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Towards Data-Centric Geospatial Applications: A Knowledge Graph Approach to Road Maintenance in Stockholm, Sweden

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Towards Data-Centric Geospatial Solutions: A Knowledge Graph Approach to Road Maintenance in Stockholm, Sweden

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Abstract

Digital twins offer great potential for transforming urban management to be more effective and sustainable. By adopting a data-centric approach, cities can become more innovative, moving away from application-centric solutions with data silos toward an interoperable modern data architecture. This thesis designs and develops a data-centric knowledge graph-based tool for road maintenance together with the Stockholm Traffic Administration Office.

The research established a workflow to develop a standardized data-centric model to manage the road space. By analyzing the current operational and asset register systems at the Stockholm Traffic Administration Office, architecture was developed for a tool that accessed similar data content. The tool was constructed integrating geospatial road data into a CityGML-3CIM data model as a knowledge-graph, which was linked with the Swedish National Road Database (NVDB). This semantic approach facilitates data description and interoperability, through established standards. The data model was specifically classified to align with existing road maintenance requirements and the open-source software QGIS was utilized for the tool's spatial visualization and management.

The results demonstrate how a data-centric approach turns data into a central resource in the organization, a "Single Source of Truth" eliminating data silos and facilitating internal and external interoperability. Any update to the knowledge graph is reflected instantly across the organization, maintaining high data quality and removing the need for manual resource-heavy data conversion typical of application-centric solutions. The research offers several recommendations for how the organization can adopt a data-centric approach to road maintenance and concludes that further work on the topic is recommended and essential for the digital transformation of urban management.

Keywords: Digital twins, data-centric, knowledge graphs, CityGML, 3CIM, road data

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List of Abbreviations

3CIM	CityGML Conceptual Information Model; an Application Domain Extension (ADE) for the Swedish 3D city models.
ADE	Application Domain Extension
BIM	Building Information Modeling
CityGML	City Geography Markup Language
Digg	The Swedish Agency for Digital Government (swe: <i>Myndigheten för digital förvaltning</i>)
ETL	Extract Transform Load
FAIR	Findable, Accessible, Interoperable and Reusable
GIS	Geographic Information Systems
GML	Geography Markup Language
IRI	Internationalized Resource Identifiers
KGBT	Knowledge graph-based tool
LoD	Levels of Details
NVDB	National Swedish road database (swe: <i>Nationell Vägdatabas</i>)
OGC	Open Geospatial Consortium
OSGeo	Open-Source Geospatial Foundation
OWL	Ontology Web Language
RDF	Resource Description Framework
SDI	Spatial Data Infrastructure
SPARQL	RDF Query Language
UML	Unified Modeling Language
URI	Uniform Resource Identifier
W3C	World Wide Web Consortium
WMS	Web Map Service
XML	eXtensible Markup Language

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1. Introduction

1.1 Background

By 2050, 68 percent of the global population is estimated to live in urban areas, with city regions consuming a massive share of natural resources and generating most of the world's waste, making innovative urban management essential to meet the UN's Sustainable Development Goals (United Nations Department of Economic and Social Affairs, 2018).

Digitalization enables organizations to make informed decisions and drive innovation (Batty, 2018). As early as 2006, Clive Humby described data as the new oil, emphasizing that data's value emerges through technological advancements (Farronato, 2025). In today's ongoing AI revolution this is more relevant than ever. Organizations tend to build data silos through an application-centric approach, where data is stored closely tied to each application. But as technology develops, we can see a shift towards a data-centric approach, an architecture where the meaning of data (semantics) is treated as a primary asset in the organization, existing independently of any specific software application and governed by a shared central data model (McComb, 2019). A single source of truth becomes the norm for working with high-quality and updated information in the organization. For example, in a data-centric architecture, multiple software applications interact directly with a single, shared central information model instead of using isolated databases. When data is modified, the change is instantly accessed across the entire organization. Applications no longer own the data, they simply act as temporary interfaces to view or analyze it.

Geospatial knowledge graphs represent a promising development in data management to facilitate data-centric solutions (Zhu, 2024). A shift from traditional relational tables to ontology schemas for structuring data, making it a semantically rich network improves integration and reasoning across different datasets. The capabilities of knowledge graphs address a critical challenge in current Geographic Information Systems (GIS) implementations, the difficulty of combining quantitative and qualitative geographic information in a unified framework. This development enables geographic data to be findable, accessible, interoperable, and reusable (FAIR), which is a set of guiding principles to facilitate good data management to drive innovation in all sectors (Wilkinson et al., 2016).

Urban development is a very large sector with both private and public stakeholders that manage large amounts of data. Digitalization is reshaping the built environment, leading to gains in efficiency and better procedures for planning, building and the environment. This increases the need for standardized data management. Lantmäteriet, Sweden's Mapping, Cadastral, and Land Registration Authority, leads the national digitalization initiative smarter Planning and Building Process (swe: *Smartare Samhällsbyggnadsprocess*) to improve efficiency, transparency, and usability in urban planning and development (Lantmäteriet, 2025).

The Strategic Innovation program *Smart Built Environment* hosts numerous projects aimed at improving urban development in Sweden by developing and demonstrating new solutions (Smart Built Environment, 2025a). One such project, *Interoperability - Digital collaboration for the built environment* (swe: *Interoperabilitet - Digital*

samverkan för den byggda miljön), focuses on knowledge graph solutions, emphasizing the importance of data sharing (Smart Built Environment, 2025b). Improved interoperability of data between GIS, Building Information Models (BIM) and urban applications can provide significant benefits for companies, consumers (e.g. citizens and infrastructure users), and society. The use of knowledge graphs to improve urban development involves both private and public actors, making it an ideal setting to study the effect that these technologies can have in this sector.

In 2023 a proposal for a Swedish national standard for 3D City Models was developed, aimed at becoming a foundation for developing Digital Twins in Sweden. It was created by the cities of Stockholm, Göteborg and Malmö in cooperation with Lund University. 3CIM is built on the international standard City Geography Markup Language (CityGML) (Gröger & Plümer 2012, Kolbe et al., 2021) and the Swedish national specifications for geospatial data and is designed for linking to external databases, registers and operational systems (Uggla et al., 2023). Making it possible for Swedish municipalities to develop Digital Twins as a data-centric foundation for data sharing and analysis in urban development. This 3CIM national standard provides a strong base for multi-stakeholder projects where data sharing is essential (Smart Built Environment, 2025c). In this report the 3CIM standard is denoted CityGML-3CIM to emphasize its strong connection to CityGML.

One external database that 3CIM can be linked to is NVDB (swe: *Nationell Vägdatabas*). It is the Swedish national road database, since 1996 it has been maintained by the National Transport Administration (swe: *Trafikverket*), and it includes information about all roads for motor vehicles, pedestrians and bicycles.

This thesis focuses on practical issues related to urban development using 3CIM and NVDB integrated in a geospatial knowledge graph, applying a data-centric approach to road maintenance and planning needs at the Stockholm Traffic Administration Office (swe: *Trafikkontoret*).

1.1 Problem statement

Many city departments gather data on their own that is integrated into their respective application for operational and asset registers. This leads to different departments gathering information for similar purposes. A standardized digital representation of the city that can be utilized by all departments and units as well as external stakeholders would be beneficial.

This study examines whether a city model based on CityGML-3CIM can function as a common description to support road maintenance, with particular emphasis on linking to external resources. How can a data-centric approach to modern IT architecture be used to enhance interoperability. Investigating how to set up the data as knowledge graphs through semantics and ontology to implement linking road surfaces to the external NVDB database for additional road information. This expansion of 3CIM is central for more complex tasks in the future, with several implementations in urban development, for example in analysis and visualization of the road space.

1.3 Aim

The aim of this master's thesis is to address a real-world problem of road maintenance by demonstrating the value of linking geographic data to a knowledge graph to obtain a data-centric solution. Explicitly, it considers the integration of 3D City Model data and geographic road data into a knowledge graph to support the Stockholm Traffic Administration Office in predicting maintenance, improvements and planning.

The following research questions are addressed:

- 1. How to design and develop a data-centric knowledge graph solution for road maintenance based on city model data (CityGML-3CIM transportation module) and a national road dataset (NVDB)?*
- 2. Which are the benefits and obstacles of semantic integration of geographic data in a Knowledge Graph (a data-centric approach) for decision making of road maintenance?*

1.4 Limitations

From a geospatial perspective, this thesis is limited to CityGML version 2.0 and the 3CIM extension (Uggla, 2023). The scope is kept manageable by using only the 3CIM transportation module, despite the possibility of exploring other external connections that the module enables.

The thesis is technically oriented toward how to use data in existing knowledge graphs; it is not about how to create these knowledge graphs. It explores a data-centric approach through developing a tool in a particular use-case, it does not implement this tool in the organization and factors like ownership of data, economic incentives etc. are not considered.

The study focuses on a small geographic area, Kista Äng in Stockholm (Figure 5.3), which is a study area developed and maintained as a testbed for research within the Smart Built Environment projects (Smart Built Environment, 2025a). The reason for choosing this area is access to CityGML-3CIM transportation data and NVDB data expressed in knowledge graphs.

1.5 Disposition

The thesis is organized as follows. Chapter 2 establishes the theoretical and technical foundation, exploring Digital Twins, CityGML, 3CIM, the national road database, and standards for Semantic Web Technologies and Knowledge Graphs. The final section introduces real-world examples of how these technologies integrate with geospatial data. Chapter 3 outlines the design of the case study to meet the aims of the thesis. Chapter 4 defines the specific requirements for a data-centric solution. Chapter 5 presents the design and development of architecture, focusing on the data, tools and the development of a knowledge graph-based tool (KGBT). Chapter 6 evaluates the tool's performance and discusses the results. Chapter 7 provides final conclusions based on the research questions and offers recommendations for the future development of data-centric solutions at Stockholm Traffic Administration Office.

1.6 Statement on the use of AI tools

Large language models, including Google Gemini, were utilized throughout this thesis to support search, correction of spelling and grammatical errors. After using the tool, the author edited the content as needed and assumes full responsibility for the publication.

2. Related work

This chapter explains the topics, techniques, and standardized data models used to address the research questions.

2.1 Application-centric vs. data-centric approach

In 2024 the European Union introduced the Interoperable Europe Act aiming to strengthen data sharing in the public sector. This aligns with EU's Digital Decade, targeting to make all public services accessible online by 2030 (European Commission, n.d.). The Swedish Agency for Digital Government (swe: *Myndigheten för digital förvaltning* [Digg]) released a similar framework for digital cooperation (swe: *Svenskt ramverk för digital samverkan*), which focuses on facilitating data sharing in Sweden (Digg, 2023). Shared data is crucial in driving innovation and establishing a connected city. It serves as the foundation for developing a 3D city model that recognizes its dependencies and integrates geospatial, energy, real estate, infrastructure, environmental, legal and Internet of Things data etc.

Application-centric

Today an application-centric approach is a common way of handling data in organizations, each application contains and produces its own data. Most large organizations don't use one data model; instead, each application has its own and with thousands of applications developed internally and purchased externally they end up with many different data models (McComb, 2019). These models are not simple and much more complex than they need to be, making integration, sharing and reuse of data in the organization a very challenging and difficult process (Figure 2.1).

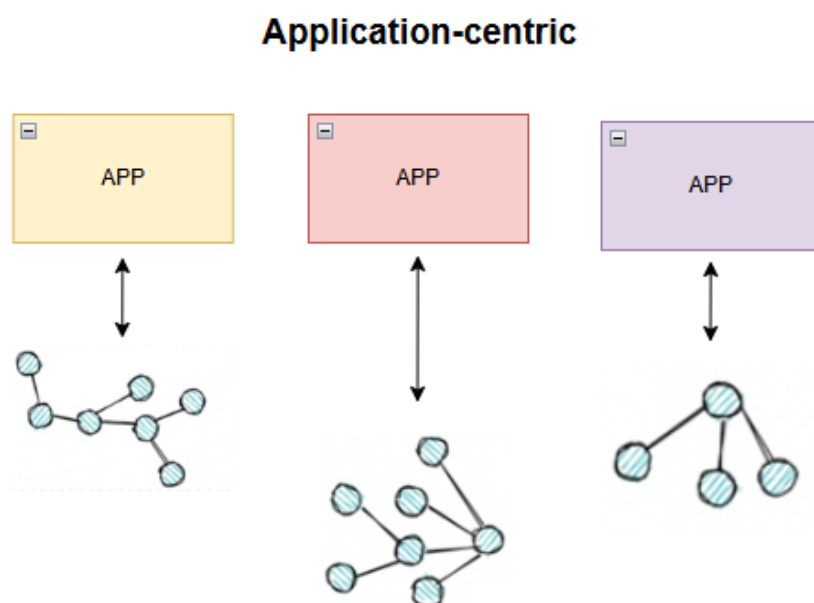


Figure 2.1: Application-centric approach, each application contains and produces its own data.

Data-centric

A data-centric approach sets the data at the center of the organization with a common core data model for shared functionalities. In a data-centric context, a data model focuses primarily on the meaning of data (semantics), only secondarily on the structure, constraints and validation to be performed on the data (McComb, 2019). Data is independent of applications and can be extracted to handle the different needs of the organization (Figure 2.2).

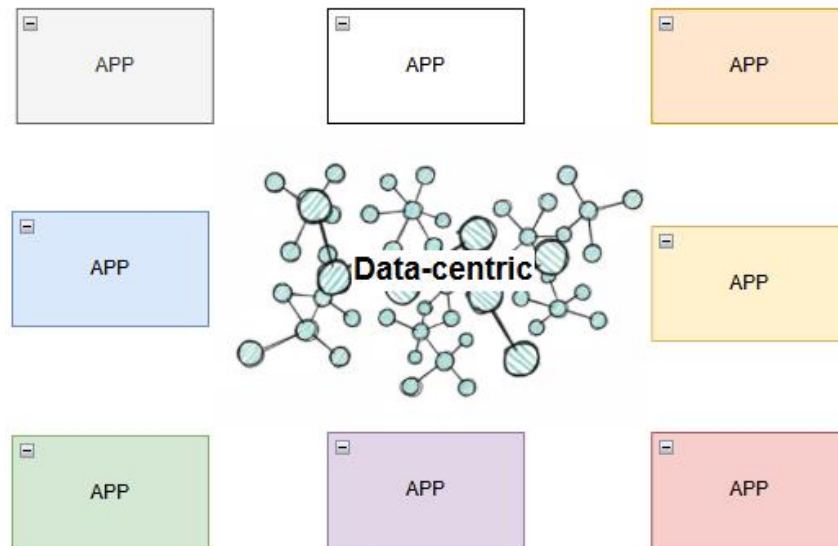


Figure 2.2: Data-centric approach, representing a common data model for shared functionalities. Here, data serves as a permanent, centralized "hub" while applications act as interchangeable "spokes"; this independence allows data to be securely extracted.

In a data-centric organization, data serves as a lasting shared asset, while applications may be replaced over time. When applications do not meet organization's needs, they are changed to new ones extracted from the common data model. Using this approach there is a minimum of data conversion and all analytics and systems will continue to work seamlessly in the organization when an application is replaced (McComb, 2019). This approach to handling information aligns with the FAIR principles, explained in section 1.1.

An initiative towards placing data at the center of every organization is the data-centric manifesto, moving away from enterprise IT systems that are complex, expensive and siloed (McComb, 2019). Striving to facilitate good data management and to drive cost efficient innovation in all sectors the data-centric manifesto states that:

"The problem, at its core, is that we have allowed applications exclusive control over the data they manipulate." (Data-Centric Manifesto, 2015, the need section)

2.2 Digital Twins

The term "digital twin" is used in many sectors, during the last decade the concept has gained attention in urban development. The digital twin technology was introduced in the late 20th century by the manufacturing industry where it is used to visualize and simulate behavior of products and systems. With technical development, capabilities for more complex functions have been added, such as analysis and simulation (Ketzler et al., 2020). With many use cases and applications varying definitions of the concept can make it challenging to comprehend (Biljecki et al. 2015). However, some fundamentals are outlined by Trauer et al. (2020, p.761):

“A Digital Twin is a virtual dynamic representation of a physical system, which is connected to it over the entire lifecycle for bidirectional data exchange.”

Urban digital twins consist of interconnected data sources and make connections to data-centric solutions possible. To provide spatial context for the data a virtual representation is required to act as the geometric backbone. The urban digital twin reflects the physical world, where 3D city models serve as a model for integrating and simulating the connected data (Batty, 2018). Dynamic and connected 3D city models are at the core of this study.

2.2.1 3D City Models

A 3D city model or digital twin for cities is a representation of a city environment that incorporates three-dimensional geometries of urban structures, with buildings serving as the primary feature. These models are today mostly based on data from photogrammetry and laser scanning, but several other data collection techniques can be combined to create a digital representation that is as realistic as possible for user's specific needs (Biljecki et al. 2015).

The first 3D city models were mainly used for visualizing urban environments in city planning projects. Today there is a need for more complex functionalities like analysis and simulations and as technology develops and models become more sophisticated this becomes the reality. Models are becoming object oriented with semantic information, this means that they consist of several individual objects which have their own attributes, the structure is semantic and describes how objects relate to each other (Uggla et al., 2023).

3D city models are static digital replicas of a city, containing varying levels of detail and therefore not complete dynamic digital twins. These models are simplified and tailored for the project application (Batty, 2018). A model based on the CityGML standard is semantic and offers methods for modeling a combination of static 3D city data with dynamic connected information. The model allows users to alter how they use the 3D city model through data connections. By linking external databases or real-time sensors, users can dynamically shift the model's purpose from a visual map to an analytical tool. This makes it possible to simulate and analyze environment, energy, noise etc. (Uggla et al., 2023). This is fundamental for integrating and analyzing data from different systems to support decision-making throughout the urban development process, the models also facilitate insight from analyses through visualization in 3D.

2.2.2 CityGML

CityGML is a global standard for semantic 3D city models developed by the Open Geospatial Consortium (OGC). It is a conceptual model that outlines a standardized way to represent, store and exchange digital and virtual 3D data (Kolbe et al., 2021). The standard provides a common, foundational definition for the basic entities, attributes and relationships for connected 3D city models. Achieving a uniform definition is essential for sustainable, cost-efficient management and reuse of data across different applications. Today most projects and applications for digital twins use this standard, it was officially adopted in 2008 and version 2.0 released in 2012 was recognized as a global standard. CityGML is continuously being developed and is currently at version 3.0. Technically it is defined as an application schema of Geography Markup Language (GML) that is adapted to exchange and modify geographic information together with web services. The model defines key physical objects and focuses extensively on their mutual relationships. GML is developed to store and exchange geographic information and is an extension of eXtensible Markup Language (XML) (Gröger & Plümer, 2012). The standard enables the implementation of a Spatial Data Infrastructure (SDI) across various industries and organizations. It is widely used for its semantics and corresponding ontology in urban development enabling analysis and visualization in urban planning, disaster management, emergency responses, energy usage etc. (Kolbe et al., 2021).

Since 3CIM the Swedish digital twin extension is based on CityGML version 2.0, all references in this work are to this version unless otherwise specified.

Structure

CityGML covers all relevant features included in the city development process, these are defined by semantic definition, attributes, relationships and 3D spatial representation. They are organized into thematic modules such as the building, transportation, vegetation, bridge etc., these can be combined for specific applications, identified as profiles. At the foundation of CityGML is the core module that consists of common attributes and properties for objects, regardless of thematic module (Figure 2.3). The core module is mandatory as it contains fundamental concepts and properties for the CityGML implementations to function (Gröger & Plümer, 2012).

