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Enhancing Geospatial Data Integration and Completeness through Semantic Web and Linked Open Data

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ABSTRACT

This paper investigates methods for improving the integration and completeness of heterogeneous geospatial datasets using Semantic Web technologies and Linked Open Data. Interoperability issues, fragmented data sources, and incomplete datasets remain persistent challenges in the geospatial domain—often exacerbated by proprietary formats and lack of coordination among stakeholders. To address these, we propose an ontology-based approach built on the principles of knowledge representation and reasoning. By leveraging the Universal Spatial Knowledge Base (USKB) and rule-based inference mechanisms, our method facilitates semantic interoperability and supports completeness analysis across diverse data sources. As a demonstration of this approach, we present SPALOD (Spatial Data Management with Semantic Web Technology and Linked Open Data), a platform designed to integrate and manage complex geospatial datasets. SPALOD illustrates how semantic reasoning can ensure consistent data quality, enhance interoperability, and enable seamless integration across systems. Our results underline the feasibility and impact of semantic-enriched data management strategies in the geospatial context, offering a scalable solution for harmonizing and enriching spatial information about bicycle network.

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Keywords: SPALOD, Semantic Web Technology, Linked Open Data, Interoperability, GIS, Ontology Based Framework, Geospatial Data Management

Abbreviations

The following abbreviations are used in this manuscript:

ADMS: Asset Description Metadata Schema
GIS: Geographic Information Systems
INSPIRE: Infrastructure for Spatial Information in the European Community
LOD: Linked Open Data
OGC: Open Geospatial Consortium
OWL: Web Ontology Language
PSS: Planning Support Systems
RDF: Resource Description Framework
SCPS: Semantic City Planning systems
SDI: Spatial Data Infrastructure
SPALOD: Spatial Data Management with Semantic Web Technology and Linked Open Data
USKB: Universal Spatial Knowledge Base
GDI: Geospatial Data Infrastructures

Introduction

The increasing availability of geospatial data on the Web and the Linked Data platforms offers significant opportunities to improve data management in various sectors. However, effective integration of heterogeneous geospatial data remains a key challenge. In domains that depend on comprehensive data models, such as infrastructure management, the ability to merge disparate data sources into a unified framework is essential. These challenges are particularly pronounced in contexts where data fragmentation, lack of interoperability, and incomplete datasets hinder informed decision-making.

Data heterogeneity, where geospatial data come from various sources and follow different standards and formats, is a fundamental obstacle. Integrating these diverse datasets requires robust data harmonization strategies to achieve a unified and accessible model. In the field of geospatial data management, the need for interoperability is especially pressing, ensuring that data can be seamlessly accessed and used across platforms, both by technical experts and non-technical stakeholders. This aligns with broader international standards, such as the INSPIRE, which promotes the standardized exchange and use of geographic information.

Another critical issue is the accessibility of geospatial data for a wide range of users. Geospatial data must be presented in a manner that addresses the needs of multiple stakeholders, including policymakers, planners, and the public. The diversity of these needs requires a flexible platform capable of offering real-time, historical, and standardized data. Additionally, proprietary solutions can create further barriers, limit collaboration and reducing the potential for unified data management.

In this context, the SPALOD platform (Spatial Data Management with Semantic Web Technology and Linked Open Data) was developed to address the challenges of data heterogeneity, interoperability, and completeness. SPALOD integrates

Semantic Web technology with an ontology-based framework to manage various spatial datasets. The platform also incorporates the Universal Spatial Knowledge Base (USKB), a repository designed to accommodate dynamic data sources through machine learning. The SPALOD ontology-based framework is central to the resolution of the complexities of spatial data management. Using ontologies, the platform standardizes diverse datasets, facilitating their integration and use across various applications. The USKB further enhances this by serving as a centralized knowledge base that supports the integration of spatial data from multiple sources, while ensuring that the data remain accessible and useful for different stakeholders.

In this paper, we examine the challenges associated with managing heterogeneous spatial data and how SPALOD addresses them. We begin by exploring issues such as data fragmentation, lack of interoperability, and the complications posed by proprietary data solutions. We then introduce the SPALOD platform, highlighting (1) its ontology-based framework, (2) its capabilities for data integration and accessibility, and (3) its approach to enhancing data completeness. Finally, we discuss the results of applying SPALOD to a case study on cycling networks, demonstrating its potential to improve spatial data management practices.

Related Work

In recent years, the growing availability of spatial data and the emergence of Linked Data platforms have created new opportunities for managing complex datasets across diverse sectors. However, the integration of heterogeneous spatial data remains a significant challenge, as the fragmentation of data sources and lack of interoperability continue to hinder effective data management. This section reviews key developments in the field, including the role of Semantic Web technologies, the application of ontologies, and the potential of platforms like SPALOD to address these challenges by harmonizing diverse spatial data into a unified framework.

