how effectively each model represents the regulatory conceptual model for automated compliance checking of the Bavarian Garage and Parking Slot Ordinance (GaStellV) as formalized by the UML model described in section 3.2. Three aspects are considered: semantic representation, geometric and topological representation. To provide a consistent basis for comparison, the capability of each data model is evaluated using a qualitative three-level rating scheme based on its ability to represent the concepts defined in the regulatory conceptual model (Section 3.2). A rating of High (H) indicates that more than 80% of the required objects, attributes, relationships, and constraints can be represented using the standard without introducing schema extensions. Medium (M) indicates that between 50% and 80% of the required concepts are supported, although additional modelling effort or partial extensions may be necessary. Low (L) indicates that less than 50% of the required concepts are directly supported, limiting the suitability of the model for automated regulation checking. A rating of Not Supported (N) denotes that the corresponding requirement cannot be represented within the standard. The percentage values are derived from the proportion of regulatory conceptual-model classes and attributes that can be directly represented by the respective standard without schema extensions. Table 2 presents a condensed result of the comparative assessment of the investigated data models. To establish the evaluation framework, four widely adopted urban data models are considered and briefly introduced below.

Regulatory Concept	CityGML	IFC	OpenDRIVE	XPlanung
Facility Classification	H	H	M	L
Access & Connectivity	H	H	H	L
Vertical Circulation	M	H	H	N
Parking Geometry	H	H	M	L
Spatial Clearance	H	H	L	N
Parking Demand	H	L	N	H

Table 2. Comparative evaluation of existing urban data models against the regulatory requirements derived from GaStellV.

CityGML 3.0 (OGC) (OGC, 2021; Kutzner et al., 2020) provides a semantic information model for 3D city objects based on the unified concepts of Space and Space Boundary. Its Building and Transportation modules support city-scale representation of parking facilities and their relationships with surrounding urban objects. The extensible data model makes CityGML suitable for semantic integration and regulatory assessment.

IFC 4.3.2 (ISO 16739) is the standard for Building Information Modelling (BIM), providing detailed semantic and geometric representations of buildings and infrastructure through entities such as IfcRoad. Its rich object hierarchy supports engineering-level verification but is primarily designed for site-scale applications.

ASAM OpenDRIVE 1.9.0 (ASAM, 2024) models road networks with respect to the requirements of the automotive industry, e.g for virtual test driving, using high-precision geometry and lane-based topology. It provides strong support for road alignments, ramps, gradients, and traffic circulation, making it suitable for transportation-related parking requirements.

XPlanung 5.2 (XLeitstelle XPlanung/XBau, 2021) is the German standard for digital spatial planning. It represents zoning regulations and planning restrictions, but provides limited semantic and geometric detail for the internal components of parking facilities, such as parking spaces, driveways, ramps, and circulation areas, as well as the internal layout of parking garages and other parking facilities

Table 3 provides an overall comparison of the investigated urban data models with respect to the regulatory concepts defined in the conceptual model. The supporting classes used to derive these ratings are summarised in Table 3. The reported values indicate the number of conceptual-model classes (C) and attributes (A) that can be mapped to corresponding concepts in each standard. To illustrate how the mappings and counts in Table 3 were derived, one representative example is provided: The Ramp class maps directly to IfcRamp in IFC, accounting for one mapped class (1C). Its six regulatory attributes can be represented through IFC attributes, property sets, and geometric descriptions, resulting in the reported 1C/6A rating. In contrast, XPlanung contains neither a corresponding class for an internal parking ramp nor suitable attributes for describing its three-dimensional configuration, resulting in 0C/0A. The following subsections discuss the evaluation results in detail according to the assessment criteria of semantic representation and geometric and topological representation.