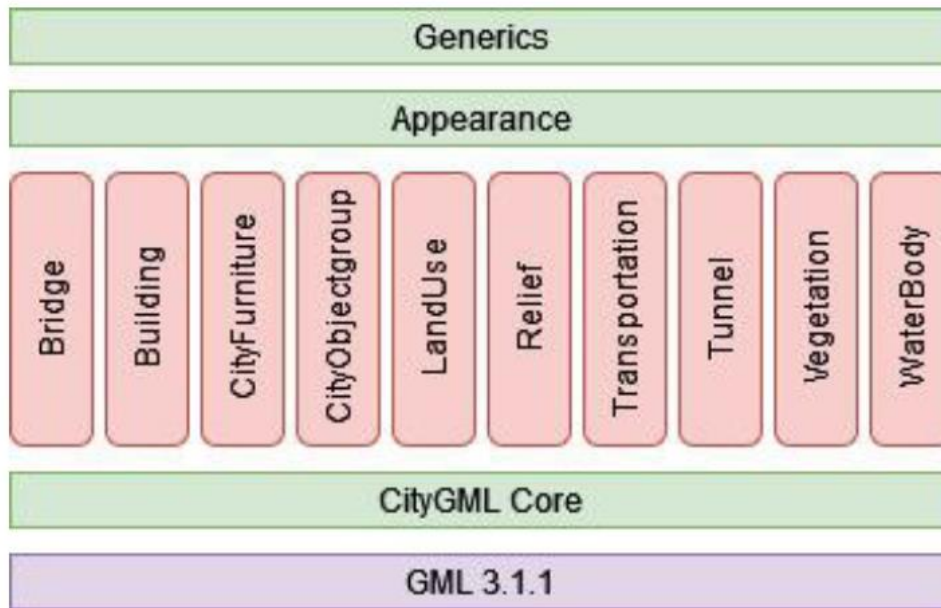


Figure 2.3: Modules in CityGML 2.0. the Core module as foundation and thematic modules as verticals. Updated figure based on Kolbe (2009).

Conceptual model

The conceptual model in CityGML is described using a Unified Modeling Language (UML) diagram, Figure 2.4 shows a simplified example. It is a language developed to provide system architects, software engineers, and developers with tools necessary for modeling processes, implementation of software-based systems, design and analysis. One of its primary goals is to enable a visual modeling tool for interoperability, this is possible through the agreement on semantics and the syntax that UML provides (Object Management Group, 2025). The graphical language efficiently handles object-oriented needs in complex urban modeling. It provides a straightforward way to visualize the modules, objects and hierarchy of the CityGML standard (OGC, 2012). The conceptual model can have several implementations, in CityGML version 2 the standard is XML/GML. In version 3.0, the underlying information model has been standardized, allowing for implementation using additional technologies. One notable format is CityJSON, an official OGC standard, recognized for its compact structure and user-friendly design encoded in Java Script Object Notation (Ledoux et al., 2019). In this thesis semantic and interoperable knowledge graphs are used, developed by converting the CityGML model with Web Ontology Language (OWL), explained in chapter 2.4.2

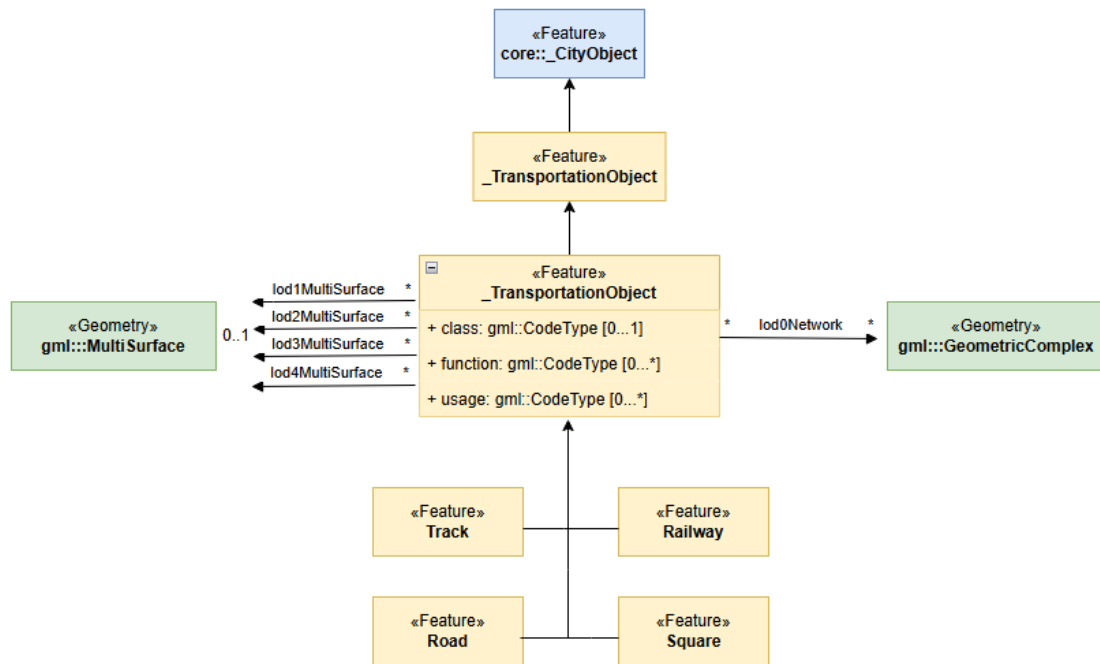


Figure 2.4: Simplified UML diagram of CityGML with notation and a color scheme, where yellow represents the Transportation module, blue the Core module, and green represents geometry elements defined in GML (OGC, 2012).

Level of Details

One of the strengths of the CityGML model is its ability to describe objects in different Levels of Detail (LoDs). It is a foundational design in the core module and is implemented through the thematic modules (Figure 2.3). It's a multiscale representation where geometric details and semantic complexity increase at each successive level. These levels allow a single information model to visualize 3D city models with varying degrees of detail, which enables the model to be inherently flexible. Eliminating the necessity for multiple models each covering an individual LoD (OGC, 2012). Figure 2.5 shows the five different LoDs for the Building module: LoD0 the least geometrically and semantically detailed representation, utilizing 2D footprints for buildings, alongside a 2.5D surface to model non-volumetric features like digital terrain models, land use classifications, and transport networks. The LoD1 model represents buildings as simple prismatic blocks that are generated by extrusion of 2D footprints for buildings and other urban objects. LoD2 extends the object's exterior into thematically distinct boundary surfaces like walls, roofs and ground. LoD3 is the most detailed representation of the exterior geometry and semantics of an object, incorporating architectural features like doors, windows and complete roof structure etc. LoD4 is the most detailed, modeling the objects internal structure as well detailed external features of LoD3 (Gröger & Plümer, 2012).

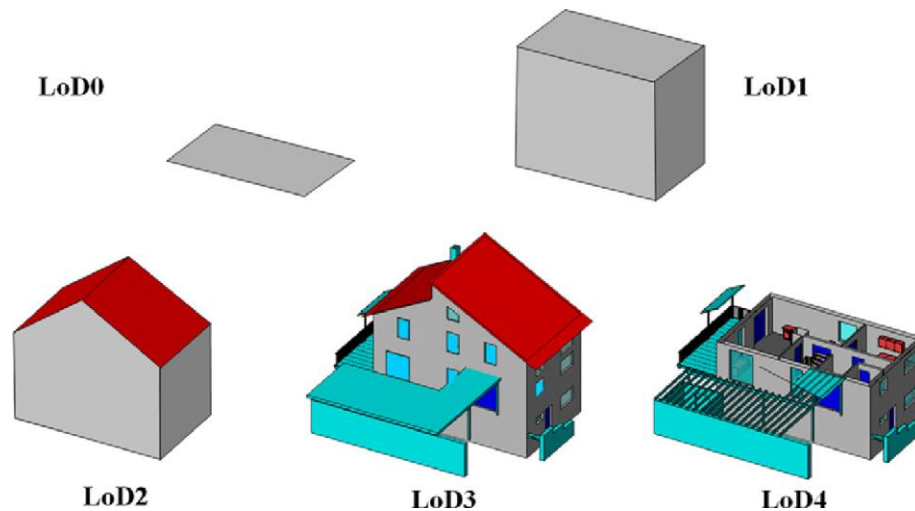


Figure 2.5: Visualization of the five LoDs in CityGML 2.0 (Gröger & Plümer 2012).

Extension of CityGML

Application Domain Extension (ADE) allows the conceptual model of CityGML to be extended for a particular application or domain. This extension is developed in the form of an XML schema in CityGML version 2.0 and as UML conceptual model in CityGML version 3.0, both methods make it possible to add a new schema, with its own namespace, where new classes and additional attributes can be added to the already existing classes. This means it is possible to adapt the model to the needs of the CityGML application while keeping its concepts and semantic structures. The difference to a generic city model and its attributes is that data can be validated against an ADE structure to guarantee interoperability (Kolbe et al., 2021).

The reason for development of ADEs in CityGML is the need for additional information in different geographic contexts and software applications that the universal CityGML standard cannot provide. It is an instrument for enriching the data model with new classes and attributes, while keeping the semantic standard (Biljecki et al., 2018). It can be used to extend national models like the Swedish 3CIM for developing digital twins. Several other countries have established national specifications using ADEs, including the PLATEAU project in Japan (Seto et al., 2023) and IMGeo in the Netherlands (Van den Brink et al., 2013) Other examples are industry use cases like the Energy ADE developed by European organizations to establish an open standard for urban energy modeling to ensure data interoperability (Agugiario et al., 2018).

CityGML is constantly being developed and evaluated. ADE functionality may be integrated into the standard, examples of this are the Tunnel and Bridge ADEs. They were developed alongside version 1.0 and integrated into version 2.0, this proves that widely used and well documented ADEs may be approved by the OGC and incorporated into the CityGML standard (Biljecki et al., 2018).

CityGML Transportation module

To the extent of this thesis the transportation module is used, it represents semantic and geometric transportation features within a city, like for example roads, tracks,

railways, or squares (OGC, 2012). Figure 2.6 shows a UML-diagram of Transportation module.

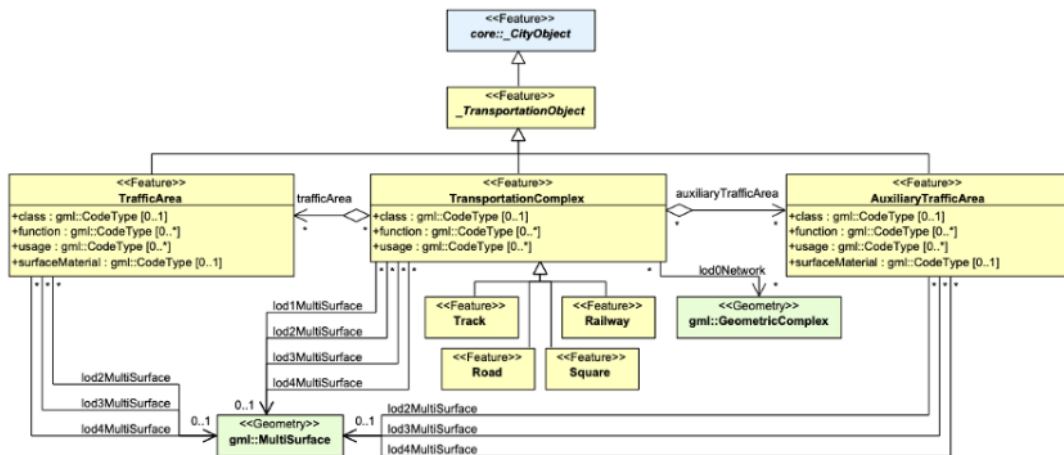


Figure 2.6: UML-diagram of transportation module in CityGML 2 (Gröger & Plümer, 2012)

The Transportation module connects to the CityGML Core module through the root class *CityObject*. *CityObject* has the subclass *TransportationObject*, which describes the rest of the transportation model with subclasses: *TransportationComplex* describes the road itself using subclasses for *Track*, *Road*, *Railway* and *Square*. *TrafficArea* describes traffic usage, like car driving lanes, cycle lanes and pedestrian zones. *AuxiliaryTrafficAreas* describes additional road components, such as curbstones, median lanes, and green areas (OGC, 2012). Figure 2.7 visualizes the different parts.

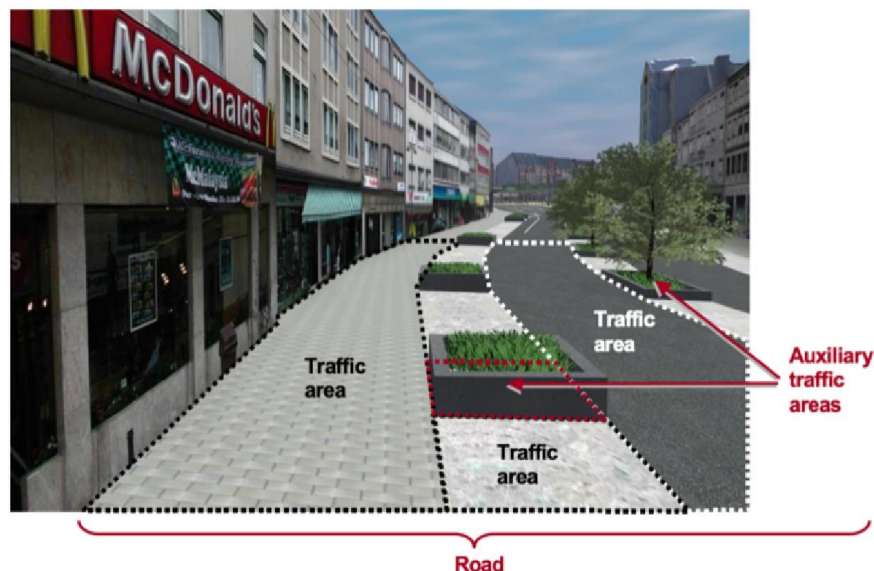


Figure 2.7: Visualization of *TrafficArea* and *AuxilliaryTrafficArea* in the Transportation module (OGC, 2012).

The Levels of Detail in the model are categorized into LoD0, LoD1, and LoD2-4 merged as one. LoD0 model roads by line objects that follow the centerline of the

road without any area, it is geometrically very simple and can be used for topological tasks like network analysis (OGC, 2012). Lod1 model roads with the *TransportationComplex* class, which gives the objects a geometry of the extent of all the road space. The LoD2-4 representation models the roads by additionally subdividing them thematically into *TrafficAreas* and *AuxilliaryTrafficArea*, providing a more detailed description of the road space as *roadway*, *parking area*, *sidewalk*, *green area*, etc. Figure 2.8 visualizes the different Levels of Details in the transportation module.

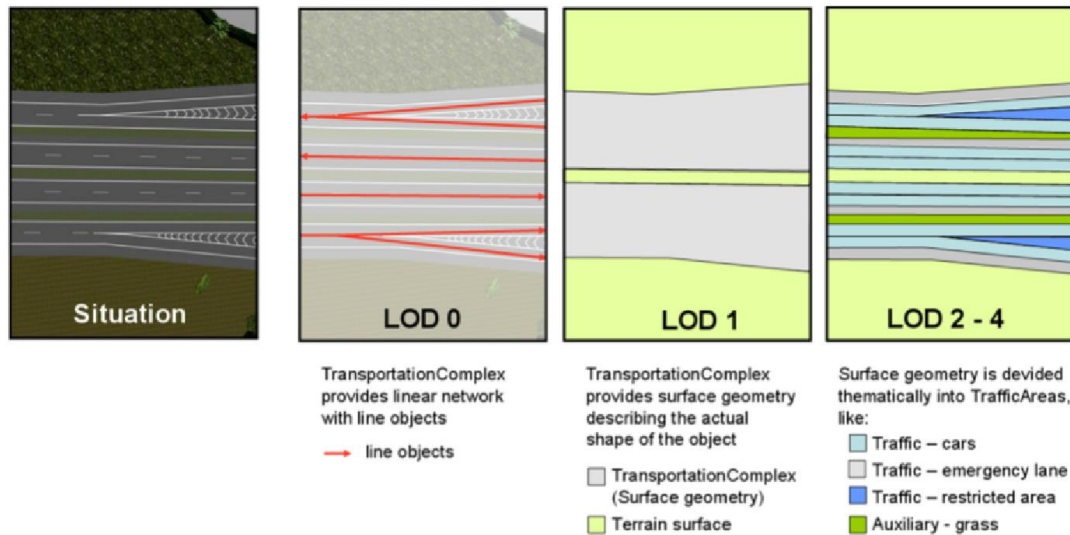


Figure 2.8: Visualization of Level of Details (LoD) in the Transportation Module (OGC, 2012).

2.2.3 3CIM

3CIM is a CityGML ADE built by Sweden’s largest municipalities (Stockholm, Gothenburg and Malmö), and Lund University, designed to support the development of dynamic 3D city models. It is based on CityGML version 2.0 because the 3.0 was not released at the time of the project start. It was built because CityGML alone was not sufficient for internal and external application needs in the Swedish municipal context (Uggla et al., 2023). 3CIM is a semantically thin model that aligns with the CityGML model with some additions. Building a semantically rich model would require extensive work keeping up to date, because of this it was not an option. Instead, the extension facilitates connections to external sources for its semantic information, this way information doesn’t have to be stored twice (Smart Built Environment, 2025c). Examples of external sources that can be connected are building permit system, cadaster system and registers like the national road database (NVDB) etc. (Figure 2.9). This setup facilitates data updates and storage while explicitly aiming to eliminate data redundancies between systems (Uggla et al., 2023). Being an ADE model, it has the same structure as CityGML with the Core module and different thematic modules described previously in Figure 2.3.

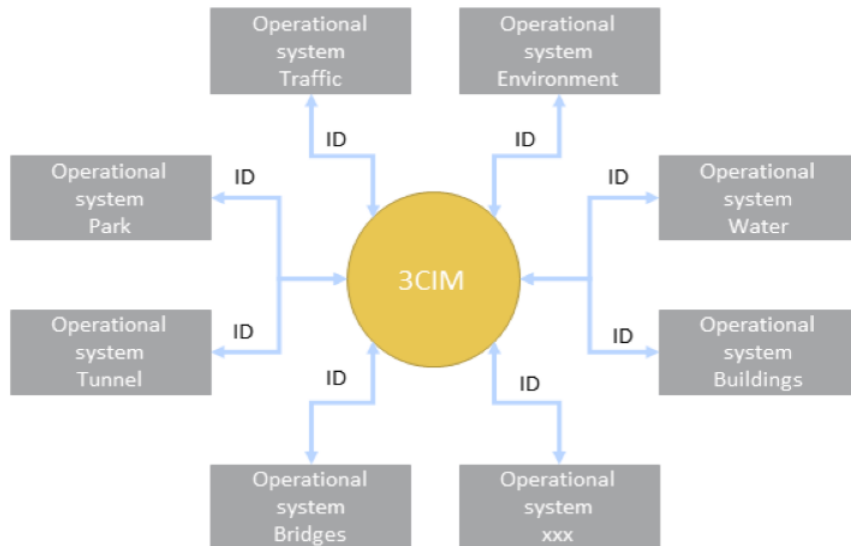


Figure 2.9: 3CIM with external data sources (Uggla et al.,2023).

Linking to external data with 3CIM

3CIM links to external information sources through the CityGML Core module and the feature *CityObject* using the functions *ExternalReference* and *ExternalObjectReference* (Figure 2.10). These functions allow the model to connect to external semantic information, transforming the model into a dynamic 3D city model by accessing external systems and databases (Uggla et al., 2023). Being part of the CityGML Core module all 3CIM objects have this functionality. Each object in the *ExternalReference* function contains a Uniform Resource Identifier (URI) that links to a source with the same URI in the external systems or databases (OGC, 2012).