Data Heterogeneity and Fragmentation in Spatial Data Management

Spatial data management faces significant challenges due to data heterogeneity, where data is sourced from various platforms, each following different formats and standards. This heterogeneity is a major obstacle for achieving integrated and unified data models necessary for comprehensive analysis and decision-making [1-3].

Several approaches have been proposed to address these issues. One common solution is schema mapping, where efforts are made to align data models from different sources by creating correspondence rules between them [4-6]. Manual data integration has also been applied in numerous cases, but this method is time-consuming and prone to inconsistencies, particularly in large-scale systems with rapidly changing data [7].

Despite these efforts, unifying spatial datasets into coherent frameworks remains challenging. The complexity of maintaining data accuracy, completeness, and consistency across different sources is a recurring issue in spatial data systems [8-10]. The need for more robust data harmonization strategies, particularly those that can scale and adapt to new data sources, is essential for advancing spatial data management practices.

Proprietary Solutions and Barriers to Data Collaboration

Proprietary formats and systems present significant challenges for data collaboration and sharing across organizations. These closed systems often restrict access to data or require specialized software, making it difficult for different entities to work together or share spatial data efficiently [11,12]. The lack of interoperability between proprietary systems creates data silos, limiting the potential for broader data analysis and decision-making.

In response to these challenges, there has been a growing movement toward open data standards and increased data sharing across organizations. These movements advocate for the use of non-proprietary formats and platforms that promote transparency, accessibility, and interoperability. Open standards such as OGC (Open Geospatial Consortium) have been instrumental in fostering collaboration by providing standardized protocols for spatial data sharing [13,14].

There are several examples of successful open data initiatives that have led to greater collaboration and more effective data management. For instance, the implementation of open geospatial data repositories has enabled researchers, policymakers, and the public to access and utilize spatial data without the restrictions imposed by proprietary systems [13,15]. These initiatives demonstrate the potential of open data movements to break down the barriers created by proprietary formats and promote more collaborative data ecosystems.

Linked Open Data for Enhancing Data Accessibility

Linked Open Data (LOD) is a set of principles for publishing structured data in a way that enables it to be interlinked and made accessible across different platforms. By adhering to these principles, spatial data can be published in formats that facilitate easier discovery, integration, and reuse, which is essential for improving the accessibility and interoperability of data across diverse systems [9,16]. The application of LOD in spatial data management has allowed users from various sectors to access high-quality data more efficiently.

There are several examples where LOD has been successfully used to improve spatial data accessibility. For instance, LOD frameworks have been implemented to create public geospatial datasets that are available for policymakers, researchers, and the general public [17-19]. These examples illustrate how LOD can make spatial data more accessible, increasing transparency and collaboration among different stakeholders.

However, despite its benefits, current LOD implementations face challenges. One of the primary limitations is ensuring data completeness, especially when spatial data is derived from multiple, inconsistent sources. Furthermore, real-time data integration remains a significant challenge, as many LOD systems are not optimized for dynamic updates or streaming data [20-22]. Addressing these gaps is crucial for realizing the full potential of LOD in spatial data management.

Interoperability and the Role of International Standards

Interoperability is crucial in spatial data management, as it ensures seamless data access and usage across platforms and user groups. The ability to integrate data from different systems is vital for creating comprehensive and accurate spatial models [23-25]. Without interoperability, data fragmentation persists, limiting the utility of spatial datasets for decision-making purposes.

Several international standards have been developed to address these challenges, with the INSPIRE directive being one of the most notable examples. INSPIRE promotes the standardized exchange and use of geographic information across Europe, helping to improve the accessibility and interoperability of spatial data [26]. This directive and similar initiatives have significantly advanced the field of spatial data management by providing a framework for harmonizing data from different sources.

However, while initiatives like INSPIRE have made progress, they are often insufficient for addressing the full complexity of spatial data, especially in contexts requiring real-time data integration or historical data management. These standards primarily focus on data formats and metadata, leaving gaps in areas such as real-time processing and the dynamic nature of spatial data [27-29]. As a result, additional strategies and technologies are needed to fully manage the challenges posed by heterogeneous spatial data.

Semantic Web Technologies in Spatial Data Integration

Semantic Web technologies have played a pivotal role in improving the sharing and interoperability of spatial data across diverse systems. Technologies such as RDF, OWL, and SPARQL provide a framework for representing, linking, and querying spatial data, which enables integration across different platforms and systems [22,30]. These technologies enhance the flexibility and scalability of spatial data management by allowing different datasets to interoperate seamlessly, despite originating from heterogeneous sources.