4.1 Semantic Representation

Parking regulations distinguish between several functional entities, including parking slots, driveways, ramps, entrances, circulation areas, and accessible parking spaces. These concepts must be explicitly represented within the underlying information model to enable machine-interpretable regulations. CityGML 3.0 provides a flexible semantic framework through its concepts of OccupiedSpace and UnoccupiedSpace, and its transportation module defining dedicated spaces like TrafficSpace and ClearanceSpace allowing both physical structures and navigable spaces to be represented consistently. IFC similarly provides detailed semantic descriptions through its spatial hierarchy and infrastructure entities, supporting detailed building-level analysis. OpenDRIVE introduces rich semantics for transportation infrastructure and lane connectivity (represented by reference lines) but is primarily limited to roadway environments. XPlanung represents planning intentions and land-use regulations without detailed classes for internal parking facility components, limiting its applicability for automated compliance checking.

4.2 Geometric and Topological Representation

Several provisions of GaStellV require the simultaneous representation of three-dimensional geometry and topology. Examples include the verification of ramp gradients (§3), vehicle circulation, and minimum clearance heights (§5).

IFC provides highly accurate geometric representations of building and infrastructure elements suitable for engineering-scale verification. OpenDRIVE complements this capability through detailed descriptions of road alignments, slopes, superelevation, and lane connectivity. CityGML supports volumetric representations of occupied and unoccupied spaces, as well as surface-based space boundaries, enabling spatial reasoning and clearance analysis at the city scale. Conversely, XPlanung remains limited to two-dimensional planning geometries and cannot support three-dimensional compliance assessment.

Concept	Direct Mapping (Classes / Attributes)	Main Supporting Classes
Facility Classification	CityGML: 1C/4A; IFC: 1C/4A; OpenDRIVE: 1C/2A; XPlanung: 1C/2A	CityGML: LandUse, OccupiedSpace; IFC: IfcFacility; OpenDRIVE: object, parkingSpace; XPlanung: zoning classes
Access & Connectivity	CityGML: 2C/8A; IFC: 2C/7A; OpenDRIVE: 2C/8A; XPlanung: 1C/2A	CityGML: TransportationSpace, TrafficSpace; IFC: IfcRoad, IfcAlignment; OpenDRIVE: road, laneSection, lane, junction, access; XPlanung: traffic-area classes
Vertical Circulation	CityGML: 1C/4A; IFC: 1C/6A; OpenDRIVE: 1C/6A; XPlanung: 0C/0A	CityGML: AbstractSpace; IFC: IfcRamp, IfcSectionedSolidHorizontal; OpenDRIVE: geometry, elevationProfile, superelevation; XPlanung: not directly supported
Parking Geometry	CityGML: 2C/6A; IFC: 2C/6A; OpenDRIVE: 2C/4A; XPlanung: 1C/1A	CityGML: TransportationSpace, TrafficSpace; IFC: IfcSpace, IfcRoad; OpenDRIVE: object/parkingSpace, lane; XPlanung: traffic-area classes
Spatial Clearance	CityGML: 2C/3A; IFC: 2C/3A; OpenDRIVE: 1C/1A; XPlanung: 0C/0A	CityGML: UnoccupiedSpace, ClearanceSpace; IFC: IfcSpace; OpenDRIVE: elevationProfile, object@height; XPlanung: not directly supported
Parking Demand	CityGML: 2C/5A; IFC: 2C/2A; OpenDRIVE: 0C/0A; XPlanung: 2C/5A	CityGML: Building, CityObjectRelation; IFC: IfcBuilding, IfcProject; OpenDRIVE: not supported; XPlanung: planning regulations

Table 3. Regulatory concepts supported by each data model. The Direct Mapping column shows the supported classes (C) and attributes (A) that can be mapped directly without extensions.

The comparative evaluation demonstrates that no existing standard independently satisfies the complete set of regulatory requirements. Nevertheless, CityGML 3.0 provides the strongest foundation because it aligns most closely with the

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identified requirements (see Tables 2, and 3). The identified gaps, particularly the representation of parking slots, accessible spaces, and explicit parking relationships, motivate the CityGML extension proposed in the following section.