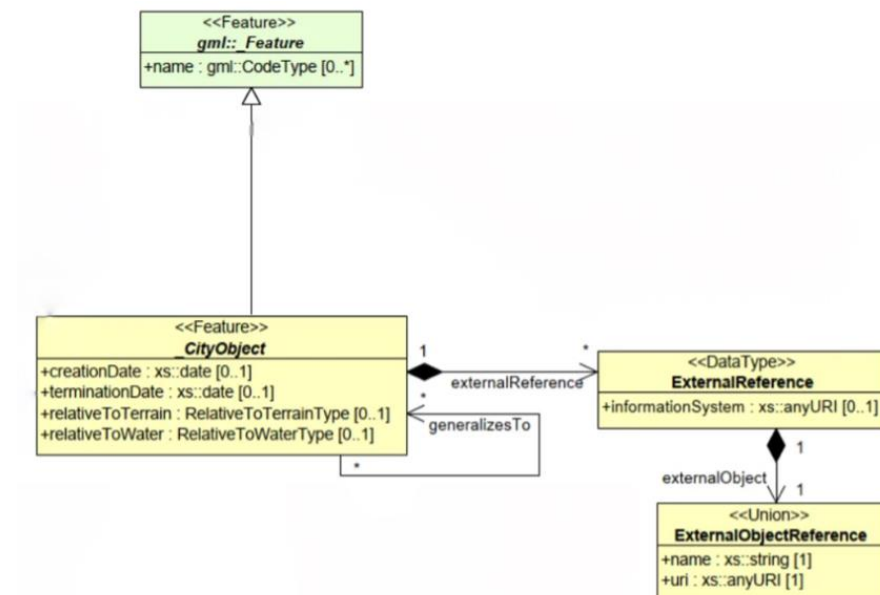


Figure 2.10: Simplified UML diagram describing the core feature *CityObject* and the functions *ExternalReference* and *ExternalObjectReference* with URI connection for external sources (Uggla et al., 2023).

Transportation module in 3CIM

The 3CIM transportation module differs in part from the basic CityGML version 2.0 structure (UML-diagrams in appendix A Figures A1 and A2). The module limits the Levels of Detail used to only include LoD1 to LoD3. The module is not intended for network analysis, this means that roads are not represented as lines, the only exception is railways. Transportation road surfaces are described as multisurface geometries, LoD1 has the same structure as CityGML version 2.0, while LoD2 and LoD3 use the structure of CityGML version 3.0, with sections and intersections surfaces (Figure 2.11) (Uggla et al., 2023).

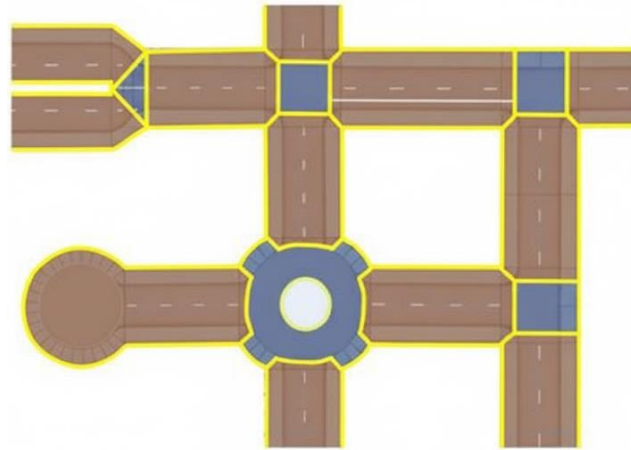


Figure 2.11: Visualizations of sections in brown and different types of intersections in blue CityGML version 3.0 (Beil et al., 2020).

A *section* is defined as a segment of a road object and an *intersection* is defined as a separate feature type to model complex areas where two or more transportation objects meet and where traffic flow changes (Kolbe et al. 2021). When belonging to the same road they share a linking attribute to that road. The size of the area being considered as an intersection can vary depending on the specific application requirements and if area calculations are to be done on road sections this need to be considered. In the subclasses *TrafficArea* and *AuxilliaryTrafficArea* surfaces are divided further into smaller sections to assign more detailed functions to the subsections in different LoDs. Surfaces get specific functions when divided and intersections get separated into specific classes, this way redundancy can be managed and reduced (Figure 2.12) (Beil and Kolbe, 2020).

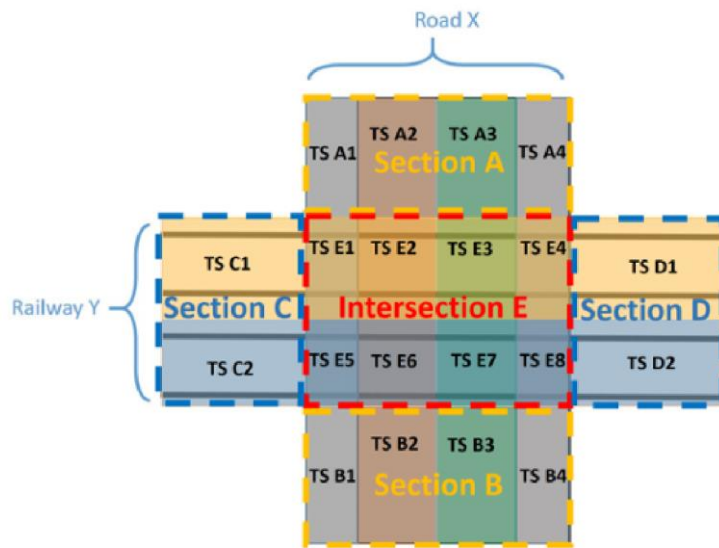


Figure 2.12: Divided intersection between Road X and Railway Y (Beil and Kolbe, 2020).

As shown in Figure 2.12, instead of representing the intersection in both X and Y, which would be redundant, the intersection surface E can now be represented independently as a linking feature between X and Y. Each transportation types is represented: Road X consists of three sections: Section A, Section B, and Intersection E. Railway Y also consists of three sections: Section C, Section D, and the same Intersection E. Road X and Railway Y are subdivided into *TrafficArea* surfaces, and the surfaces that exist in the intersection are all included in E to manage redundancy.

The creation of subsections using the CityGML version 3.0 transportation structure (Kolbe et al. 2021) enables an efficient link to the National Road Database (NVDB), where roads are described as road links (swe: *ReferensLänk*) and directly connect to a corresponding 3CIM section (Figure 2.13).

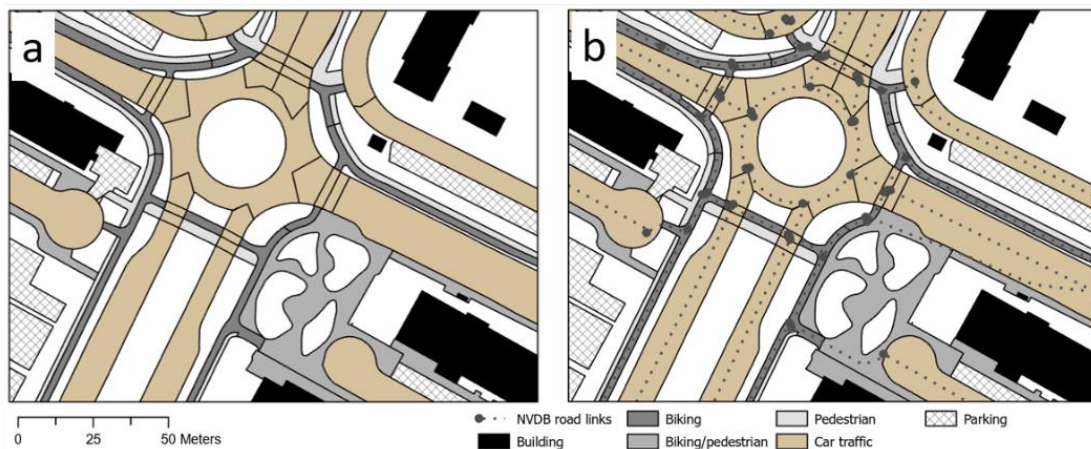


Figure 2.13: Visualization of traffic areas from the transportation theme according to 3CIM without (a) and including (b) the road links from NVDB (Uggla et al., 2023).

All transportation surfaces follow the hierarchical structure of CityGML version 2.0 including attributes like *class* and *function*. In 3CIM the attribute *class* is used for *TransportationComplex*, *AuxilliaryTransportArea* and *TrafficArea*. It describes what *class* the object belongs to (e.g. sections of a road). The attribute *function* is used only for *AuxilliaryTransportArea* and *TrafficArea* where it specifically describes the surface (e.g. a driving lane or footpath). Both attributes are described with a five-digit code specifying the different LoDs (Figures 2.14 and 2.15). Most data type, attribute and code list names are kept in Swedish, since accepted English terms have not yet been developed within the 3CIM project.

TransportationComplex TrafficArea		TrafficArea		TrafficArea	
Class		Function		Function	
LOD1 – LOD3		LOD2		LOD3	
10000	Vägtrafik	10100	Körbana	10101	Bilväg
				10108	Gågata
				10113	Korsning
		10200	Gångväg	10201	Trottoar
				10202	Stig
				10204	Övergångsställe

Figure 2.14: Hierarchical structure for *TrafficArea*, the different LoD levels for *class* and *function* (Smart Built Environment, 2025b). (See Appendix B for the English translation).

TransportationComplex AuxilliaryTrafficArea		AuxilliaryTrafficArea		AuxilliaryTrafficArea	
Class		Function		Function	
LOD1 – LOD3		LOD2		LOD3	
10000	Vägtrafik	10100	Vägren	10101	Mjuk vägren
				10102	Hård vägren
				10103	Dragväg
		10200	Separering	10203	Mittenfil
				10204	Refug
				10205	Mittremsa

Figure 2.15: Hierarchical structure for *AuxilliaryTrafficArea*, the different LoD levels for *class* and *function* (Smart Built Environment, 2025b). (See Appendix B for the English translation).

2.3 National road database

The Swedish national road database NVDB (swe: *Nationell Vägdatabas*) is developed and maintained by the National Transport Administration (swe: *Trafikverket*) since 1996. It was developed on government mandate by the Traffic authority, Municipalities and Regions, forest industry, National Land Survey and Transport Agency. All these Swedish organizations maintain data that is important for keeping the national road network updated. The classification of the data is conducted based on an ontology developed from the ISO 19148 (Linear Referencing) standard and the INSPIRE Transport Networks schema, offering a structured framework for representing Swedish road attributes (Trafikverket, 2012). The database consists of all roads (pedestrian, bicycle and motor vehicles). The NVDB information model

consists of two parts: The first part is the road network, which describes how the roads stretch through the landscape and how they are connected. It maps the topological (nodes) and geometrical properties (reference lines) of the traffic system. The second part are attributes that describe the roads assets and constraints. For example, information about road width, permitted speed, road name and load-bearing capacity etc. (Trafikverket, 2024).

NVDB road network

The road network model is based on an abstract object class called *NätElement*, which represents road segments within a system, and it is composed of reference links (swe: *ReferensLänk*), nodes (swe: *NätNod*) and a network (swe: *Nätverk*). Figure 2.16 depicts the UML-diagram describing the model (Trafikverket, 2021). The reference link is the most important concept of the model, it is used to represent parts of connecting road segments within the road network, it has a length, a location and ports. This entity topologically represents a road segment that is stored in the database. Nodes are defined as start and end points for reference links, a node can be placed anywhere on a reference link. Ports are a type of connectors for different network elements (swe: *NätElement*) and define a point on the reference link that can be connected to the rest of the road network. Even if a reference link becomes invalid, it remains permanently stored in the database to ensure traceability. Reference links can be divided into parts, specifying which segments of the link are valid and in use. This makes mapping of active and inactive reference links and their parts possible in the road network (Trafikverket, 2024).

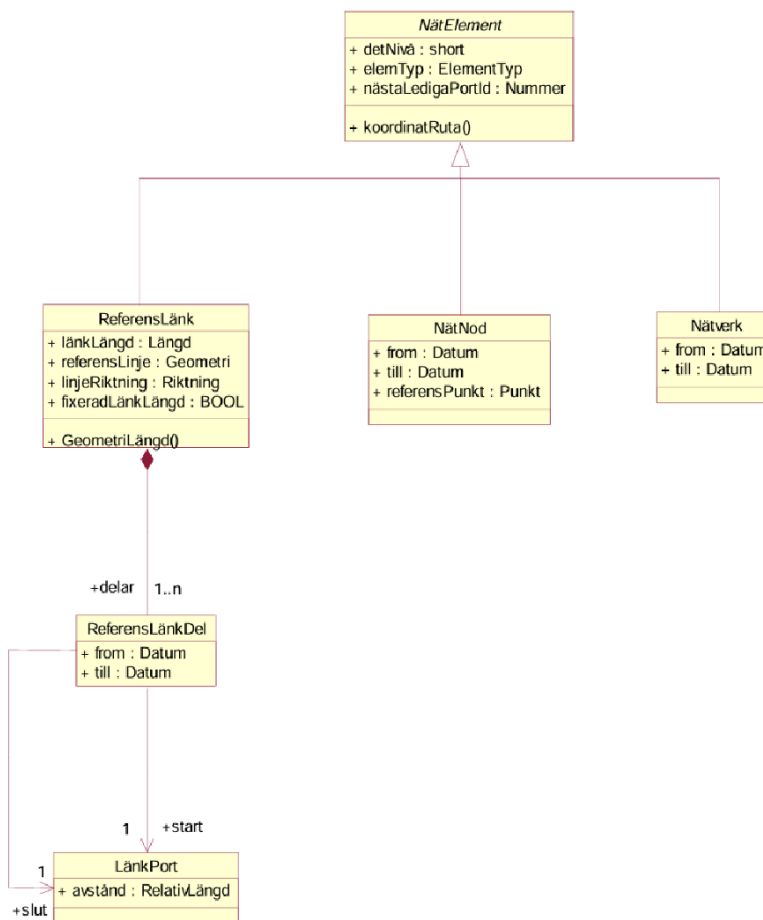


Figure 2.16: UML-diagram for NVDB road network model (Trafikverket, 2024).

In Figure 2.17 a more detailed description of reference links in the road network model is visualized. RL1 and RL3 are two reference links, the red nodes are start and endpoints but also connection nodes to other reference links in the model. There are four ports (P1, P2, P3, P4) that connect the links for geometric reasons (Trafikverket, 2021).

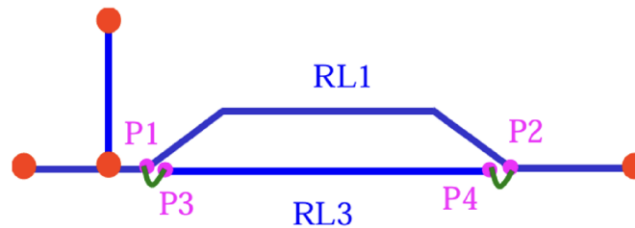


Figure 2.17: Example of reference links including nodes and ports in the NVDB road network model (Trafikverket, 2021).

NVDB Road information

Describing road information attributes like width, permitted speed, road name and load-bearing capacity is an essential part of the NVDB information model. It is handled through feature types (swe: *Företeelsetyper*) and features (swe: *Företeelse*). A feature type can have zero or several attributes that describe the characteristics of the features that are associated with the road network. A description can be found in the data product specifications, where the feature types and their features (attributes) are defined (swe: *Trafikverket, Dataproduktspecifikationer, Vägdata*). The connection to the road network is done by giving the feature a spatial extent on the road network and linking it to a reference link object identity. The spatial extent is defined as a distance relative to the starting point of the reference link (Trafikverket, 2025). An example to illustrate this: The maximum speed on E4 north of Stockholm is 100 km/h and 70 km/h on two different road sections; they are the attribute values of two different features belonging to the feature type Speed Limit.

2.4 Semantic Web Technologies

The semantic web builds on the current web by adding clear definitions to information, making it easier for both computers and people to collaborate effectively. The creator of the World Wide Web Sir Tim Berners-Lee developed this concept in the end of the 90s, a network of standardized data that machines can interpret to understand and link related information (Berners-Lee et al., 2001). To enable the creation of a web with linked data the World Wide Web Consortium (W3C) has developed open standards: Resource Description Framework (RDF), Ontology Web Language (OWL), and SPARQL query language. These technologies let users develop explicit data semantics by describing data vocabularies, defining logic and processing rules and establishing web-accessible data storage. Together, these standards enable the creation of formalized ontologies, providing a flexible framework for the data management of the linked web (W3C Semantic Web 2025).

While these standards provide general guidelines, the need for detailed implementation is evident and related work to address this is currently ongoing. To

address this, Digg released a more detailed framework for implementing knowledge graphs called INSPEC (swe: *Profil för interoperabla specifikationer*) (Digg, 2025). The exact role of knowledge graphs in organizing public sector data, particularly within 3D city models, remains an interesting area of research. This thesis contributes to the ongoing national and international research, by providing real world example and evidence on how to implement Semantic Web Technologies into the urban development in Stockholm, Sweden.

2.4.4 Knowledge graphs

The general definition of a knowledge graph is data intended to collect and represent knowledge of the real world in a graph (Hogan et al., 2021). In contrast to traditional relational databases, which view data as rows in a table, a knowledge graph sees the world as it is; a network of interconnected objects with relations. In a graph-based data model, nodes represent entities and edges indicate their relationships. An ontology provides a structured description and representation of a specific field, facilitating the sharing of knowledge in an accessible format. A UML model can be used to create an ontology, but adjustments are usually needed to follow the standard of the semantic web. The combination of RDF and OWL languages enables the development of a standardized ontology model. An example of a knowledge graph using flight data is visualized in Figure 2.18. To be effective, the model must be comprehensive and broadly accepted. Graphs that have shared ontologies will have greater interoperability (Hogan et al., 2021).

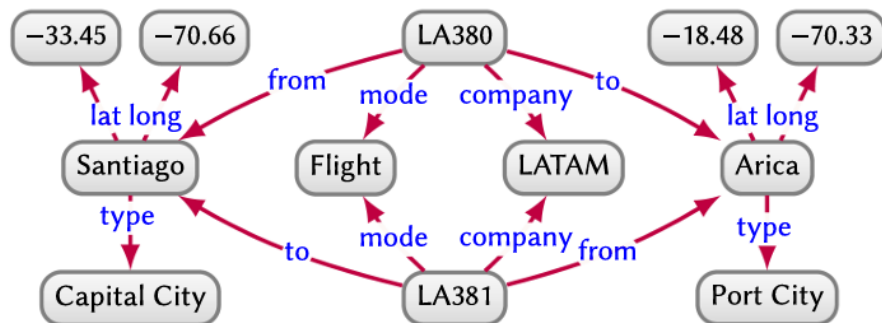


Figure 2.18: Knowledge graph example using Flight data (Hogan et al., 2021). Expressed as a *del graph* with RDF triples and unique IRI. Examples of triples: *Santiago is a Capital City, Arica is a Port City, LA 380 from Santiago, LA380 to Arica. LA380 company LATAM, etc.* (see Section 2.4.1 for a description of *del graph*)

2.4.1 RDF

To develop knowledge graphs structures, RDF serves as a core framework representing web-based resources. Structurally, it is implemented as a directed edge-labelled graph (*del graph*) where modeling defines a set of nodes with labelled edges between them, representing binary relations. A foundation of the development is the creation of RDF triples that uses subject, predicate and object to outline the relations between the nodes, it is very similar to how a language form sentences. An example to illustrate this in Figure 2.19: *TransportationComplex X* has part *Road Y*. RDF

defines the three node types as Internationalised Resource Identifiers (IRI) and they are used to outline the principal entities and the relations between them (Hogan et al., 2021). Each IRI is a globally unique identifier in a graph model that describes resources (W3C RDF, 2014). An IRI is an extension of URI that is referred to in the section 2.1.3 about 3CIM. Triples are composed of entities containing diverse datatypes such as integers, dates, and strings etc. (Hogan et al., 2021).