Ontologies have been particularly useful in structuring and standardizing spatial data, ensuring that diverse datasets can be integrated and used effectively. By defining shared vocabularies and relationships between spatial concepts, ontologies enable more consistent data integration and make it easier for systems to interpret and utilize the data [31-33]. This ontology-driven approach is crucial for improving the accessibility and usability of spatial data, particularly in complex, multi-source environments.

Several platforms and case studies have demonstrated the effectiveness of Semantic Web technologies in spatial data integration. For instance, projects that have implemented Semantic Web frameworks to manage large-scale spatial data have shown improvements in data accessibility, interoperability, and overall system performance [21,34]. These platforms highlight the benefits of applying RDF, OWL, and SPARQL, but also reveal challenges such as the complexity of ontology development and the need for efficient querying mechanisms in large datasets.

The Use of Ontologies and Rule-Based Inference in Data Completeness

Ontologies play a crucial role in standardizing and structuring diverse data sources, enabling the creation of a unified framework for managing spatial data. By defining shared vocabularies and relationships, ontologies provide a formalized structure that facilitates the integration of heterogeneous data. This standardization is essential for ensuring that spatial data from different sources can be interpreted and utilized in a consistent and reliable manner [3,35,36].

In addition to ontologies, rule-based inference mechanisms are used to ensure data completeness and consistency within spatial data management systems. Rule-based inference allows systems to automatically deduce missing or implicit information based on predefined rules and relationships between data elements. In platforms like SPALOD, rule-based inference plays a critical role in verifying data integrity and ensuring that datasets are complete and accurate [4,37,38]. This approach is particularly beneficial in complex systems where manual validation of data completeness is infeasible.

Several existing frameworks and platforms have successfully implemented ontologies and rule-based inference to manage spatial data completeness. These systems demonstrate the effectiveness of combining semantic technologies with automated inference for improving data quality and reliability. Examples of such frameworks illustrate the practical benefits of ontologies in structuring data and inference in maintaining the accuracy of large-scale spatial datasets [37].

Discussion

Despite advancements in spatial data management platforms like SPALOD, several key challenges remain, particularly around the integration of heterogeneous data sources and the effective management of evolving datasets. As spatial data becomes increasingly diverse—ranging from structured geospatial records to unstructured sensor data—the ability to harmonize and integrate this information within a unified framework is essential. Current systems often face limitations when dealing with semantic inconsistencies, varying data formats, and incomplete metadata, which complicate data fusion and analysis.

Another critical aspect is managing data versions across time. Spatial datasets are not static; they evolve, are corrected, and updated over time. Ensuring traceability, consistency, and the ability to retrieve and work with specific versions of a dataset is a growing concern, particularly in applications such as urban development, environmental monitoring, and public policy planning. Yet, many existing platforms lack comprehensive mechanisms for tracking changes or linking updates semantically.

Furthermore, the usability of these systems plays a crucial role in their broader adoption. Many platforms still require advanced technical knowledge, making them less accessible to stakeholders without specialized training. There is a clear need for user-centric tools that allow domain experts to interact with spatial data more intuitively and effectively.

Semantic Web technologies and Linked Open Data (LOD) offer promising opportunities to address these issues by enabling more interoperable, flexible, and extensible data frameworks. In this paper, we present the SPALOD platform, which aims to address two major challenges identified in this context. First, SPALOD enhances the scalability of semantic technologies to support efficient querying and integration of large, diverse datasets. Second, it introduces novel approaches for managing dynamic and evolving datasets within LOD frameworks, facilitating improved data accessibility, traceability, and reuse in spatial data ecosystems.

Use Case: Spatial Data Integration for Bicycle Network Management in Germany

The use case under consideration focuses on bicycle network management in Germany. Each year, the Federal Agency for Cartography and Geodesy updates the data on the German bicycle network by gathering and integrating data from the various Bundeslaender and comparing them with the current data on the German cycling network. Therefore, the Federal Agency for Cartography and Geodesy has to deal with the challenges of integrating spatial data from various sources. In this context, we explore how the SPALOD platform can support them by harmonizing heterogeneous spatial datasets for different administrative levels. The datasets chosen as a use case for SPALOD platform experimentation aim to promote sustainable and environmentally friendly transportation systems, particularly focusing on bicycle infrastructure at different scales (city-level for Hamburg and national-level for Germany).

The dataset at the city-level for Hamburg is called Hamburg's "Verkehrsentwicklungsplanung". It is composed of 30 Shapefiles containing different infrastructures such as leisure routes, cycle path, or cycle road for example. The dataset called "Bicycle Network Germany" [39] is centered around the development of a comprehensive national cycling network at the national-level for Germany. It is a GeoJSON file that contains also different infrastructures whose D-Routes and other cycling infrastructures. The D-Routes include D-Route 1 "Nordseeküstenroute," D-Route 7 "Pilgerroute," and D-Route 10 "Elberadweg," that are integral components of the "Bicycle Network Germany" initiative. These routes are designed to connect different regions of the country and provide cyclists with safe and scenic pathways for long-distance cycling, tourism, and commuting.