5. Proposed Extension of CityGML 3.0 via the Generics Module

Building on the evaluation in Section 4, this section details the technical framework for customizing CityGML 3.0 to support automated parking regulation compliance. This extension follows a "minimum extension" principle, aiming to integrate regulatory objects into the existing CityGML Conceptual Model first and utilizing the Generics module only for missing concepts. This strategy was selected to maintain full compatibility with existing CityGML toolchains during the implementation and evaluation phase, avoiding the additional complexity associated with Application Domain Extension (ADE) based workflows. In future work, however, a dedicated ADE could provide a more formally defined and semantically robust data structure for parking-regulation compliance assessment.

5.1 Mapping Principles and Semantic Rationale

The mapping process prioritizes semantic fit and informational flexibility. Regulatory objects are mapped to the CityGML classes that provide the most comprehensive data structure for automated workflows **(**Figure 3**)** (Chu, 2024).

Parking Facility to TrafficSpace: While classes like Square can represent large parking lots, they often cause ambiguity by focusing primarily on open-air areas and failing to model indoor or multi-story structures effectively. Mapping the ParkingFacility to TrafficSpace is more logical because it represents the volumetric space where traffic occurs and includes an optional association with ClearanceSpace to host the clearHeight attribute (§5 GaStellV). This selection also clarifies the hierarchical relationship between the facility (space) and its sub-components like driveways or slots (surface boundaries).

Parking Slots and Ancillary Objects to TrafficArea: Components such as ParkingSlot, Driveway, Ramp, EntranceExit, and Footpath are mapped to the TrafficArea class using the native CityGML attribute class, enabling discrimination of the above objects. As the actual ground surface where traffic takes place, TrafficArea allows for fine-grained definitions. These features are distinguished using the native CityGML attribute *function* (e.g. parking slots, code "7" for drive lanes, "1" for driving lanes, and "2" for footpaths).

Building Integration: The CityGML Building class is utilized to host data required for Capacity Calculations (§20). This includes roomNumber, usableArea, and the requiredNumberOfPS. Crucially, the originalNumberOfPS (actual existing slots) is also placed in the Building properties, as not all parking slots are located within formal parking facilities.

5.2 Detailed Attribute Extension and Universal Reusability

To capture the technical depth of the GaStellV, several domain-specific attributes are introduced via the Generics module.

Facility Attributes (TrafficSpace): Five new attributes are added, including classOfPF (size category), formOfPF (open-air, garage, multi-story), usageOfPF (public/private), typeOfPF (automatic/traditional), and usableAreaOfPF.

Parking Slot Attributes (TrafficArea): Six attributes are integrated to define individual stall compliance: isAccessible, angleOfParking, widthOfParkingSlot, lengthOfParkingSlot, typeOfParkingSlot (e.g., classic or horizontally movable), and isInFrontOfElecPlattform.

Circulation and Ancillary Attributes: For driveways and ramps, attributes such as isThroughTraffic, widthOfDriveway, numberOfLanes, slopeOfDriveway, radiusOfDriveway, and superelevation are added. Footpaths are extended with footPathHeightsAboveGround and widthOfFootpath.

Decomposition for Reusability: Complex regulatory parameters are decomposed into simpler attributes to ensure they are universally applicable across different features. For example, the specific requirements for spiral ramps are split into separate attributes for slope, width, and radius. This allows these attributes to be used in any combination on any TrafficArea feature (e.g., standard lanes), avoiding the need for redundant, ramp-specific classes.