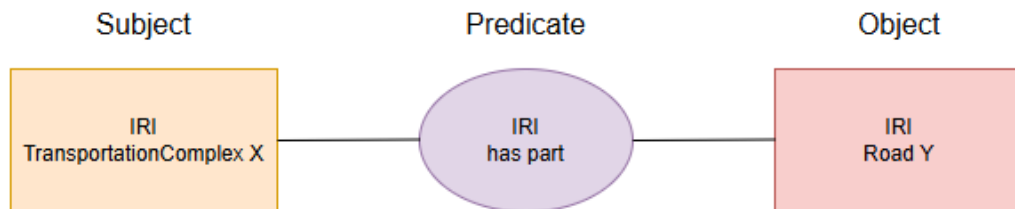


Figure 2.19: Tripple with subject, predicate and object. Each resource with a unique IRI.

2.4.2 OWL

OWL is a semantic web language designed to capture rich and complex knowledge concerning resources, their classifications and the relations connecting them. The language is based on RDF for creating ontologies including more advanced functionality. By first creating OWL ontologies and then applying profiles onto them, it is possible to handle data depending on project requirements. One important functionality is the ability to add restrictions to different parts of the data model such as constraints, class hierarchies, and logical relationships. Which enables semantic reasoning to automatically detect logical inconsistencies within the data (OWL Working Group, 2012).

2.4.3 SPARQL

SPARQL is a query language defined by the structure and semantics of the RDF framework. It supports queries like union, filters, value aggregation, path expressions and nested queries. The language has four distinct query forms and can generate results as tables (SELECT, ASK) or as triples (CONSTRUCT, DESCRIBE). It enables querying a wide range of data resources, regardless of whether it is stored in native RDF format or accessed as RDF through middleware (W3C SPARQL, 2013).

GeoSPARQL

GeoSPARQL is an extension to SPARQL developed by the OGC (OGC, 2024). Enabling spatial querying for the semantic web, to answer questions about where things are in relation to each other, not just what properties they have. It adds essential tools for spatial analytics and geospatial data interpretation (Battle & Kolas, 2012). While SPARQL only can compare numbers or text, GeoSPARQL adds functions for spatial relationship queries like within, intersect, overlaps and distance etc. It also includes an RDF/OWL ontology (technical vocabulary) that specifies how geospatial data is to be handled in an RDF graph, defining if the object has a geometry and coordinates for different geometries.

2.5 Semantic web technologies and geospatial data

In many organizations an effective SDI faces difficulties due to data silos (Huang et al., 2019). Geospatial data is frequently isolated from other information, connecting this information is a critical component of modern data architecture. Linked spatial data provides means to solve this, semantic web technologies address this by providing a language and framework. The increasing complexity of spatial data integration across organizations in Europe has driven interest in linked spatial data and knowledge graphs as transformative technologies. These techniques can enhance interoperability, especially when spatial datasets are isolated (Bucher et al., 2021). For example, by integrating Building Information Models (BIM) “which provide detailed digital representations of the physical and functional characteristics of buildings” with geospatial data into knowledge graphs, a solution of semantic web technologies and domain ontologies becomes possible (Huang et al., 2021). This integration addresses a fundamental challenge in urban development by bridging the gap between architectural data and geographic contexts, acting as a foundation for a dynamic city model.

Data-centric approach for interoperability

A shift from working application-centric to data-centric defines a core paradigm of a modern data architecture. Combining knowledge graphs with a data-centric strategy creates a robust architecture that tackles issues with data silos that have been developed over time, eliminating Extract Transform Load (ETL) data conversion required by legacy systems with relational databases. The implementation and value of this approach is described by Buchmann et al. (2021). It shows that this approach enables flexible data integration to support decision making, conflict of interest detection and that linking data to other applications are facilitated. The technology to build knowledge graphs based on standards for a semantic structured data model is described in detail in section 2.4.

Real world examples

The Netherlands and Belgium have combined the governance framework and semantic linked spatial data into their data architecture, this approach enhances data quality, promotes reuse, and improves connectivity ((Bucher et al., 2021). The Flemish OSLO (flemish: *Open Standaarden voor Lokale Overheden*) project, which is built on open standards, is particularly relevant because it shows how a semantic framework can be used, linking spatial information such as land parcels, buildings and roads in the city infrastructure. A real test of this architecture has been conducted on road networks to support specific needs e.g. in Emergency Vehicle Priority (Bucher et al., 2021; Be-Mobile, 2022).

In Germany, the Federal Agency for Cartography and Geodesy has investigated how to manage the bicycle network through integration of geospatial datasets in knowledge graphs (Ponciano et al., 2025). Through the development of the application and platform SPALOD (Spatial Data Management with Semantic Web Technology and Linked Open Data) that integrates various datasets and identifies missing information. The creation of ontologies introduces structure and standardization to the field of cycling infrastructure. The platform tackles the issue of fragmented data in different systems; it highlights the practicality and benefits of using semantics and ontology to get structure within geospatial applications. The platform provides a scalable way to

harmonize and enhance spatial information related to bicycle networks.

In Finland, the *Helsinki Energy and Climate Atlas* offers comprehensive data on heating demand for individual buildings in a web map (Rossknecht and Airaksinen, 2020). It is a central component of Helsinki's strategy to achieve carbon neutrality by 2035 and makes it possible to track the city's development. Technically it is an integrated 3D city model using CityGML and the Energy ADE extension to provide linked updated energy information based on a standardized data model stored in 3DCityDB. Implementing a standardized data-centric approach has removed interoperability problems that were consistent in early versions of the application that relied on fragmented datasets.

These findings provide strong evidence that handling spatial data through semantic integration in knowledge graphs to support decision making in organizations is both beneficial and realistic.

3. Case study - Stockholm Traffic Administration Office

The Stockholm Traffic Administration Office is responsible for managing the city's traffic infrastructure. To achieve this, the office systematically collects and generates extensive spatial and operational data. This case study was developed in collaboration with the office to evaluate if they can plan and manage road space in a more efficient way by adopting a data-centric approach.

The case study examines whether a CityGML-3CIM city model expressed as knowledge graph can function to support road maintenance. This standardized, data-centric approach aims to include similar data content as in the current operational tool. To achieve this a Knowledge graph-based tool (KGBT) is designed and developed.

Dorothy Furberg and Josefin Isaksson have demonstrated the office's current operational and asset register system, TK Gata. Screenshots and data from the application are utilized in the following chapters to illustrate the current system requirements.

3.1 Workflow

The case study is conducted in three steps.

1. Requirement of a KGBT

The application TK Gata is the current operational and asset register system for traffic space at the Stockholm Traffic Administration Office. It is used for planning and maintenance of the road space. TK Gata contains data created for the road maintenance operation unit and is developed based on operational information needs. The requirement is that the solution developed in the case study should have access to similar data content as (part of) TK Gata and follow principles of a data-centric approach.

2. Design and develop a prototype of a KGBT

Develop a prototype tool for a data-centric solution using knowledge graph techniques and GIS, showing the potential of CityGML-3CIM transportation module with linked NVDB data.

3. Evaluation of the KGBT

Evaluate if the data-centric solution expressed as a KGBT could be a valuable alternative for replacing the current TK Gata solution for road maintenance.

4. Requirement of a Knowledge graph-based tool

4.1 Method

To determine the requirements for the KGBT, a comprehensive technical overview of the current application TK Gata is performed. This process involved a detailed analysis of its technical description, an evaluation of the operational maintenance areas dataset, and discussions with personnel at the Stockholm Traffic Administration Office. The description includes the operational procedures and documentation of the stakeholders using the application.

On a comprehensive level there are two requirements:

- 1) *Have access to similar data content as part of the current operational tool TK Gata.*
- 2) *Follow the principles for a data-centric approach.*

4.2 Data content of TK Gata

Technical overview

According to the documentation provided by the Stockholm Traffic Administration Office, TK Gata serves as an operational and asset register specifically designed for managing traffic spaces (Figure 4.1). The objective of the application is to enable the management of street related geospatial information for the Urban Environment Department (swe: *Stadsmiljöavdelningen*). This includes the storage, distribution, and update of datasets managed by various units. The application includes several datasets from within and outside the organization: Operational maintenance areas (swe: *Gatudrifts skötselytor*), Pavement surfaces (swe: *Gatuunderhåll beläggningsytor*), Public spaces under development (swe: *Stadsrum utvecklingsytor*), Local road database (swe: *Lokal Vägdatas* or *LV*) and National road database data (swe: *NVDB*).

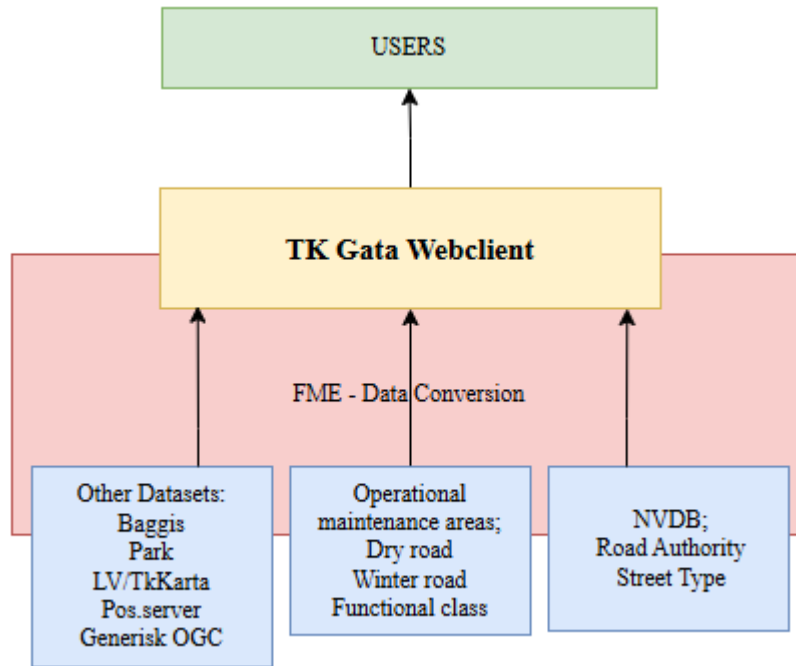


Figure 4.1: Simplified architecture of TK Gata, including data from within and outside the organization.

Road maintenance in TK Gata

The data used for management of the road space in TK Gata is the operational maintenance areas. These areas are manually created by using the city planning administration's (swe: *Samhällsbyggnadskontoret*) road edges from their basemap or technical documentation such as construction drawings, in combination with the latest orthophotos and street view imagery. The areas include columns classified for managing the road space; Dry road (swe: *Barmark*) and Winter road (Figure 4.2) (swe: *Vinterväg*) have a classification system from 0 to 9, where 0 is the most prioritized roads. The areas also include a column for Functional class (swe: *Användning*) that indicates how different areas are used: Bus Stop (swe: *Busshållplats*), Shared-use path (swe: *GC, Gång och cykelbana*), Roadway (swe: *Körbana*), Traffic island (swe: *Refug*), Stairs (swe: *Trappa*). As the city changes these areas are manually updated and generated using QGIS, then loaded into the application.

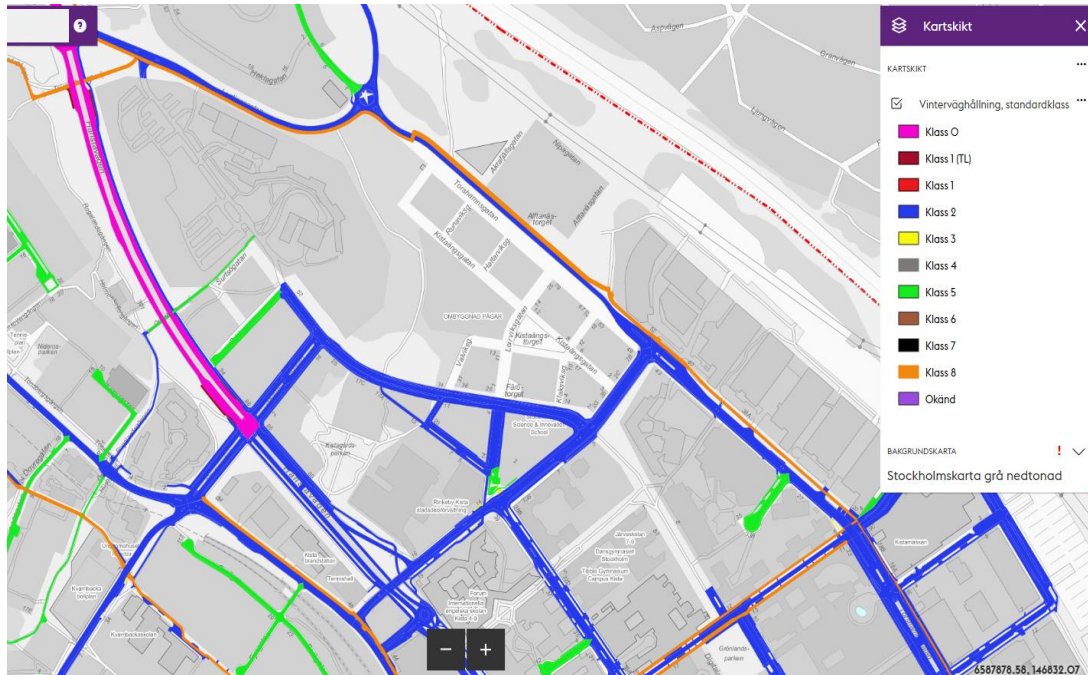


Figure 4.2: TK Gata operational maintenance areas, classified for Winter Road maintenance.

Most units working with city planning in TK Gata use NVDB data for reference information, e.g. the application displays Road Authority (swe: *NVDB väghållare*) and Street Type (swe: *NVDB gatutyp*). This information is visualized in TK Gata through a Web Map Service (WMS) streamed from the Stockholm city local road database (Figure 4.3).

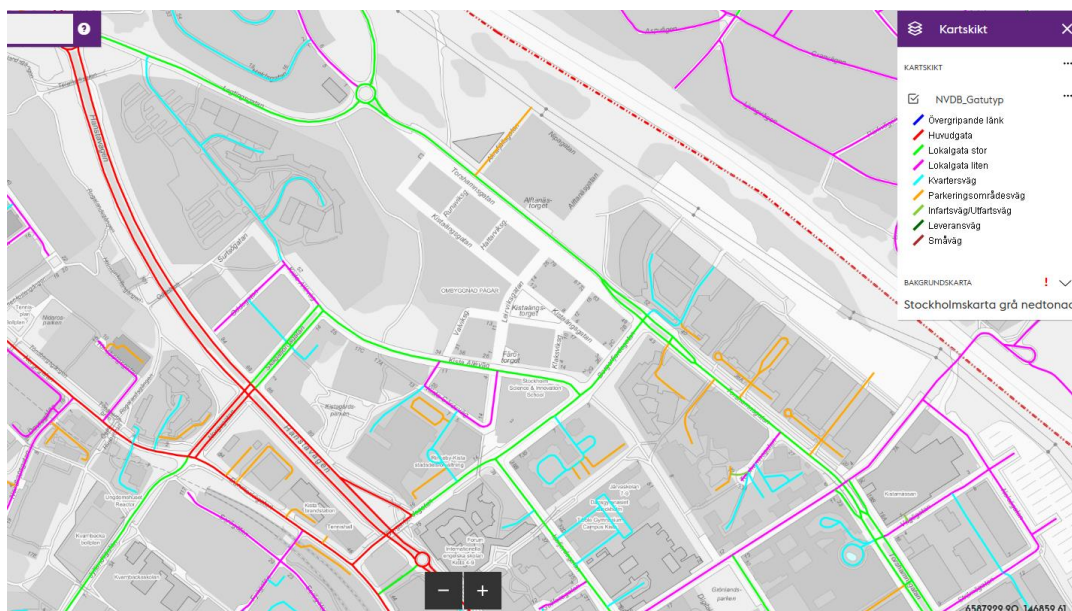


Figure 4.3: TK Gata, NVDB Street Type streamed as a WMS.

Users

The system supports approximately 100 internal users at the Stockholm Traffic

Administration Office (swe: *Trafikkontoret*), a management organization within Stockholm City. The users are primarily from the Urban Environment and other departments within the Traffic Administration Office.

There are several units within the Urban Environment Department (swe: *Stadsmiljöavdelningen*) that maintain their own data in the TK Gata application and need access to updated data in near-real time. The units are:

- Street Operations (swe: *Gatudrift*)
- Street Maintenance (swe: *Gatuunderhåll*)
- Supervision and Operations (swe: *Tillsyn och Drift*)
- Analytics and Support (swe: *Analys och stöd*)
- Urban Space Development (swe: *Stadsrum utveckling*)
- Urban Space Activation (swe: *Stadsrum aktivering*)
- Urban Space Projects (swe: *Stadsrum projekt*)

Other units and departments that use TK Gata to access information are:

- The Traffic Planning Department (swe: *Trafikplaneringsavdelningen*)
- The Permitting Department (swe: *Tillståndsavdelningen*)

Contractors for street maintenance also have access to TK Gata, this is provided through an external map application.

4.3 Requirements of a data-centric solution

A data-centric approach shifts the focus from the application to how the data used can be trusted, shared, and reused. Resulting in more resilient, interoperable and extensible organizations, described in chapter 2.1. Since there is no concrete definition of a data-centric approach (McComb, 2019) the bullets in the data-centric manifesto is used to outline key data-centric principles (Data-Centric Manifesto, 2015):

- Data is a Key Asset

A shift from managing application lifecycles to managing data lifecycles. Enhanced data reuse and high quality.

- Data is Self-Describing

The data carries its own meaning through semantics, making it interoperable by default. A flexible schema is at the core of the semantic web technologies using RDF.

- Data expressed in Open, Non-Proprietary Formats

Universal interoperability by using open standards like URIs and Linked Data to connect to the web and other systems. This facilitates breaking down problems with data silos in organization.

- Security & Access at the Data Layer

Protecting the data at the source rather than at the application. Controlling who can modify the record directly at the storage level, ensures a “Single Source of Truth” information model in the organization.

- Applications “Visit” the Data

Data is the “hub” and apps are the “spokes” (Figure 2.2), new apps can analyze and

append data without breaking existing "visitor" apps. Optimizing spatial queries at the data layer is important if apps are to be light weight and not have to perform heavy geometric calculations.

5. Design and develop a prototype of a knowledge graph-based tool

The focus of the development is to meet the two requirements listed in chapter 4. To facilitate this a general data-centric dataset (that potentially could be used by the entire city of Stockholm) that contains the required information is designed. By exploring how the CityGML-3CIM knowledge graph can be implemented as a data-centric alternative to the TK Gata application, focusing on access to similar data. This is implemented by adding the 3CIM/NVDB knowledge graph into the QGIS software and classifying the dataset for road space maintenance.

The thesis is part of the project Interoperability – Digital collaboration for the built environment (Smart Built Environment, 2025b). Per-Ola Olsson and Lars Wikström within the project have assisted with various technical implementations, e.g. construction of ontologies and knowledge graphs, SPARQL data endpoints (on project servers) and SPARQL queries.

5.1 Method

A general overview of the steps to design and implement a KGBT for road maintenance is presented in Figure 5.1, the technical details for each step are outlined explicitly in Section 5.2 (Study Area), Section 5.3 (Data), Section 5.4 (Tools) and Section 5.5 (Implementation of a Knowledge graph-based tool).