The method presented in the next section will detail how SPALOD integrates and standardizes spatial data from diverse sources including specific data for bicycle network, using a common vocabulary to provide a unified view for infrastructure management and decision-making processes.

Method

In the evolving landscape of infrastructure management such as cycling network, the integration of diverse spatial datasets has become increasingly important. Recognizing the need for a systematic approach to manage and understand the complexities of infrastructure networks, we have developed the SPALOD (Spatial Data Management with Semantic Web Technology and Linked Open Data) platform. This platform provides a structured, semantic framework for representing the diverse spatial elements, enabling better decision-making and data analysis across different sectors or different administrative levels.

Purpose and Scope

The primary purpose of SPALOD is to offer a standardized model for representing various aspects of geospatial data, including physical characteristics, connectivity, and maintenance status. By creating a common vocabulary and structure for these datasets, the platform facilitates improved data management, interoperability, and informed decision-making. SPALOD serves as a foundational tool for policymakers, infrastructure managers, and researchers, enabling the efficient integration, accessibility and analysis of heterogeneous geospatial data.

To fulfill this purpose, the platform's design satisfies several key requirements. It allows for the representation of (i) geospatial data and their attributes, (ii) bicycle network and their components, and (iii) geospatial datasets, including their versions and metadata.

Moreover, ensuring accessibility and interoperability of geospatial data within SPALOD is crucial for infrastructure management. The platform has been designed to maximize interoperability, enabling seamless data exchange and use across different systems and stakeholders. This section explains how the ontological representation and geospatial data accessibility have been designed to address the challenges of managing heterogeneous spatial data for bicycle network management.

Ontological Representation to Support Bicycle Network Management through Spatial Data Integration

Developed using RDF and OWL, the ontology reflects our commitment to leveraging standard Semantic Web technologies. The development process involved consulting existing standardized vocabularies, available datasets, and incorporating feedback from experts in bicycle network management. We acknowledge that this process is an ongoing endeavor, with ample room for future growth and improvement.

Overview of the Ontology

The created ontology integrates various vocabularies that have been harmonized to meet the requirements outlined earlier. To represent geospatial data and their attributes, the ontology builds upon the Universal Spatial Knowledge Base (USKB) presented in, incorporating the GeoSPARQL vocabulary for geospatial data representation and the schema.org vocabulary to capture the diverse attributes that geospatial data may possess [40,41].

To represent more specially the cycling routes, an ontological representation of the "National Bicycle Network Schema" has been added and linked to the ontology. This ontological representation is a modest attempt to bring structure and standardization to the domain of cycling infrastructure. It is based on the work provided by the Federal Agency for Cartography and Geodesy, Germany. While it represents an initial step towards addressing complex data representation challenges in this field, it is very much a work in progress, and we are aware of its limitations and the need for ongoing refinement.

Finally, to meet the requirement of managing geospatial datasets and their various versions, we have integrated the Asset Description Metadata Schema (ADMS) (https://www.w3.org/TR/vocab-adms/) and GeoDCAT [42]. Additional classes and properties were developed to bridge the gaps between the various ontologies and vocabularies used, ensuring a uniform and complete knowledge base for infrastructure management.

Figure 0 summarizes the different components that make up the ontological representation within the USKB framework.

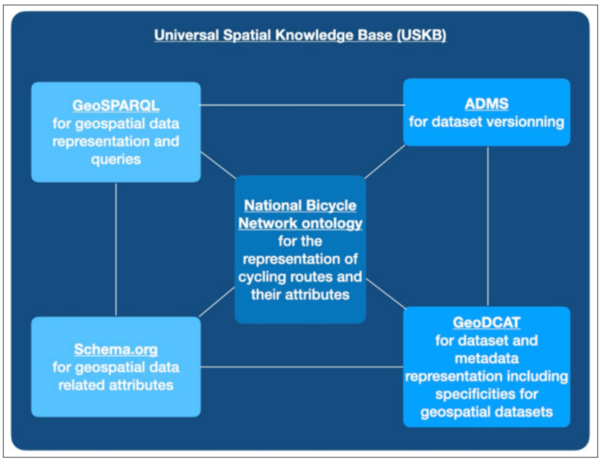

Figure 1: Overview of the Ontology Components

Geospatial Data Representation

The geospatial data representation is built upon previous work, incorporating the GeoSPARQL and schema.org vocabularies to form the Universal Spatial Knowledge Base (USKB) [40]. The purpose of this USKB is to harmonize geospatial data from diverse sources, enabling seamless integration and interoperability. Furthermore, intelligent mechanisms have been developed to map and link integrated data to these vocabularies, ensuring a standardized approach to managing infrastructure-related geospatial information. The USKB serves as our foundation for improving infrastructure management and decision-making through comprehensive spatial data integration.