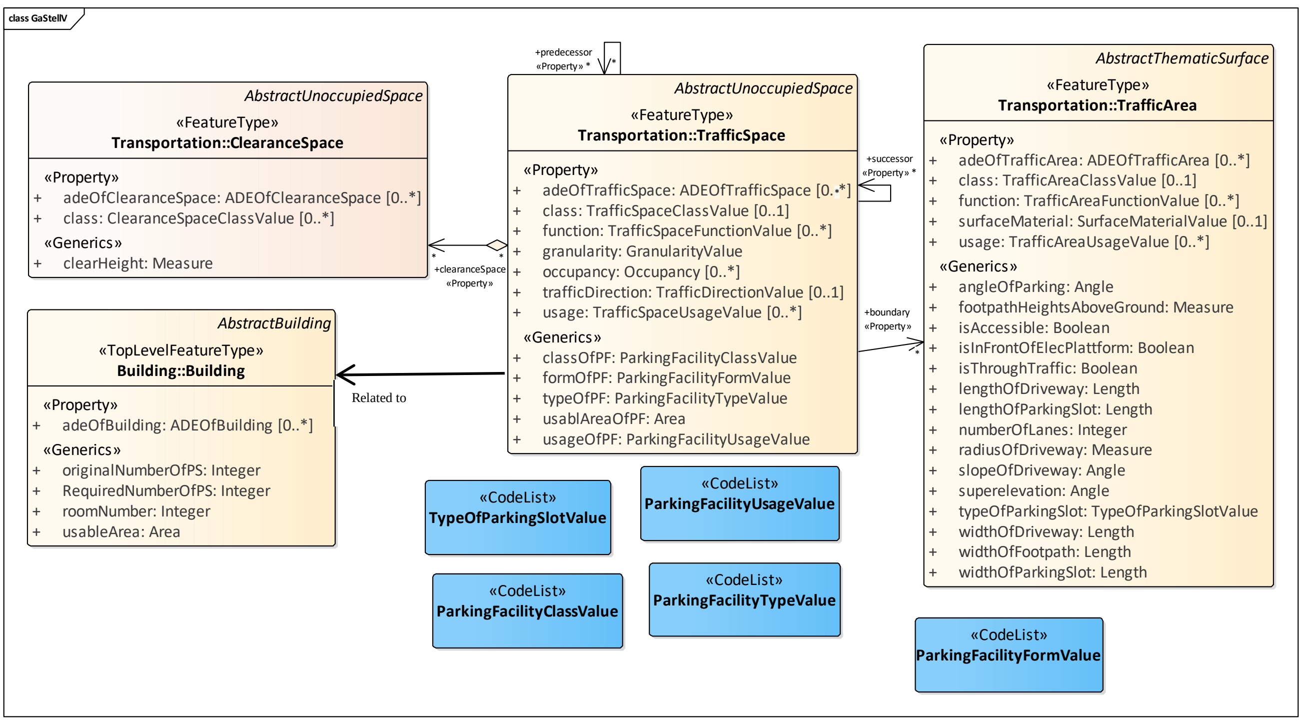

Figure 3. UML diagram of the CityGML extension (Chu, 2024).

5.3 Integration of Inspection and Assessment Results

To support automated compliance checking, assessment outcomes are stored directly within the *TrafficArea* class using four Generic attributes: *administrationArea* records the legal jurisdiction, *articleNumber* identifies the assessed regulation, *assessmentResult* records the compliance status, and *failureReason* documents the reason for non-compliance. Thus, the extended CityGML 3.0 model combines spatio-semantic representation with machine-readable regulatory results that urban planners can query, review, and reference within a unified 3D city environment.

6. Proof of Concept with a Use Case from the City of Ingolstadt and Case Study Results

To validate the proposed CityGML extension, a case study was conducted in the city of Ingolstadt, Bavaria, applying the automated workflow to diverse parking zones, including parking lots, private slots, and roadside parking.

6.1 Model Transformation and Data Enrichment

The implementation employed two complementary transformation workflows. First, r:trån[1] was used to validate and transform the OpenDRIVE transportation dataset into CityGML 3.0. The tool converts the parametric OpenDRIVE road network into a spatio-semantic CityGML transportation model. Second, FME Workbench was used to transform the LoD2 building dataset and integrate it with the CityGML transportation data generated by r:trån. Within FME, TrafficArea features were filtered to identify the parking-related elements, which were subsequently enriched with values for predefined CityGML attributes and generic attributes, like the function attribute to distinguish between driving lanes (code 1), footpaths (code 2), and parking slots (code 7). Where source datasets lacked complete information, reasonable attribute values were inserted manually to enable the regulatory assessment.