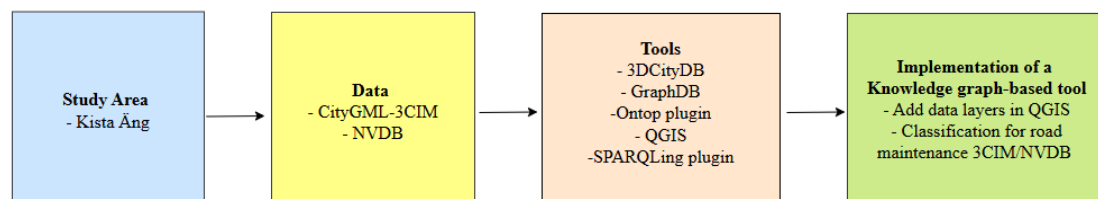


Figure 5.1: Steps for developing a KGBT for road maintenance.

5.2 Study area

The study focuses on a small geographic area Kista Äng in Stockholm, which is a study area developed and maintained as a testbed in the project *Interoperability – Digital collaboration for the built environment* (Smart Built Environment, 2025b). The choice of this study area is due to access to CityGML-3CIM data with linked NVDB data expressed as a knowledge graph.

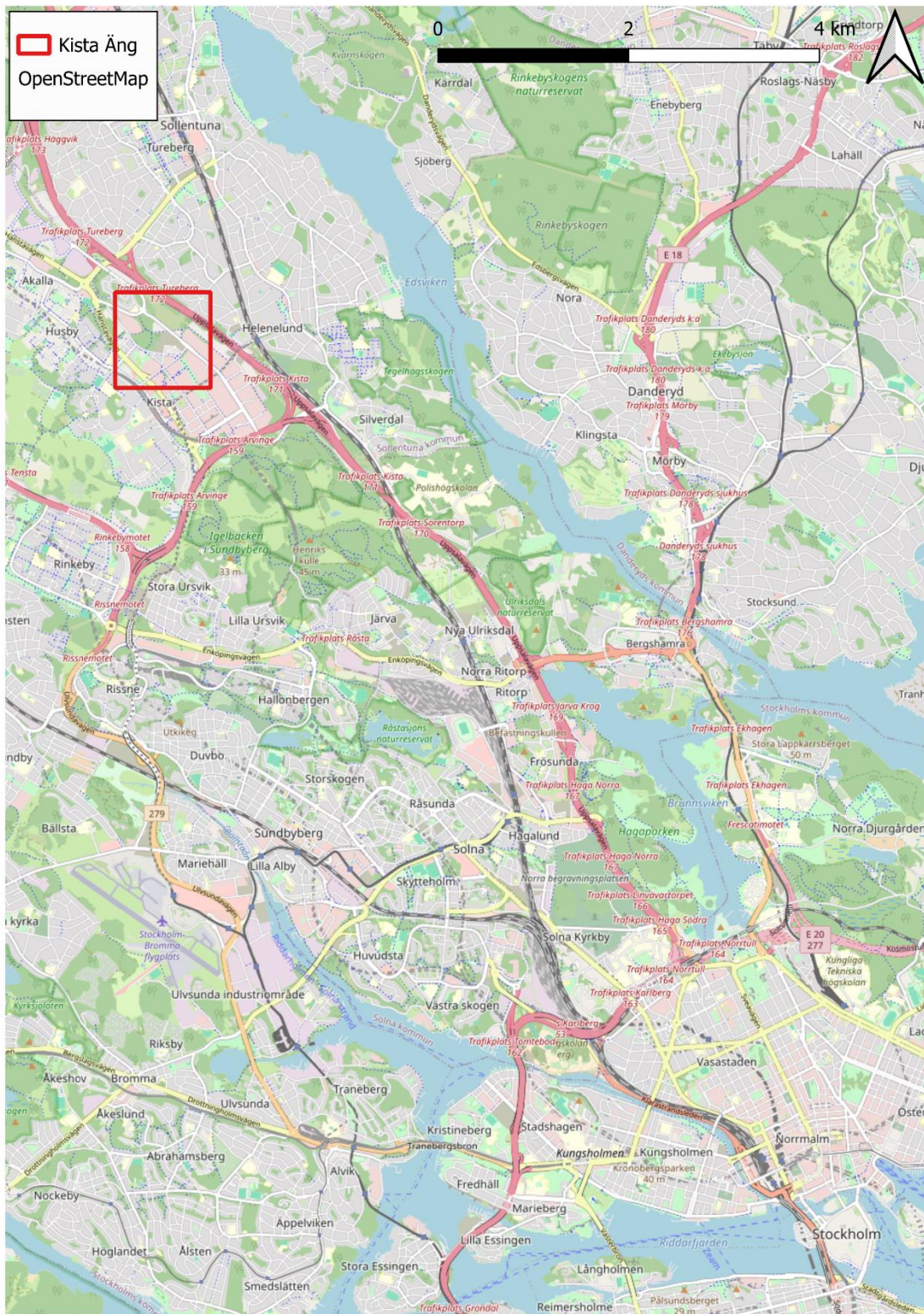


Figure 5.2: Map of northern Stockholm with the study area Kista Äng in red.

5.3 Data

This section contains detailed description of the data used to design and implement the solution. A lot of exploration of the datasets has been critical to configure the

knowledge graph data correctly, ensuring that it provides functionalities equivalent to those of the current operational tool TK Gata. The following datasets are used:

CityGML-3CIM

CityGML-3CIM transportation data as a knowledge graph within the study area, reached through a SPARQL endpoint. A 3CIM ontology, extended from a CityGML 2.0 ontology (OGC, 2013) is used to classify the data (see 2.2.2-2.2.3). LOD 2-4 data with *Trafficarea* and *Auxilliarttrafficarea* are used and a column with reference link for external connection to the NVDB data.

NVDB

NVDB data as a knowledge graph, reached through a SPARQL endpoint. The NVDB data is classified using an ontology derived from the ISO 19148 (Linear Referencing) standard and the INSPIRE Transport Networks schema, which provides a semantic framework for mapping Swedish road attributes (cf. 2.3). The attributes included are: Road authority (*swe: Våghållare*), Street type (*swe: Gatutyp*) and five additional attributes not used in this study. The NVDB data reference link prefix is converted to link sequence due to naming convention in the INSPIRE (Infrastructure for Spatial Information in the European Community) directive.

Knowledge graph for road maintenance

In Figure 5.3 the 3CIM/NVDB Knowledge graph is visualized as triples, the graph is classified for road maintenance and linked to external NVDB data.

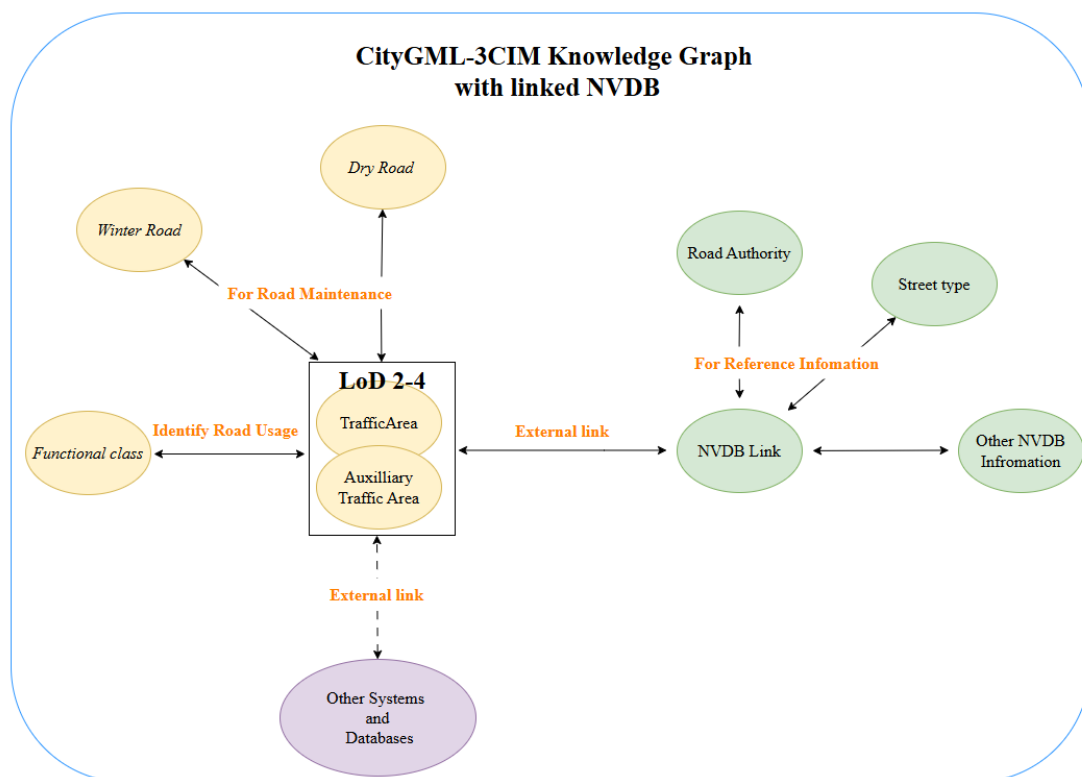


Figure 5.3: Knowledge graph for road maintenance, CityGML-3CIM with linked NVDB data visualized as triples.

For classification and comparison with the TK Gata application the following data is used:

Operational maintenance areas

In the TK Gata application, the operational maintenance areas are the foundation for management of the road space. They are manually constructed and include Dry road and Winter road classification, Functional class for road usage.

Open data

Is free data accessed on the internet and updated by a company or large community of users. The datasets used are: OpenStreetMap and Google Satellite, they are used for orientation, reference information and visualization.

5.4 Tools

The tools were selected because they are used in other research within the smart build environment project. I looked into using ArGIS instead of QGIS, but as it does not support RDF graphs this was not an alternative.

3DCityDB

3DCityDB is a free and open-source collection of software tools and a database schema, created to import, manage, analyze, visualize, and export virtual 3D city models based on the CityGML standard. It converts CityGML's object-oriented data model into relational tables for use in spatially enabled database management systems like PostgreSQL with the PostGIS extension (3D City Database, n.d.).

GraphDB

GraphDB is software to store, manage, and query data represented as knowledge graphs. It is developed by Ontotext and supports W3C standards for SPARQL querying, updating data and scale large amount of RDF statements. It has a web-based interface, the workbench lets you administer GraphDB to load, transform, explore, manage, query, and export graph data (Ontotext, 2025). In addition to SPARQL querying and data management, GraphDB offers virtualization capabilities as well as extensions for the querying of geographic data.

Ontop plugin

Data virtualization in GraphDB is achieved using Ontop Virtual Knowledge Graph (VKG) plugin, enabling users to query relational databases dynamically without the need to materialize large or frequently updated RDF datasets into a physical store. Ontop translates SPARQL queries into SQL making the use of traditional data storage systems with the knowledge graph functionality possible (Ontotext, 2025). The virtualization and materialization of relational data into semantics and ontology have been developed and updated into knowledge graphs within the smart built environment project.

QGIS

QGIS is a widely used open-source GIS software. It is maintained by the Open Source Geospatial Foundation (OSGeo). The tool is free and very popular among professionals and scientists because of its support by a large community of users and developers (Rosas-Chavoya et al., 2022). QGIS offers a comprehensive and reliable

system for managing, processing, analyzing and visualizing spatial data. This involves vector data, such as points, lines, and polygons as well as raster data, which involves satellite images, elevation models, and various types of thematic maps (QGIS Development Team, 2025).

SPARQLing plugin

The SPARQLing plugin connects QGIS to a SPARQL endpoint for querying knowledge graphs, it adds the answers as a GeoJSON layer to the application (Thiery & Homburg, 2025).

System architecture

In Figure 5.4 the system architecture of the KGBT is described, it visualizes how the tools and data in system are connected.

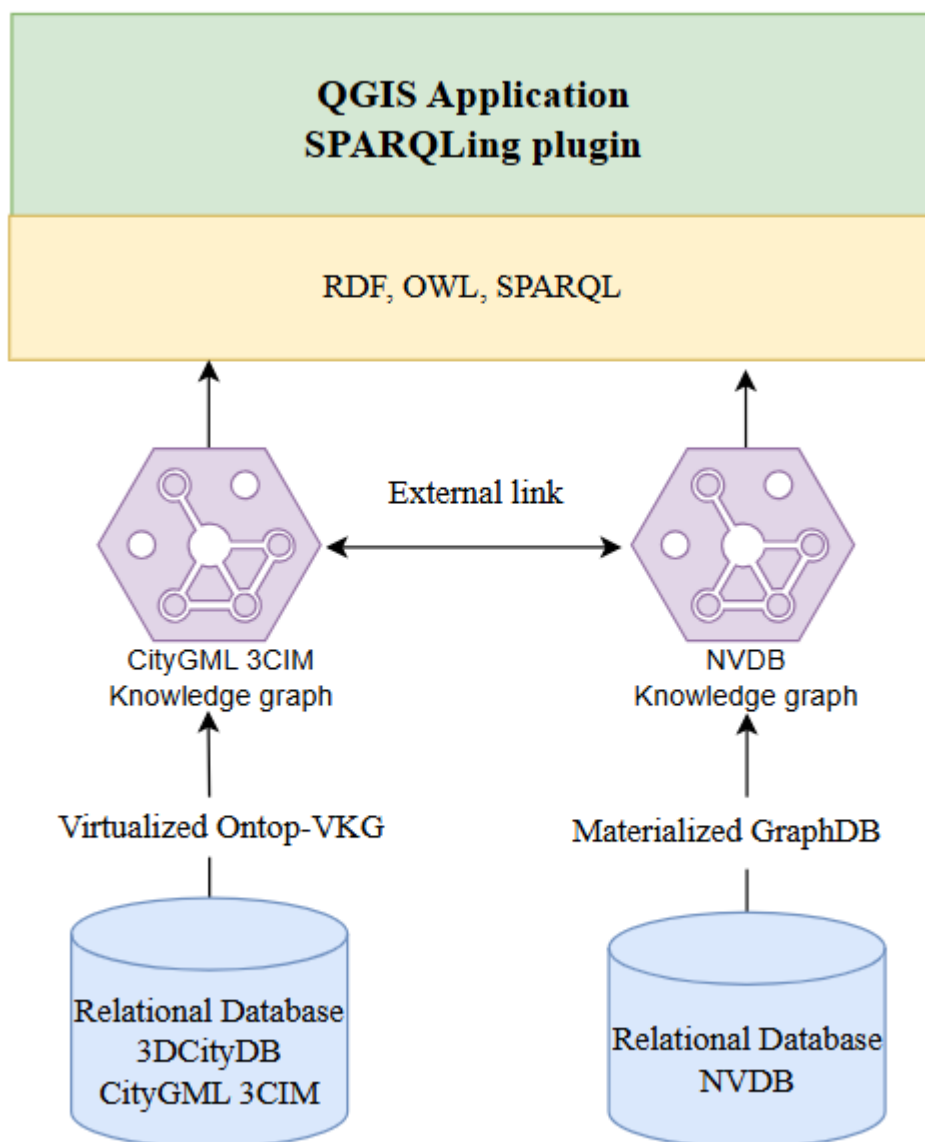


Figure 5.4: Architecture of the KGBT for road maintenance.

5.5 Implementation of a Knowledge graph-based tool

The general workflow of the implementation of the KGBT is visualized in Figure 5.5. Each step of this workflow is critical to achieving data uniformity with the current operational tool, TK Gata, within a QGIS environment. The steps of the implementation is described in detail in sections 5.5.1 (Add data layers), 5.5.2 (Classification for road maintenance) and the final tool presented in section 5.6 (Knowledge Graph Based Tool – KGBT).

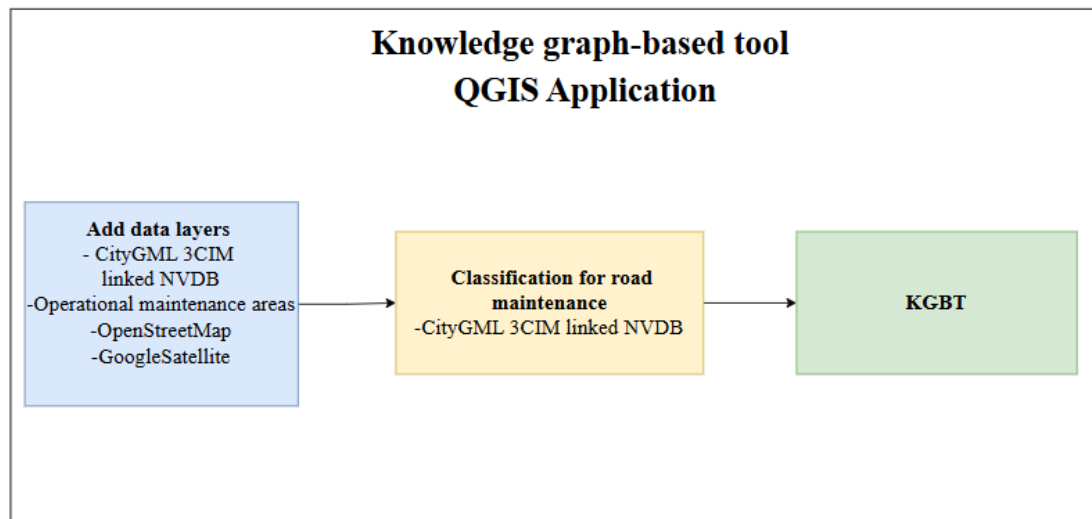


Figure 5.5: Workflow showing how the KGBT for road maintenance is developed in QGIS by adding the different data layers and classifying the 3CIM/NVDB knowledge graph for road maintenance.

5.5.1 Add data layers

Add Knowledge graph data

In QGIS a SPARQL query (Appendix C, SPARQL query B1) in the SPARQLing plugin is used to extract the 3CIM/NVDB data from the SPARQL endpoint in GraphDB (Figure 5.6). The linking to the external NVDB data is done within the SPARQL query.

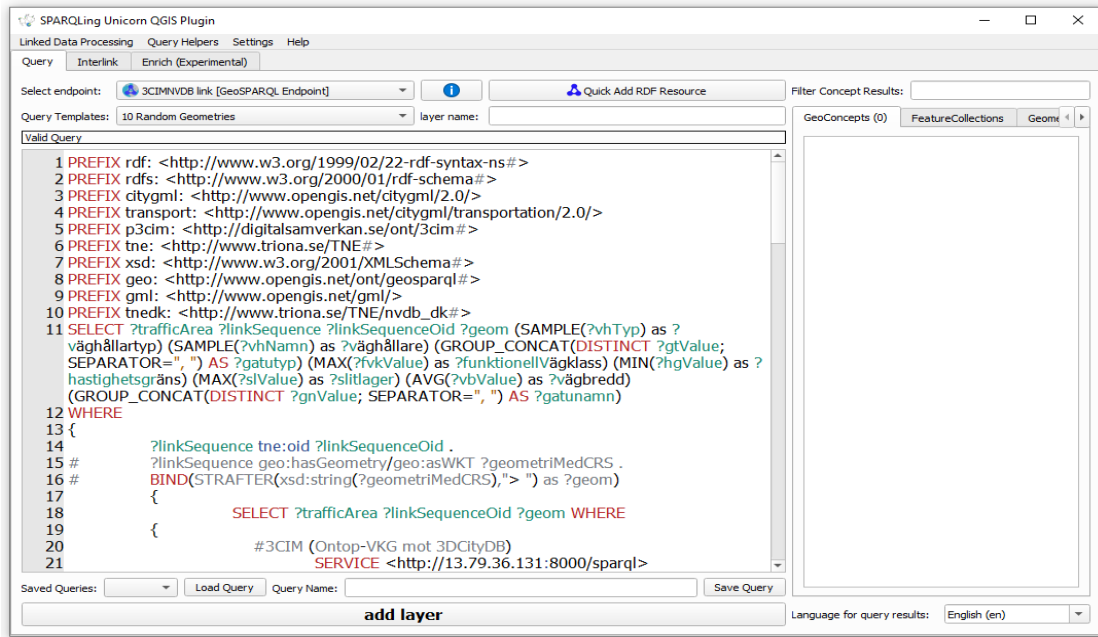


Figure 5.6: QGIS SPARQLing plugin extracting the 3CIM/NVDB knowledge graph data using the SPARQL endpoint form GraphDB.