Cycling Routes Representation

To address a specific focus on the cycling network integration, we have incorporated an ontological representation of cycling routes inside the USKB. This ontological representation is based on the "National Bicycle Network Schema" created by the Federal Agency for Cartography and Geodesy, Germany (c.f. Figure 1).

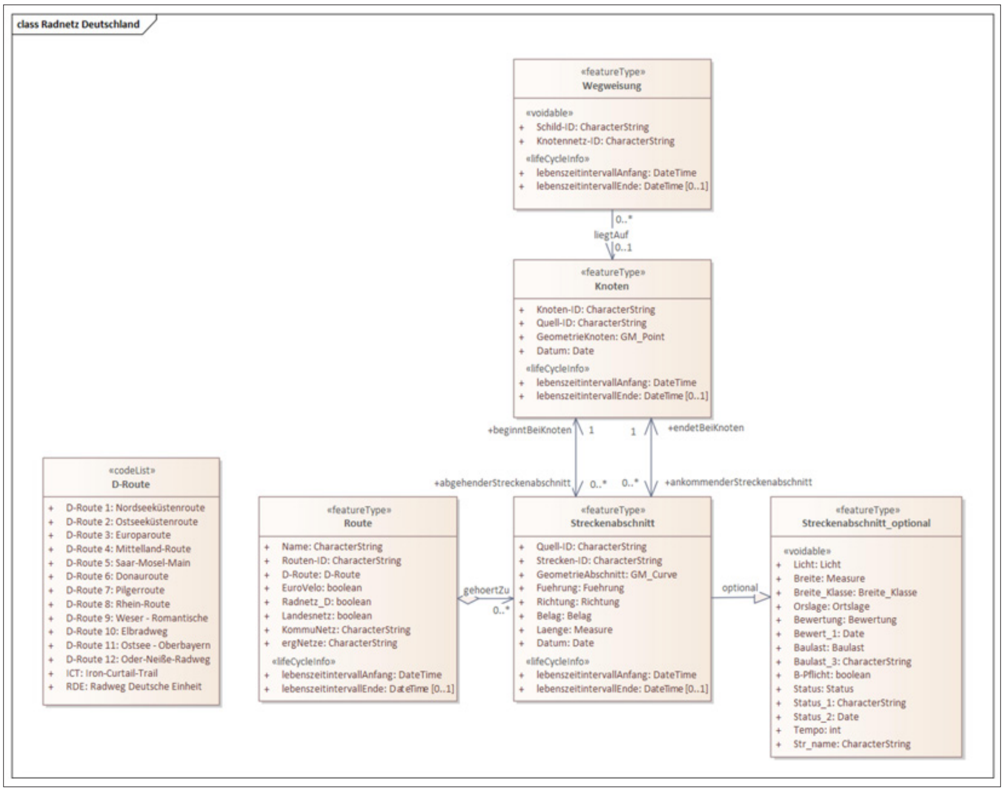

Figure 2: UML Diagram "National Bicycle Network Schema" (Schema made by F. Würriehausen)

The derivation of ontologies is crucial in this context, as it allows for the systematic categorization and organization of complex information into a structured format. Ontologies facilitate the representation of knowledge in a way that is both comprehensible and manageable, especially in domains that involve spatial and geographical data. By mapping this knowledge into classes and properties, we can create a semantic framework that not only accurately represents the real-world structure of cycling networks but also enables efficient querying and analysis. Classes in the ontology represent distinct entities or concepts within the cycling network, such as routes, junctions, and amenities, while properties describe the relationships and attributes of these classes. This structured approach enhances data interoperability and supports advanced spatial reasoning, ultimately contributing to more effective planning and management of cycling infrastructure.

In detail, the following basic components are included:

Classes

Fundamental elements representing key entities in the cycling network. For instance, Route for cycling paths: KnotenType (Node Type) for junctions or intersections, and Streckenabschnitt Type (Route Segment Type) for specific segments of a route.

Properties

These are divided into: Object Properties: Linking classes to establish relationships. For example, abgehenderStreckenabschnitt (departing route segment) connects nodes to route segments. Data Properties: Assigning specific data values to classes. For instance, datum (date) provides temporal information about route segments or nodes.

Relationships and Constraints

Defining the interaction between classes. For instance, a route segment (StreckenabschnittType) must connect to at least one node (KnotenType), establishing a network of interconnected paths.