Figure 4. Types of parking zones and auxilairy traffic surfaces.

6.2 Automated Regulatory Workflow

The automated assessment evaluated the proposed CityGML regulatory attributes against the legal requirements defined in GaStellV and the municipal parking regulations. Rule-based evaluation was performed using FME to verify: (1) dimensional compliance: Checking if individual parking slots' lengths and widths met minimum requirements. (2) Geometric interdependencies: Evaluating driveway widths in relation to the specific parking angles defined in the model. Capacity assessment: (3) Calculating the required number of slots based on building usable area and comparing it with the available supply within a defined proximity.

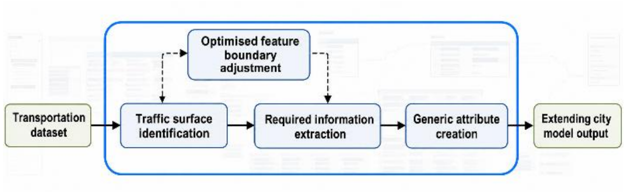

Figure 5. Transportation data conversion workflow in FME.

6.3 Results and Visualization

The assessment results were stored within the extended CityGML model and exported to an interactive HTML report for visualization and inspection. This report features a Leaflet-based web map that allows users to interactively inspect non-compliant features. Figure 6 shows the automatically generated HTML compliance report produced after evaluating the parking facility against the selected provisions of the Bavarian Garage and Parking Ordinance (GaStellV). The report summarizes the assessment of 1,333 parking slots within the selected study area and is organized into sections corresponding to the evaluated regulations, including §2 (Driveways at Entrance/Exit), §3 (Driveways in Ramps), §4 (Parking Slots), §4 (Driveways Near Parking Slots), §20 (Necessary Parking Slots), and the assessment of parking area markings and signs. Each section provides an overview of the assessed objects and, where violations are detected, presents a table listing the non-compliant parking slots, their location, and an explanation of the violated regulation(s). For example, the report identifies parking slots whose width does not satisfy the minimum requirement of 2.3 m specified in §4-1, together with the measured values and the corresponding legal reference. This structured report enables

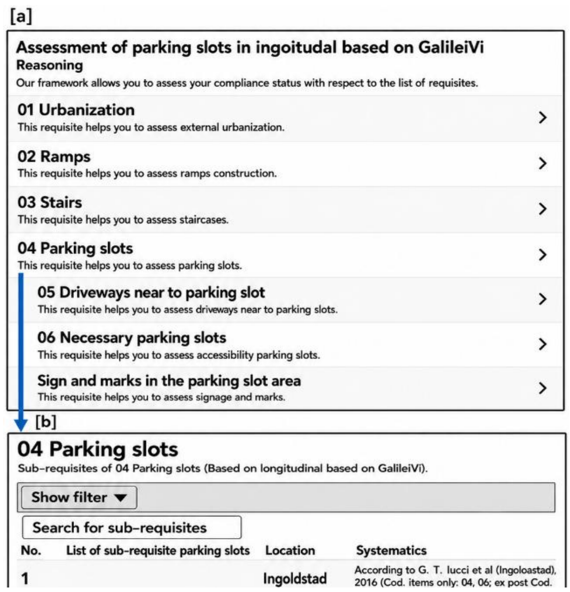

Figure 6. The interactive HTML report (Chu, 2024).

[1] https://github.com/tum-gis/rtron

users to efficiently review compliance results and directly investigate the detected violations.

7. Conclusion

This study demonstrates an automated workflow for assessing parking facilities at the city scale. The Ingolstadt case study shows that GaStellV requirements can be formalized and operationalized within a machine-interpretable CityGML 3.0 model. Using existing CityGML classes and attributes as well as the Generics module, the minimal-extension approach supports efficient large-scale compliance checking.

Future work should develop a dedicated ADE for complex regulations and integrate the model with XPlanung. LLM-assisted extraction and mapping of regulatory concepts should also be investigated under expert validation. Assessments should be continuously refined as urban data and 3D city models mature, supporting long-term data-driven governance.

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