Add vector layers and XYZ tiles

The Operational maintenance areas, OpenStreetMap and Google Satellite are imported into QGIS into the Layers panel (Figure 5.7).

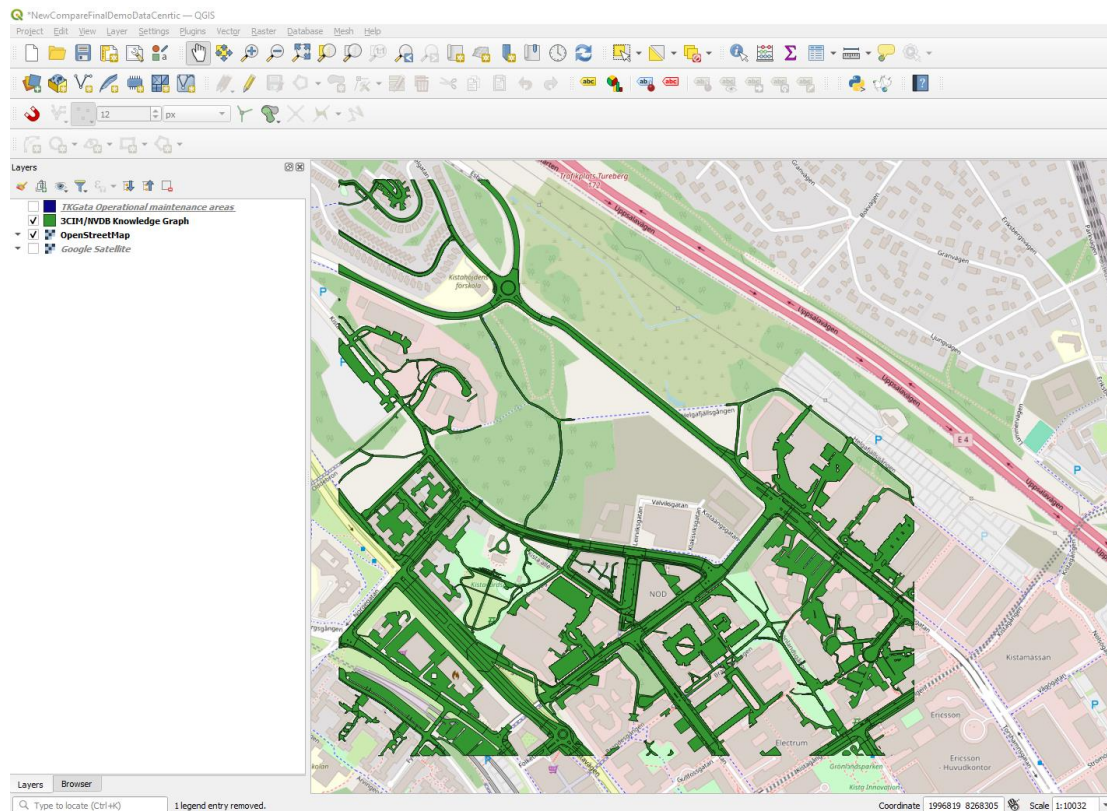


Figure 5.7: QGIS software with the imported data layers; 3CIM with linked NVDB, TK Gatas Operational maintenance areas, OpenStreetMap and Google Satellite.

Alternative technical solution for adding/importing Knowledge graph data

The QGIS SPARQLing plugin is not completely reliable as it is still in development. An alternative to extracting the knowledge graph data into QGIS is using the same SPARQL query (Appendix C, SPARQL query B1) in GraphDB (Figure 5.8). The data is exported from GraphDB and imported into QGIS.

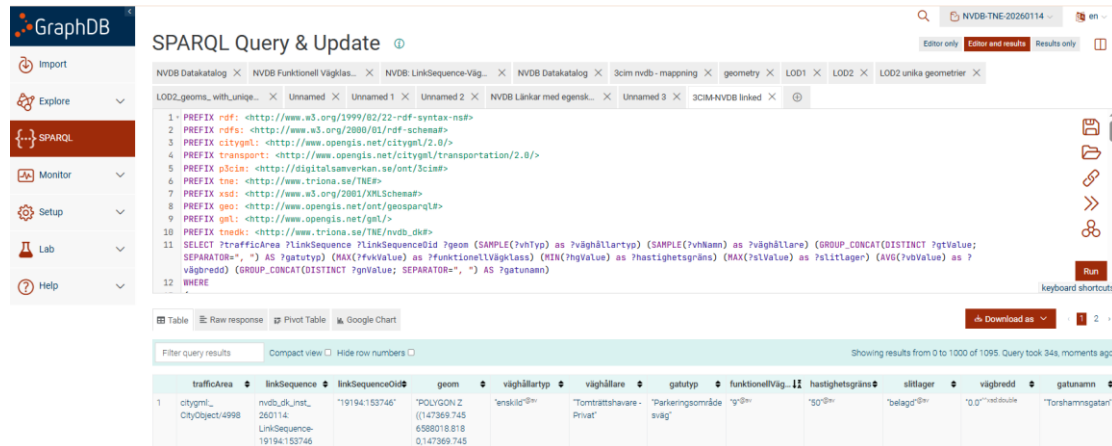


Figure 5.8: SPARQL query to extract the 3CIM/NVDB knowledge graph data with GraphDB web interface.

5.5.2 Classification for road maintenance

The 3CIM/NVDB knowledge graph is classified in QGIS to include similar data content for road maintenance as the current operational tool TK Gata. The TK Gata operational maintenance areas include three columns for road maintenance, Dry road, Winter road and Functional class. These columns were added to the 3CIM/NVDB knowledge graph and populated by using the select by location tool in QGIS. First a select by attribute on the column class of the operational maintenance areas were performed, followed by a select by location on the 3CIM/NVDB data. The areas that intersect with the selected areas of the operational maintenance areas were selected, then the column/areas in NVDB/3CIM were classified with the same value. This was done to classify the three columns for road maintenance in the 3CIM/NVDB data. In figure 5.9 the 3CIM/NVDB is classified for Winter Road maintenance.

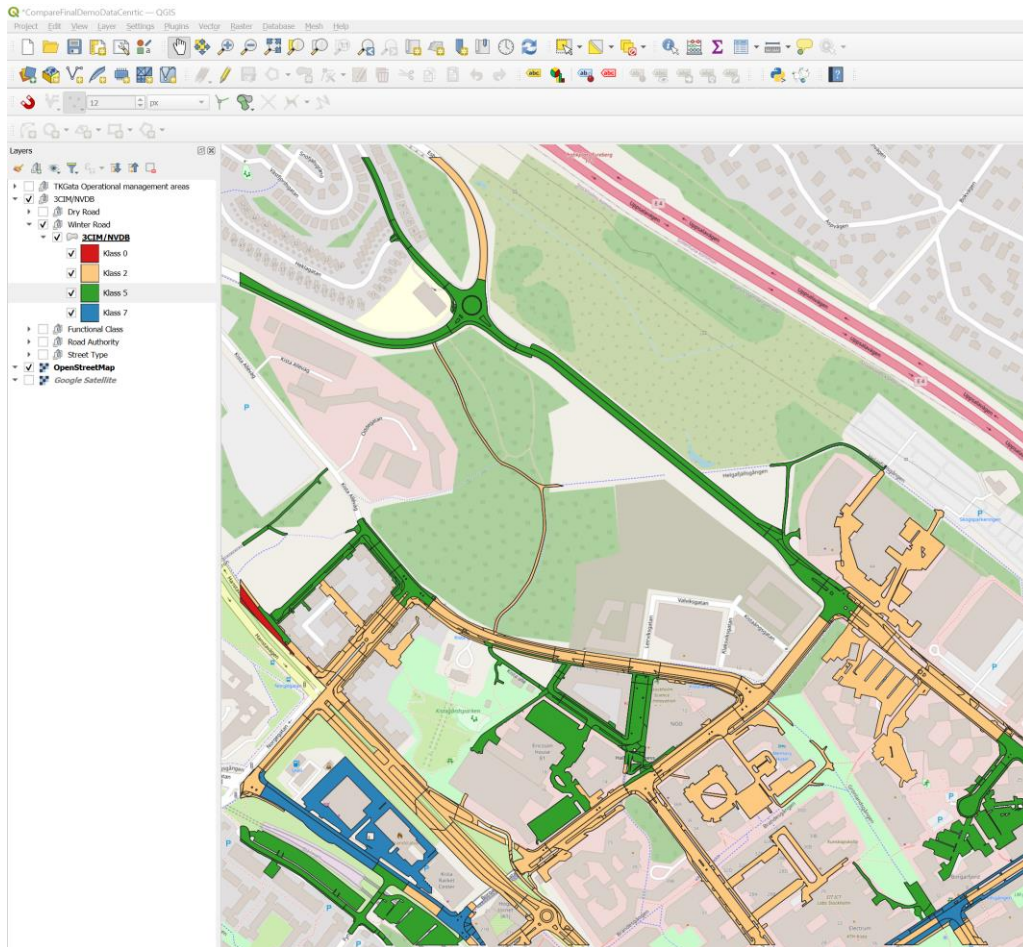


Figure 5.9: 3CIM/NVDB classified for Winter Road maintenance.

5.6 Knowledge Graph Based Tool – KGBT

The KGBT for road maintenance is created as a QGIS-based solution (Figure 5.10), using the 3CIM/NVDB knowledge graph as its underlying data source. Within the QGIS Layer panel, several specific layers are styled and structured for operational use: Dry Road and Winter Road are classified for road space maintenance, while Functional Class, NVDB Road Authority, and Street Type provide reference information regarding road usage and ownership. Additionally, OpenStreetMap and Google Satellite layers are integrated to provide general orientation. The QGIS workspace makes it possible for the user to interact with and explore the 3CIM/NVDB layers with all its attributes to manage the roads space in the study area.

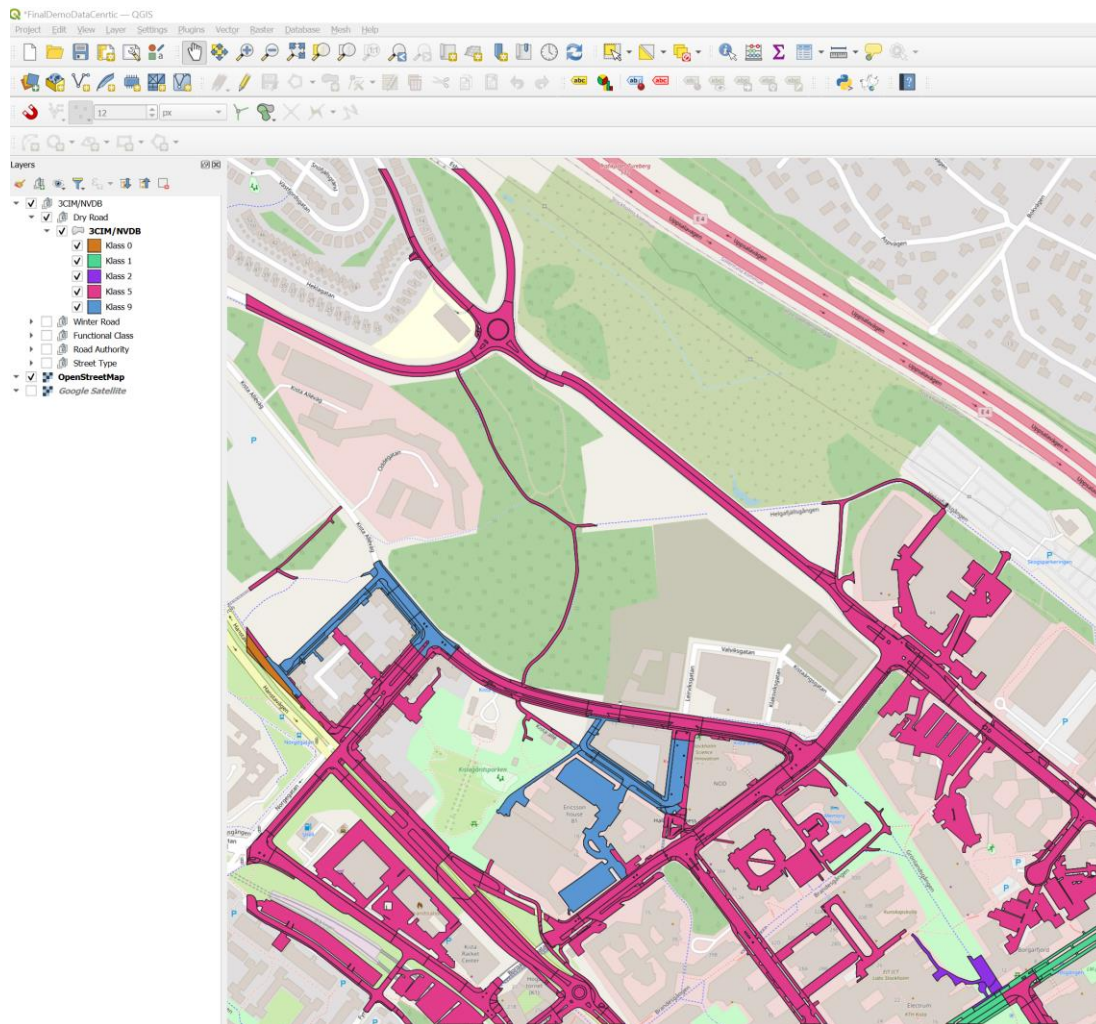


Figure 5.10: KGBT for road maintenance in QGIS. In the Layers panel the 3CIM/NVDB dataset is presented in different layers: Dry Road (presented in the map), Winter road, Functional class, road Authority, Street type, OpenStreetMap and Google Satellite.

6. Evaluation and discussion of the knowledge graph-based tool.

To evaluate the KGBT against TK Gata, the comparison focuses specifically on data accessibility, by a factual comparison of the information accessed by both systems and examining the differences between data models. Rather than comparing full system functionality, that remains to be implemented by the organization.

In the following chapter an evaluation and discussion of the two requirements in chapter 4 is performed, with a final section about the future outlook of this technique.

6.1 Does KGBT have access to the same data content as TK Gata?

6.1.1 3CIM/NVDB road maintenance classification

Aspect 1: Dry Road Classification

The 3CIM/NVDB dataset is classified with a column for *Dry road* class with the attributes 0-9 for road maintenance. The classification process is straightforward, resulting in spatial geometries that are more numerous than the polygons defined by the TK Gata operational maintenance areas. A comparative visualization of the differing extents between the two datasets is presented in Figure 6.1.

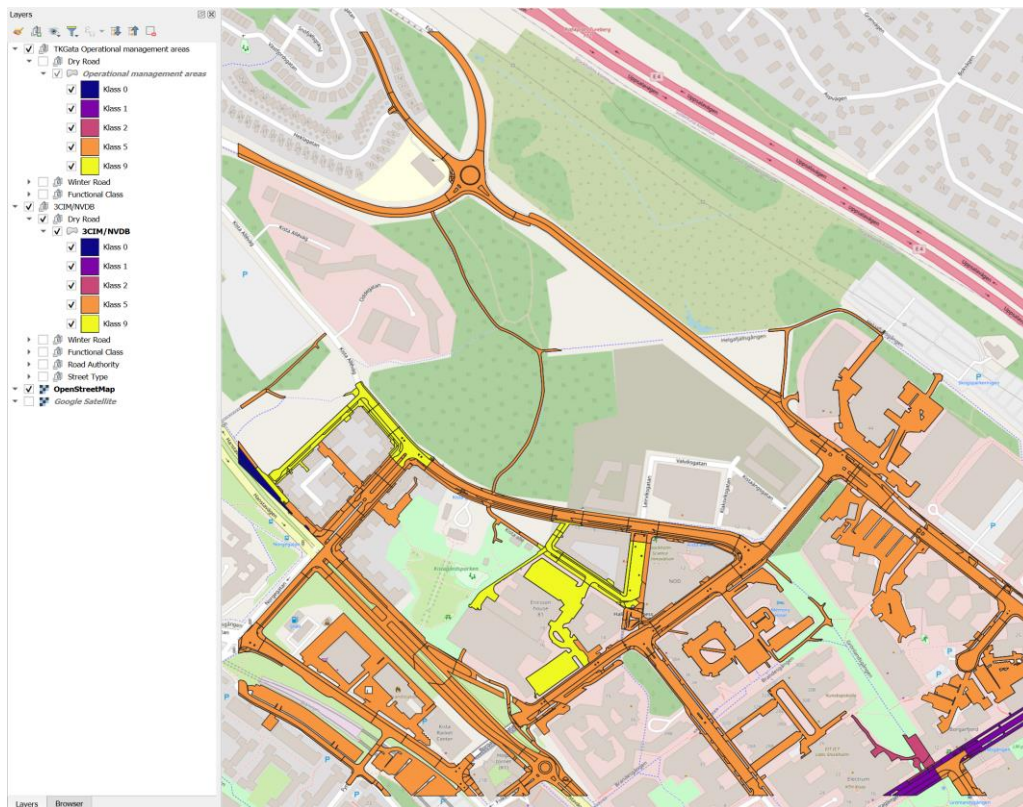
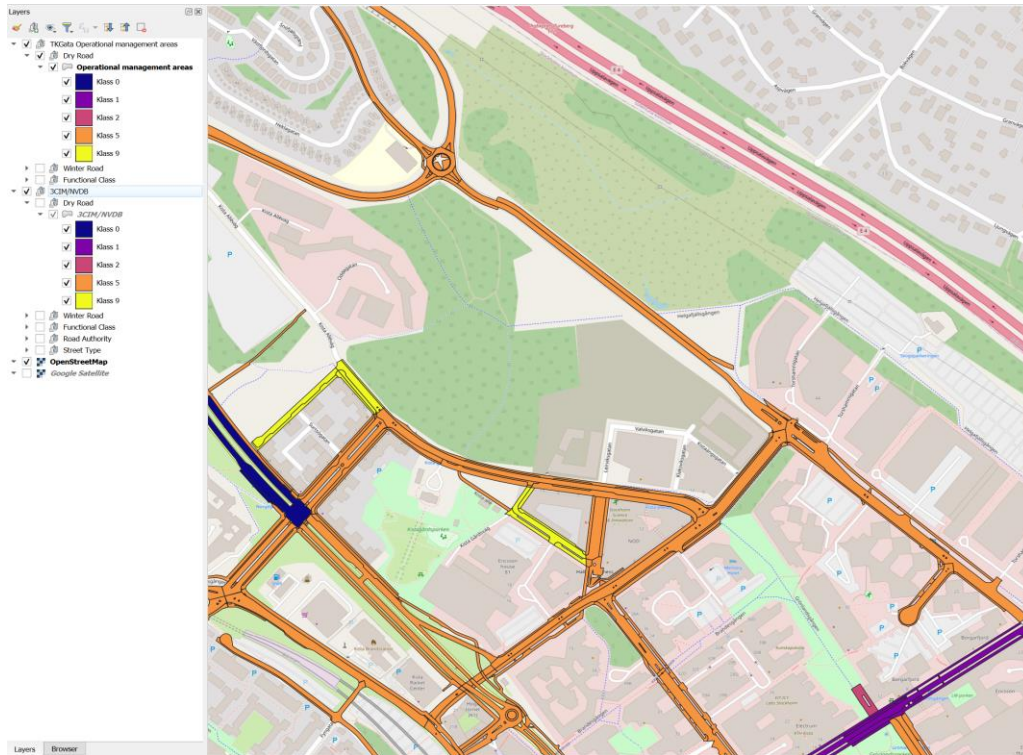


Figure 6.1: Dry road classification 0 to 9, comparison between TK Gata - Operational maintenance areas (Top) and the result in 3CIM/NVDB (Bottom).