To provide a comprehensive understanding of the ontology we've developed for cycling infrastructure, it's essential to delve into its primary concepts and how they are organized. The ontology's main concepts revolve around the physical and administrative aspects of cycling infrastructure:

- Route and Segment Concepts: Representing different types of cycling routes or portion and their specific characteristics, such as surface type, width, and maintenance status.
- Node Concepts: Describing junction points in the network, which are critical for mapping and navigation purposes.
- Interrelationships: For instance, a route segment is related to nodes at both ends, and segments are interconnected to form complete routes.
- Hierarchical Structure: The ontology includes subclasses to represent specific types of routes and nodes, such as primary, secondary, or recreational paths, each with unique attributes and roles in the network.
- Logical Rules and Axioms: These govern the relationships and constraints within the ontology. For example, a logical rule might state that every: Streckenabschnitt Type must connect two different: Knoten Type entities.

The ontology introduces fundamental concepts such as route types and node characteristics. The relationships established, such as between route segments and nodes, are basic and might not fully encapsulate the intricacies of actual cycling networks.

Datasets and Metadata Representation
The Asset Description Metadata Schema (ADMS) is a vocabulary presented by the W3C to describe datasets, including their versioning and metadata. It is a profile of DCAT, an RDF vocabulary designed to facilitate access to and interoperability of data catalogs published on the Web. GeoDCAT, also based on DCAT, has been developed as a standard by the Open Geospatial Consortium (OGC) specifically for geospatial datasets. These two vocabularies, rooted in DCAT, allow us to meet the requirements for representing geospatial datasets, their metadata, and different versions in the context of infrastructure management.

Geospatial Data Accessibility for Infrastructure Management
The integration of various ontological representations within the SPALOD platform, combined with the implementation of Open Geospatial Consortium (OGC) API standards and the use of Semantic Web technologies, represents a significant advancement in infrastructure management. This integration aims to fully leverage the capabilities of the knowledge base, making it more accessible and actionable for infrastructure managers and decision-makers. The development of a SPARQL endpoint that interfaces with GIS tools such as QGIS (a widely-used open-source Geographic Information System) further enhances the practical application of this integrated system.

Integration into the Universal Spatial Knowledge Base (USKB)
The USKB serves as a central repository for infrastructure data, including geospatial information, regulations, and technical details of infrastructure networks. By integrating infrastructure-related ontologies into the USKB, we enrich this knowledge base with structured, standardized data specific to infrastructure management. This integration facilitates more effective data retrieval, comparison, and analysis, leading to more informed decision-making in infrastructure planning, monitoring, and development.

Implementation of OGC API Records
The adoption of OGC API Records is a crucial step in ensuring that our spatial data remains accessible and interoperable with other geospatial data systems [43]. OGC standards promote the seamless sharing and integration of geospatial data, thereby enhancing the reach and utility of our ontology and the USKB. By adhering to these standards, we ensure that our data is compatible with a wide range of infrastructure management tools and platforms, making it a valuable resource for a broader audience.

Exploiting the Knowledge Base with Semantic Web Technologies
The use of Semantic Web technologies, such as RDF and OWL, in the USKB enables advanced data management and querying capabilities. These technologies allow for the representation of complex relationships and hierarchies within the data, making it possible to conduct sophisticated analysis that can reveal insights not readily apparent in traditional database systems. For example, semantic querying can identify patterns in infrastructure usage, maintenance needs, or connectivity gaps in transportation networks, thus informing targeted interventions and improvements across various sectors.

SPARQL Endpoint and QGIS Plugin Connectivity
A key feature of our system is the development of a SPARQL endpoint, which allows for direct querying of the USKB using the SPARQL query language. This capability is especially significant when combined with connectivity to QGIS. By developing a plugin for QGIS those interfaces with our SPARQL endpoint, we enable infrastructure managers and planners to perform complex spatial queries and analysis directly within their familiar QGIS environment [44]. This integration bridges the gap between Semantic Web technologies and practical geospatial analysis tools, supporting more informed and efficient decision-making.

Process of Data Management to Optimize Data Completeness
The proposed method based on Ontology, Linked Open Data and the SPALOD platform aims at supporting decision-making through the identification of missing information inside the knowledge base of cycling routes.

The first step consists in integrating spatial data about cycling routes and segments in Germany into the SPALOD Platform. Each spatial elements are integrated as geo: Feature and as gdi: Route or gdi:Streckenabschnitt according to their related information in accordance with the structure defined by the ontology and illustrated in Figure 1.

The second step consists in using Linked Open Data as Wikidata to complete integrated data. For this step, we use the Wikidata service to retrieve instances (and their linked information) of the following classes: long-distance cycling route (Q353027), cycling route (Q102307360), bike path (Q221722), urban cycling route (Q2512606), bike lane (Q1378400), and cycling infrastructure (Q5198662).

The third step is the inference applied to the ontology, in which the different data have been integrated. This step will firstly match similar instances through the property owl:SameAs and secondly identifies inconsistencies of the data according to the constraints defined in the ontology.