Aspect 2: Winter Road Classification

The 3CIM/NVDB dataset is classified with a column for *Winter road* class with the attributes 0-9 for road maintenance. The classification process is straightforward, resulting in geometries that are more numerous than those defined by the TK Gata

operational maintenance areas. In Figure 6.2 the areas for *Winter road* class 5 are compared, the same challenges occur for the other classes to various extents.



Figure 6.2: *Winter road* classification 5 in Green, comparison between *Tk Gata* operational maintenance areas (left) and the result in 3CIM/NVDB (right).

Aspect 3: Functional Class Classification

The 3CIM/NVDB dataset is classified with a column for Function class, with the attributes: Bus stop (*swe: Busshållplats*), Multi-use path (*swe: Gång och Cykelbana*), Roadway (*swe: Körbana*), Traffic islands (*swe: Refug*) and Stairs (*swe: Trappa*). The classification process is straightforward but has various challenges. The Roadway classification was the most accurate because road geometries are continuous across both data models. In contrast, Bus stops and Multi-use paths often consist of long, unsegmented features. During attribute matching, this caused the workflow to select more polygons, resulting in a more numerous selection. Meanwhile, Traffic islands and Stairs consist of very small geometries. Because of minor spatial misalignments between the datasets, these features either fell outside the matching thresholds or were missed entirely, making the classification invalid for some of them. The Functional class of the two datasets are visually compared in Figure 6.3.

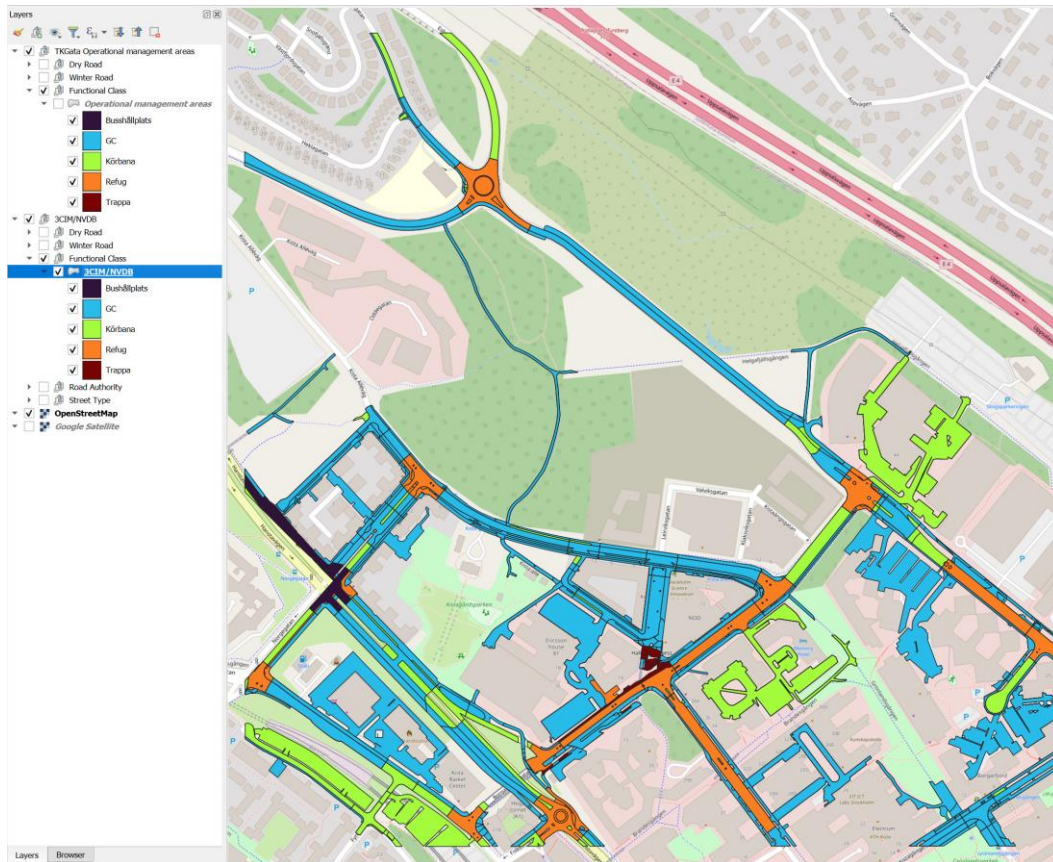
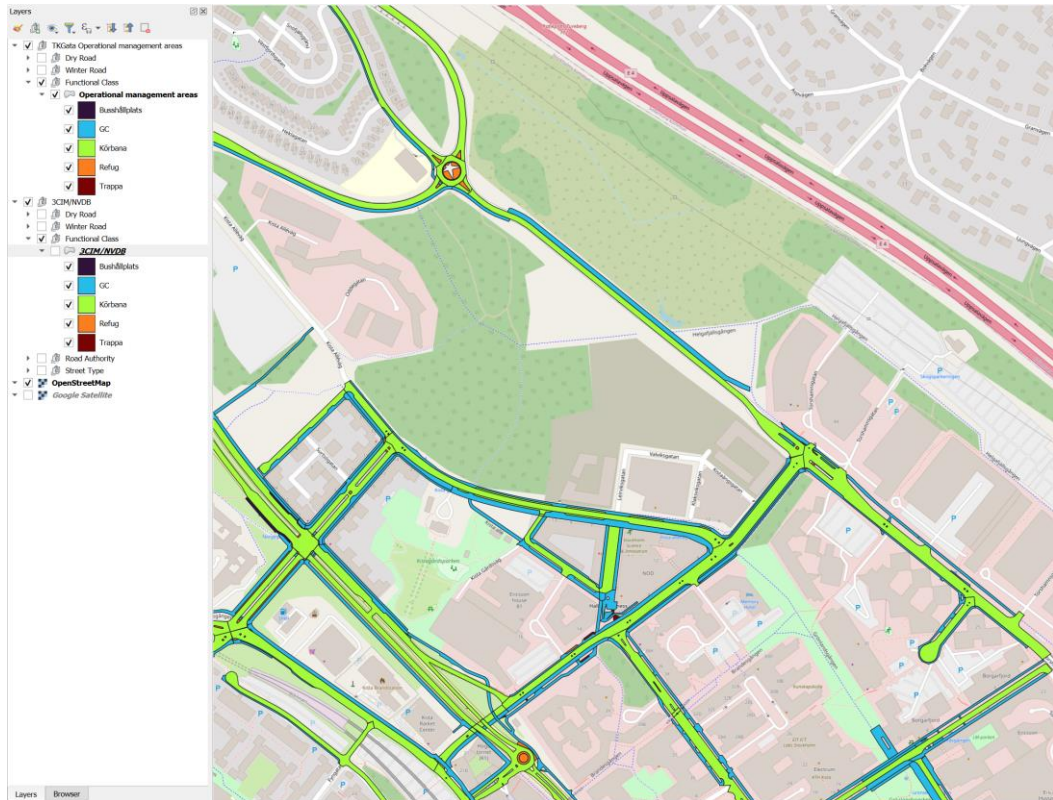


Figure 6.3: Functional classification, comparison between TK Gata - Operational maintenance areas (Top) and the result in 3CIM/NVDB (Bottom)

Aspect 4: Overall Classification

An overall issue observed is that the classification of 3CIM/NVDB produces more areas than those in the TK Gata operational maintenance areas. As the classifications do not align, it populates the 3CIM/NVDB LoD geometries *TrafficArea* and *AuxilliarTrafficArea* to various extent with the classification used for TK Gata for road maintenance. These differences are particularly challenging when it comes to classifying smaller areas for *Dry* and *Winter road* maintenance, as well as for very small Functional class areas like Traffic islands and Bus stops.

Discussion of data classification

The classification of Dry road, Winter road, and Functional class reveals a consistent challenge regarding geometries and spatial alignment between the datasets. The accuracy varies based on the physical extents of the classified features.

Aspect 1-2

In both the Dry and Winter road classification, a consistent issue is the generated geometries exceed the boundaries of the defined TK Gata operational maintenance areas. The classification process is straightforward, following the intersect logic but it fails as the data models don't share boundaries. This results in spatial overlaps for both classifications, which is particularly problematic for winter maintenance where precision is vital for snow clearing since contractors are paid per square meter. To resolve this, the Traffic Administration Office together with Urban Environment Department should ideally agree on a standardized road model to ensure the areas aligns with the physical road width, length and even functional class (via standardized lengths and divisions for functional class if possible).

Aspect 3

In the Functional class classification the challenge correlates to the physical size of the areas of the attributes. The Roadway classification worked best because of its geometry extent and consistency, better matching the data model of the 3CIM/NVDB knowledge graph. In contrast, the Bus stop and Multi-use paths classification resulted in too many features due to long geometries, comparable to the classification of Dry and Winter roads. For very small geometries like Traffic islands and Stairs, the classification is invalid or missing due to that the 3CIM/NVDB extent does not capture some of these areas.

Aspect 4

The overall classification is challenging. As the geometries of the data models do not align, this results in that the 3CIM/NVDB LoD *TrafficArea* and *AuxilliarTrafficArea* geometries are not classified in a good way. By adopting a standardized semantic data model for city planning it is possible to use the power of the CityGML transportation module dividing the data into different LoDs, described in detail in section 2.2.2. This functionality makes it possible to categorize the road maintenance data into *TrafficArea* for traffic usage like driving and cycling lanes or pedestrian zones and *AuxiliaryTrafficArea* for additional road components like curbstones, median lanes and green areas. Using the 3CIM/NVDB data model as the foundation when planning for road maintenance would be an advancement instead of continuing developing the application dependent TK Gata operational maintenance areas. The benefits of using semantics and ontologies to establish structure within geospatial applications are powerful. One example of this is the SPALOD application and platform in Germany (Ponciano et al., 2025), which utilizes semantic web technologies to integrate

heterogeneous cycling data from different municipal sources into a knowledge graph. By establishing a shared vocabulary, it enables automated, cross-organizational data validation and complex spatial queries that were previously impossible due to data fragmentation.

6.1.2 Data Integrity

To get an overview of the datasets, the attributes and geometries of the application-centric and data-centric solutions are presented in table 6.1. It is important to note that the TK Gata operational maintenance areas are developed and maintained manually in QGIS for road maintenance, which is a process requiring substantial resources from the Stockholm traffic administration office each year. To get access to similar data content for road maintenance as in TK Gata the 3CIM/NVDB data is manually classified, this comes with challenges described and discussed in section 6.1.1.

Table 6.1: Attributes and Geometries in the application-centric vs the data-centric solutions

Data	Application-Centric: Tk Gata Operational maintenance areas	Data-Centric: Knowledge graph CityGML-3CIM/NVDB
Geometries		
Operational Management Areas	Yes - Manually developed and maintained	No
TrafficArea	No	Yes
AuxiliarTrafficArea	No	Yes
LOD 1-4	No	Yes
Attributes		
Dry Road	Yes	Yes - Added manually, select by location
Winter Road	Yes	Yes - Added manually, select by location
Functional Class	Yes	Yes - Added manually, select by location
NVDB Road Authority	Yes - WMS	Yes - External link
NVDV Street Type	Yes - WMS	Yes - Externa link

Discussion

The implementation of the KGBT reveals that a major obstacle in transitioning from the TK Gata application-centric model is the conversion from the operational maintenance areas attributes and geometries to the standardized 3CIM/NVDB model. Application-centric models often use geometries designed for a niche purpose such as the TK Gata operational maintenance areas developed for road management. Using these geometries is resource heavy because they require constant manual updates and are hard to automate since they don't follow any standards. It is counterintuitive, but even though 3CIM/NVDB is a standardized model, it currently requires a lot of manual work to get the same functionality as the current TK Gata application.

6.1.3 Data Interoperability

Linking to internal and external data is a very powerful functionality of the 3CIM/NVDB standardized data model. The 3CIM/NVDB knowledge graph is linked to columns for NVDB Road Authority and Street type. In figure 6.4 the link to Street Type is shown. There is no problem with the geometries aligning as the attributes are linked directly to the areas of the 3CIM/NVDB data model.

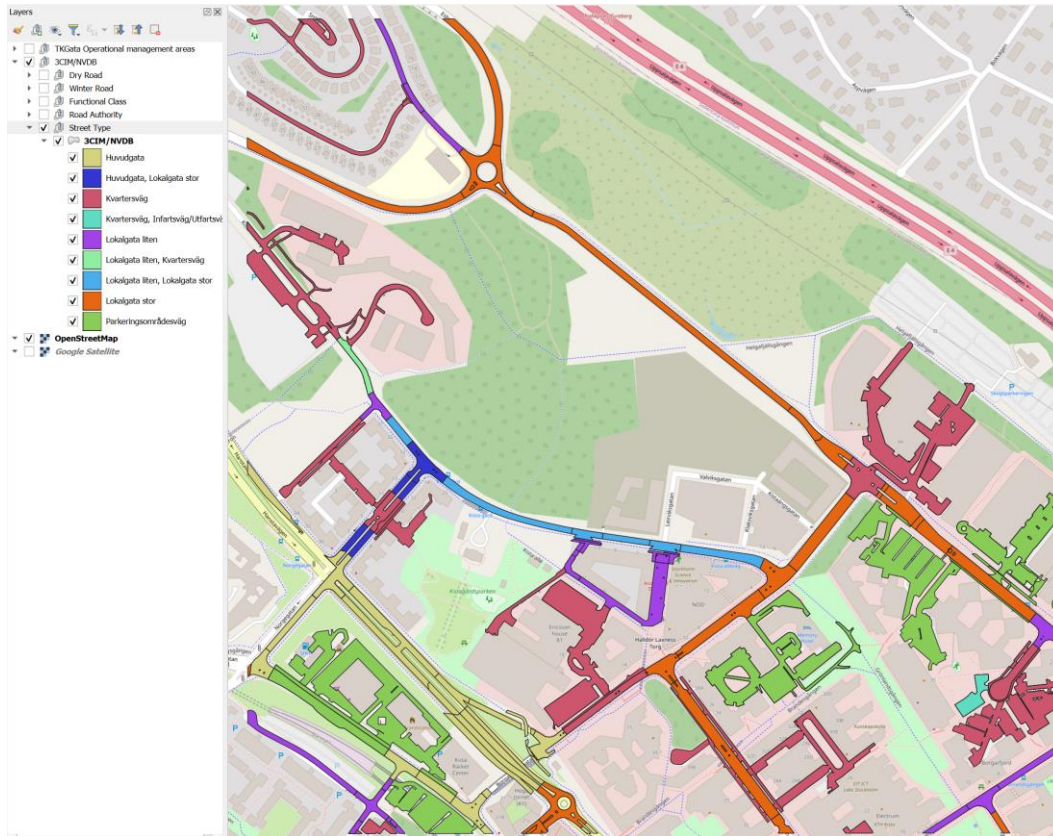


Figure 6.4: 3CIM/NVDB with linked NVDB Street Type data.

Discussion

By using the 3CIM/NVDB data model it is possible to link data through semantic information, transforming the organization's data into a dynamic city model by accessing internal and external systems and databases, described in detail in section 2.2.3. The 3CIM/NVDB is connected to the NVDB database to support road maintenance and more information can easily be added. For a comparison with the NVDB data in the TK Gata application see Figure 4.3. The datasets are very similar but do not align completely depending on when the data was extracted. Implementing a data-centric approach could meet both current and future organizational information and interoperability needs. The benefits of incorporated semantic linked spatial data are demonstrated in the Flemish OSLO project. By implementing the technique into the governance framework and their data architecture, this approach enhances data quality, promotes reuse, and improves interoperability (Bucher et al., 2021).

6.2 Does KGBT fulfill the requirement of a data-centric solution?

To evaluate whether the KGBT meets the requirements of a data-centric solution, the data-centric requirements outlined in section 4.3 are compared with the application-centric approach and the KGBT (data-centric) in table 6.2

Table 6.2: Comparing the requirements of a data-centric solution with the data models of the application-centric and data-centric solution.

Requirement of a Data-Centric Solution	Application-Centric: Tk Gata Operational maintenance areas	Comparison: Obstacles	Data-Centric: KGBT CityGML-3CIM/NVDB	Comparison: Benefits
Data is a Key Asset	No	Each application has its own data, creates data silos	Yes	Data is a key asset, enhanced data reuse and high quality
Data is Self-Describing	Yes	A description needs to accompany each data model	Yes	The Data carries its own meaning through semantics, making it interoperable by default.
Data expressed in Open, Non-Proprietary Formats	No	Data expressed in software specific formats creates proprietary dependency and vendor lock in and data silos	Yes	Interoperable by default using open standards like URIs and Linked Data
Security & Access at the Data Layer	No	Security and Access to data in different applications creates data silos	Yes	Security and Access at the datalayer makes data accurate and updated
Applications "Visit" the Data	No	Each application has its own data model any change risk breaking analysis and data transfers to other systems	Yes	New apps can analyze and update data without breaking existing "visitor" apps

Discussion

By analyzing the table it is obvious that this is more than a technical upgrade, it's a change in how the organization values and interacts with its information.

Data as a Strategic Asset

The primary difference identified in the evaluation is the transition from data as a byproduct to data as a strategic central resource in the organization. In traditional application-centric models, each software application owns its data, creating isolated silos. As shown in Table 6.2, this creates significant obstacles because the TK Gata application has its own data model and any change risks breaking analysis or data transfers. By transitioning to a data-centric approach, the organization moves away from manually managing the operational maintenance areas and being application dependent on TK Gata. The 3CIM/NVDB model allows road data to be managed independently, ensuring that the information remains updated, high-quality and reusable regardless of application or tool and could, potentially being used by the entire city of Stockholm. The implementation and value of this approach is described in the study *From the application-centric to the knowledge-centric university* (Buchmann et al. 2021). The study demonstrates that integrating knowledge graphs with data-centric architecture removes data silos and eliminates the need for ETL processes typically found in application-centric legacy systems.

Semantics, Open Standards and Linked data

A data-centric model is self-describing by using open standards like RDF, URIs and semantic modeling. This means the data carries its own meaning and context, making it interoperable by default, described in section 2.4. The 3CIM/NVDB knowledge graph provides a standardized rich data model, the structure significantly improves linking to external and internal systems, data reuse, decision-making and analysis for the entire city of Stockholm. The flexibility of the data-centric model allows for smart queries that pull data from across the entire knowledge graph, effectively breaking down barriers that previously limited information flow. On the contrary, application-centric systems like TK Gata tend to create barriers with software-specific information models and formats that create vendor lock-in.

Security and Architectural Transition

Perhaps the most significant and challenging architectural change is managing security at a central data resource rather than by each application (McComb, 2019). This transition addresses who has access to which data through centralized rules established at the organization level. By managing security from a single location, permission can be granted at a granular level, ensuring total control over the information landscape. The data becomes a “single source of thought”. This allows different departments in the City of Stockholm to consume the same high-quality updated data, eliminating data redundancy and prevents the creation of data silos. It ensures that the data remains accurate, updated and protected for all users in the organization.

The architectural transition supports a “hub-and-spoke” approach where applications “visit” the data (Figure 2.2). Instead of converting data between apps with resource-heavy ETL processes, the information remains in a central data resource. This allows new applications to analyze or append data without the risk of breaking existing dependencies, while also optimizing spatial queries centrally, allowing applications to remain lightweight so called “thin clients”.

6.3 Future outlook

Although the semantic web has existed for two decades, it remains largely unadopted in geospatial applications. One of the problems is handling geometries effectively, the tools aren't fully developed for this (Huang et al., 2019). Because of this shortage the technique is only used to a limited extent in the geospatial domain.

A main issue is the scaling up of the semantic web solution here demonstrated for a small study area. This scaling would require an expansion in multiple domains to move from a local area prototype tool to entire city deployment. From a road data perspective, a larger area introduces more complex geometric variations that make maintaining data consistency with legacy TK Gata boundaries more difficult. From a database perspective, the large increase in data volume would require optimized graph databases with spatial indexing and hardware optimization (Huang et al., 2019). From an organizational perspective, sharing a central data hub across multiple departments demands strict data governance (McComb, 2019). However, managing these organizational and structural shifts remains outside the scope of this thesis, as outlined in Section 1.4.

However, the AI revolution is changing this. With “hallucinating” AI-system there is a growing demand for traceable, understandable truth, a need that knowledge graphs can meet. They provide the structural foundation required to prepare organizations for advanced AI implementation, particularly through Retrieval-Augmented Generation (RAG). A technique that connects the AI model to a reliable data source, such as a company's internal knowledge graph, to ensure its answers are based on facts. Instead of relying only on its own training, it “looks up” relevant information first to provide more accurate and traceable results (Lewis et al., 2020).

Additionally, the steep technical barrier to querying knowledge graphs with SPARQL is diminishing, as AI makes a Natural Language Interface (NLI) possible (source).

With this change, those responsible for road maintenance will be able to access complex spatial and semantic details about infrastructure without needing advanced semantic web skills. This functionality, currently seen as a feature within platforms like GraphDB, suggests that the semantic web's original vision may finally be realized through the technical implementation of artificial intelligence.

7. Conclusions

Structured in the two research questions with some final recommendations.

7.1 Research question 1

How to design and development a data-centric knowledge graph solution for road maintenance based on city model data (CityGML-3CIM transportation module) and a national road dataset (NVDB)?

This thesis demonstrates the strength of a data-centric data model and provides a concrete example of how it can be designed and developed for road maintenance. It is best achieved by moving away from the TK Gata application-centric solution and towards a standardized semantic model like the 3CIM/NVDB knowledge graph.

From a technical and methodological standpoint, the research concludes that geometric mismatch between the solutions makes it challenging to classify road maintenance in 3CIM/NVDB accordingly to TK Gata. By adopting a data-centric approach when planning road maintenance, it is possible to use the rich data model of the 3CIM/NVDB, ensuring that road data is no longer trapped in a single application. This approach puts the road data in the center of Traffic Administration Office and Urban Environment Department, potentially the entire city of Stockholm. By using the open source QGIS-based solution for managing the data model, it becomes possible to move away from software-specific information models and formats that create vendor lock-in.

7.2 Research question 2

Which are the benefits and obstacles of semantic integration of geographic data in a Knowledge Graph (a data-centric approach) for decision making of road maintenance?

The semantic integration of geographic data in a knowledge graph works as intended, the 3CIM/NVDB data is self-describing and interoperable. Data becomes a central resource in the organization, a "Single Source of Truth", making it possible to move away from data silos. When the knowledge graph is updated, all connected applications and analysis reflect that change instantly, maintaining high data quality. This allows different departments in the city of Stockholm to access the same information without the need for resource-heavy ETL processes.

However, technical, methodological, and organizational obstacles remain:

- Technical and methodological: Integrating data from application-centric solutions introduces common data mismatches resulting in significant additional manual verification from domain experts. Furthermore, for this specific study, there is a technical challenge, the QGIS SPARQLing plugin is not completely reliable. This highlights a discrepancy, while the 3CIM/NVDB model is ready, the QGIS desktop applications have not yet fully aligned with the semantic web standards.

- **Organizational:** Transitioning to a data-centric model requires a cultural change from an application and relational database mindset to a semantic, graph based. However, managing these organizational and structural shifts remains outside the scope of this thesis, as outlined in Section 1.4.

7.3 Recommendations for future development

To fully realize the benefits of the research in this master thesis, discussions are required at the City of Stockholm to establish a geometric description of the roads that all departments can use (and implement it in CityGML-3CIM). It is recommended that the Stockholm Traffic Administration Office initiates an agile transition toward a data-centric approach for road management. By prioritizing the 3CIM/NVDB knowledge graph as the primary data model, the organization can replace manual, resource-heavy processes with automated more effective approaches to handling the organization's needs.

It is critical to acknowledge the importance of starting small when implementing data-centric solutions (McComb, 2019). In any large organization, this type of cultural and architectural change takes time and the implementation is not binary. By demonstrating the value in pilots, such as managements of road space with knowledge graphs, the project manager can build internal credibility. And as legacy application-centric systems reach end of life, a new data-centric approach can gradually be adopted, eventually forming the foundation of a standardized flexible data model in the entire organization.

Building 3D city models that understand their own dependencies is critical for innovation. By interconnecting geospatial, energy, infrastructure, environmental and Internet of Things (IoT) data etc., it can create the decision-making framework needed to manage cities more sustainably. A knowledge graph data-centric approach makes this integration possible, providing the foundation to reach the goals of a circular economy and climate neutrality.

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Appendices A - UML-diagrams

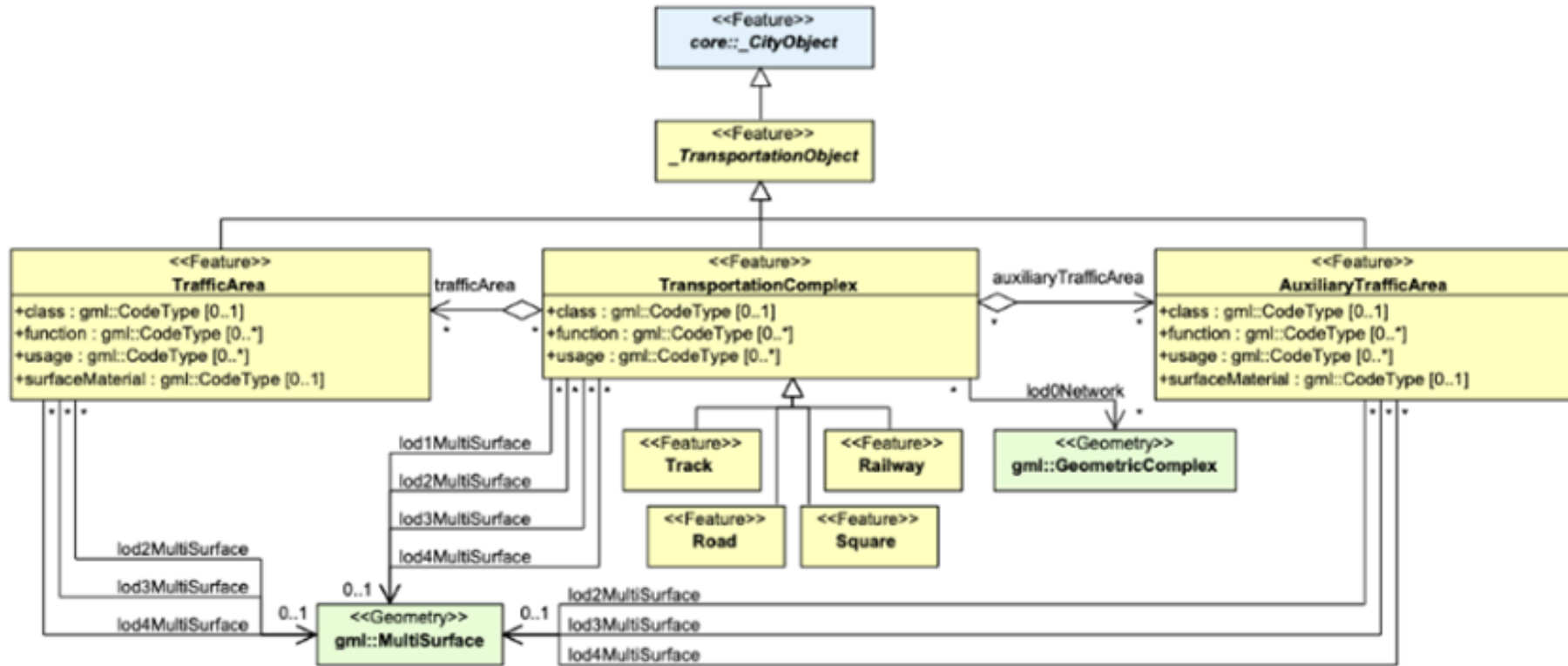


Figure A1. UML-diagram of transportation module in CityGML version 2 (Gröger & Plümer, 2012)

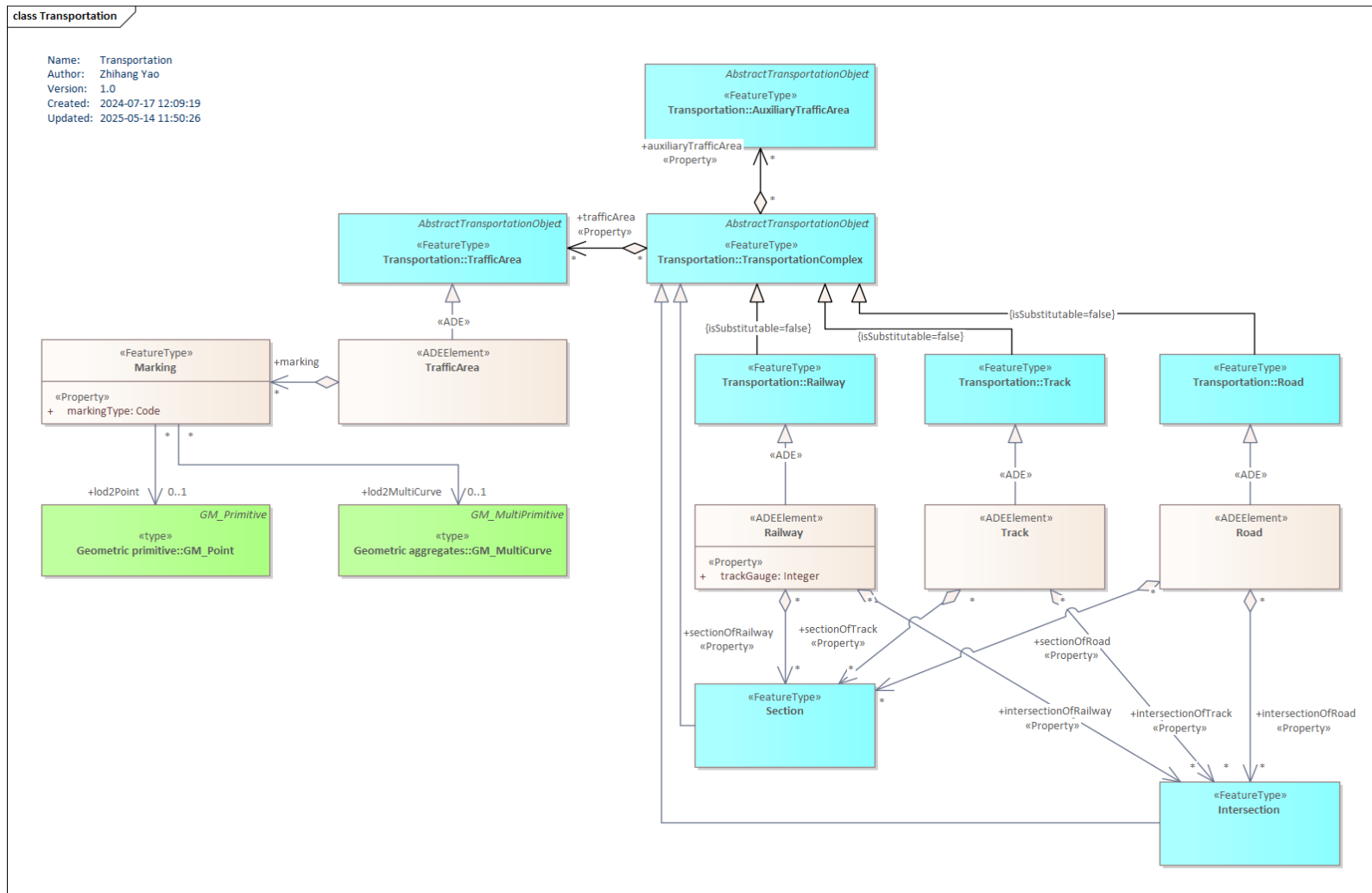


Figure A2. UML-diagram transport model in in 3CIM. (Smart Built Environment, 2025d)

Appendices B - English translation of figures technical terms

Figure 2.14 - English translation	
Swedish Term	English
Vägtrafik	Road Traffic
Körbana	Roadway
Gångväg	Footpath
Bilväg	Public Road
Gågata	Pedestrian Street
Korsning	Intersection
Trottoar	Sidewalk
Stig	Trail
Övergångsställe	Pedestrian Crossing

Figure 2.15 - English translation	
Swedish Term	English
Vägtrafik	Road Traffic
Vägren	Shoulder
Separering	Separation
Mjuk vägren	Soft Shoulder
Hård vägren	Hard Shoulder
Dragväg	Towpath / Haul Road
Mittenfil	Center Lane
Refug	Pedestrian Refuge
Mittremsa	Median Strip

Appendices C – SPARQL queries

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX citygml: <http://www.opengis.net/citygml/2.0/>
PREFIX transport: <http://www.opengis.net/citygml/transportation/2.0/>
PREFIX p3cim: <http://digitalsamverkan.se/ont/3cim#>
PREFIX tne: <http://www.triona.se/TNE#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX geo: <http://www.opengis.net/ont/geosparql#>
PREFIX gml: <http://www.opengis.net/gml/>
PREFIX tnedk: <http://www.triona.se/TNE/nvdb_dk#>
SELECT ?trafficArea ?linkSequence ?linkSequenceOid ?geom (SAMPLE(?vhTyp) as ?väghållartyp) (SAMPLE(?vhNamn) as ?väghållare)
(GROUP_CONCAT(DISTINCT ?gtValue; SEPARATOR=", ") AS ?gatutyp) (MAX(?fvkValue) as ?funktionellVägklass) (MIN(?hgValue) as
?hastighetsgräns) (MAX(?slValue) as ?slitlager) (AVG(?vbValue) as ?vägbredd) (GROUP_CONCAT(DISTINCT ?gnValue; SEPARATOR=",
") AS ?gatunamn)
WHERE
{
    ?linkSequence tne:oid ?linkSequenceOid .
#    ?linkSequence geo:hasGeometry/geo:asWKT ?geometriMedCRS .
#    BIND(STRAFTER(xsd:string(?geometriMedCRS), "> ") as ?geom)
    {
        SELECT ?trafficArea ?linkSequenceOid ?geom WHERE
        {
            #3CIM (Ontop-VKG mot 3DCityDB)
            SERVICE <http://13.79.36.131:8000/sparql>
            {
                ?trafficArea a transport:TrafficArea .
                ?trafficArea citygml:externalReference ?extRef .
                ?extRef p3cim:name ?linkSequenceOid .
            }
        }
    }
}
```

```

        ?trafficArea a transport:TrafficArea .
        ?trafficArea transport:lod2MultiSurface/gml:surfaceMember/geo:asWKT ?geomCRS .
            BIND(STRAFTER(xsd:string(?geomCRS),"> ") as ?geom)
        }
    }
}
# Vāghållare
OPTIONAL
{
    ?vh a tnedk:PropertyObjectType-1-2 .
    ?vh tne:validFrom ?vhValidFrom .
        ?vh tne:expiredFrom ?vhExpiredFrom .
    FILTER(?vhValidFrom <= "2026-01-12"^^xsd:date && ?vhExpiredFrom > "2026-01-12"^^xsd:date)
    ?vh tne:hasExtent ?vhExtent .
    ?vhExtent tne:hasNetworkElement ?linkSequence .
        ?vh tnedk:PropertyObjectPropertyType-1-2-6/rdfs:label ?vhTyp .
        ?vh tnedk:PropertyObjectPropertyType-1-2-7 ?vhNamn .
    }
# Hastighetsgrāns
OPTIONAL
{
    ?hg a tnedk:PropertyObjectType-1-48 .
    ?hg tne:validFrom ?hgValidFrom .
    ?hg tne:expiredFrom ?hgExpiredFrom .
    FILTER(?hgValidFrom <= "2026-01-12"^^xsd:date && ?hgExpiredFrom > "2026-01-12"^^xsd:date)
    ?hg tne:hasExtent ?hgExtent .
    ?hgExtent tne:hasNetworkElement ?linkSequence .
        ?hg tnedk:PropertyObjectPropertyType-1-48-225/rdfs:label ?hgValue .
    }
# Gatutyp

```

OPTIONAL

```
{
  ?gt a tnedk:PropertyObjectType-1-100 .
  ?gt tne:validFrom ?gtValidFrom .
  ?gt tne:expiredFrom ?gtExpiredFrom .
  FILTER(?gtValidFrom <= "2026-01-12"^^xsd:date && ?gtExpiredFrom > "2026-01-12"^^xsd:date)
  ?gt tne:hasExtent ?gtExtent .
  ?gtExtent tne:hasNetworkElement ?linkSequence .
  ?gt tnedk:PropertyObjectPropertyType-1-100-512/rdfs:label ?gtValue .
}
```

Funktionell vägklass

OPTIONAL

```
{
  ?fvk a tnedk:PropertyObjectType-1-38 .
  ?fvk tne:validFrom ?fvkValidFrom .
  ?fvk tne:expiredFrom ?fvkExpiredFrom .
  FILTER(?fvkValidFrom <= "2026-01-12"^^xsd:date && ?fvkExpiredFrom > "2026-01-12"^^xsd:date)
  ?fvk tne:hasExtent ?fvkExtent .
  ?fvkExtent tne:hasNetworkElement ?linkSequence .
  ?fvk tnedk:PropertyObjectPropertyType-1-38-181/rdfs:label ?fvkValue .
}
```

Slitlager

OPTIONAL

```
{
  ?sl a tnedk:PropertyObjectType-1-30 .
  ?sl tne:validFrom ?slValidFrom .
  ?sl tne:expiredFrom ?slExpiredFrom .
  FILTER(?slValidFrom <= "2026-01-12"^^xsd:date && ?slExpiredFrom > "2026-01-12"^^xsd:date)
  ?sl tne:hasExtent ?slExtent .
  ?slExtent tne:hasNetworkElement ?linkSequence .
}
```

```

        ?sl tnedk:PropertyObjectType-1-30-152/rdfs:label ?slValue .
    }
# Vägbredd
OPTIONAL
{
    ?vb a tnedk:PropertyObjectType-1-31 .
    ?vb tne:validFrom ?vbValidFrom .
    ?vb tne:expiredFrom ?vbExpiredFrom .
    FILTER(?vbValidFrom <= "2026-01-12"^^xsd:date && ?vbExpiredFrom > "2026-01-12"^^xsd:date)
    ?vb tne:hasExtent ?vbExtent .
    ?vbExtent tne:hasNetworkElement ?linkSequence .
    ?vb tnedk:PropertyObjectType-1-31-156 ?vbValue .
}
# Gatunamn
OPTIONAL
{
    ?gn a tnedk:PropertyObjectType-1-20 .
    ?gn tne:validFrom ?gnValidFrom .
    ?gn tne:expiredFrom ?gnExpiredFrom .
    FILTER(?gnValidFrom <= "2026-01-12"^^xsd:date && ?gnExpiredFrom > "2026-01-12"^^xsd:date)
    ?gn tne:hasExtent ?gnExtent .
    ?gnExtent tne:networkElementRef ?linkSequenceOid .
    ?gn tnedk:PropertyObjectType-1-20-130 ?gnValue .
}
}
GROUP BY ?trafficArea ?linkSequence ?linkSequenceOid ?geom

```

SPARQL query B1. Linking CityGML 3CIM and NVDB

Department of Physical Geography and Ecosystem Science

Master Thesis in Geographical Information Science

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