The fourth step consists in highlighting the missing information from the detected inconsistencies in the ontology. This step aims at highlighting incompleteness of integrated data through the identification of missing information and data of a route or a segment. Indeed, Wiki data provides only Point geometries, that are thus integrated as gdi: Route. With the inference step (step 3), Routes from Wiki data will be linked to Routes from other integrated data. Routes that have no link to Segment instances means that there is a lack of data that need to be solved by the integration of new spatial data containing missing segments or missing information, which corresponds to the fifth step.

This method aiming at providing the most complete information of the German cycling network, the steps 5 (new spatial data integration), 6 (inference) and 7 (highlighting of missing information) must be repeated until no more inconsistencies is detected.

Figure 2 shows the different steps of the proposed method based on the SPALOD platform and Linked Open Data to provide the most complete information of the German cycling network to support its management.

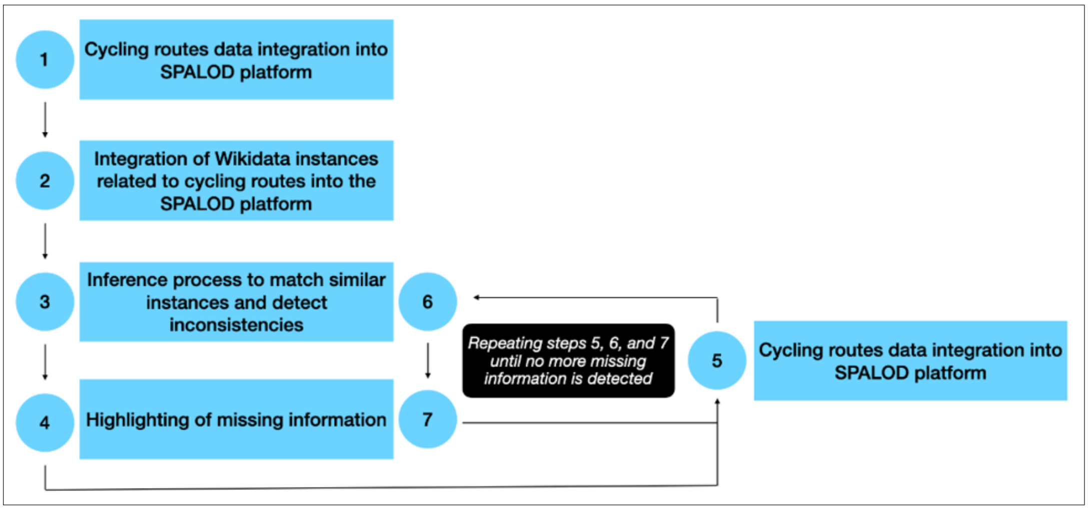

Figure 3: Overview of the Proposed Method (Schema made by C. Ponciano)

Results

The development and implementation of the SPALOD platform represents a significant milestone in our project. SPALOD is a platform designed to manage, integrate, and utilize spatial data effectively. In this section, we discuss the platform's introduction, its rationale key objectives, and its potential impact, along with specific results from its usage in the use case presented in section 3.

SPALOD Platform

The development of SPALOD was driven by the need for a more integrated and intelligent approach for geospatial data management. Traditional spatial data management systems often operate in silos, leading to fragmented data landscapes. SPALOD (available at https://spalod.geovast3d.com/) addresses this challenge by providing a unified platform where different data types and sources can be integrated and queried in a more cohesive and meaningful manner thanks to Semantic Web technologies and Linked Open Data principles.

Figure 11 shows the platform's ability to integrate data from different sources and of different types, ranging from classic geospatial data with various geometries (such as points in Figure 4, and lines in Figure 6), to point clouds as shown in Figure 8 and 9.

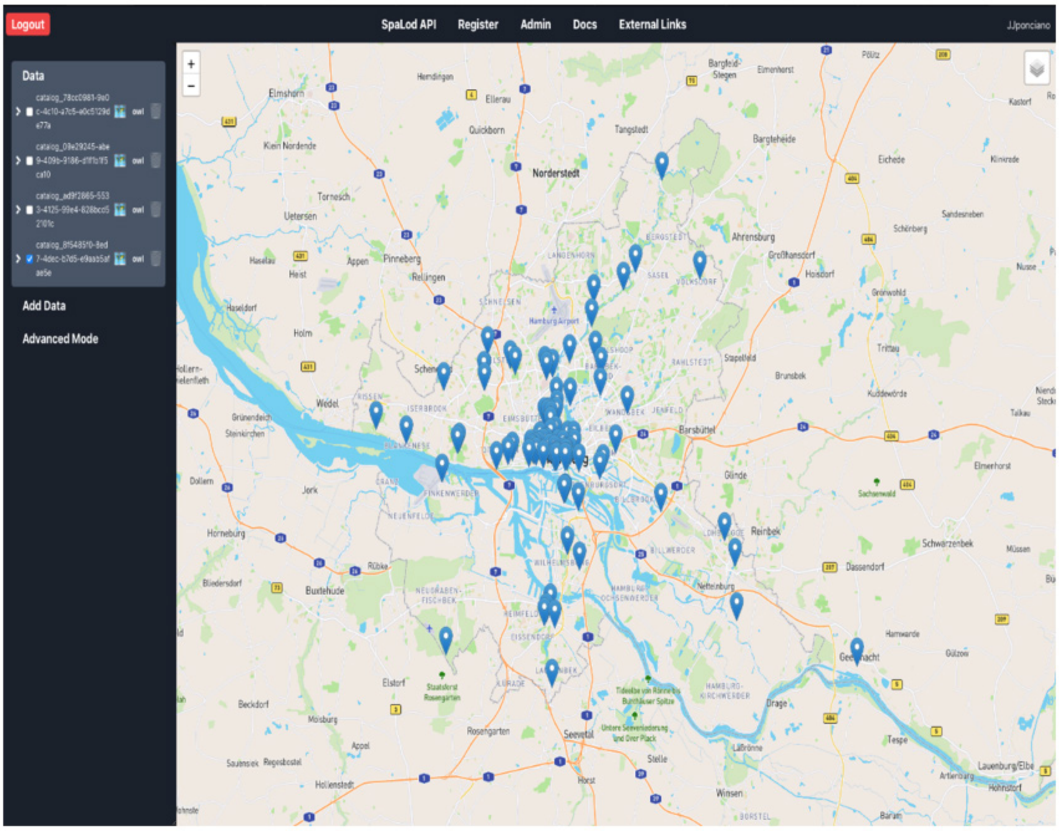

Figure 4: Example of Point Data

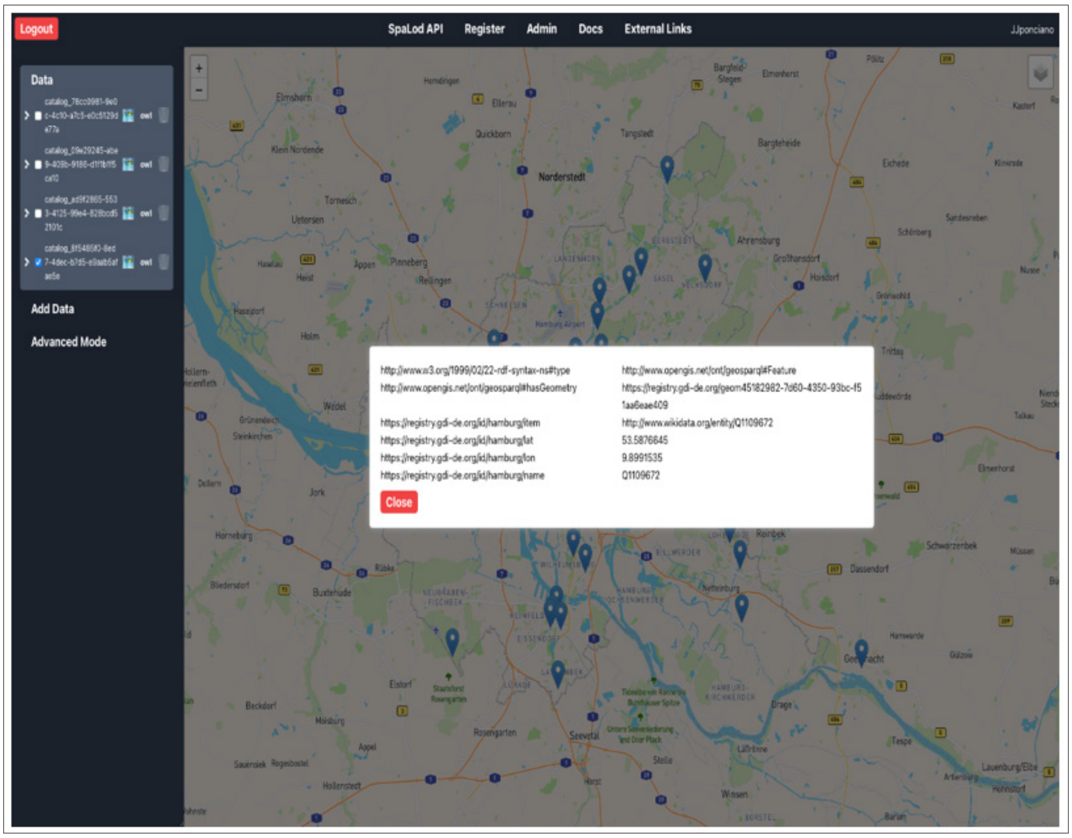

Figure 5: Example of Point Data Information

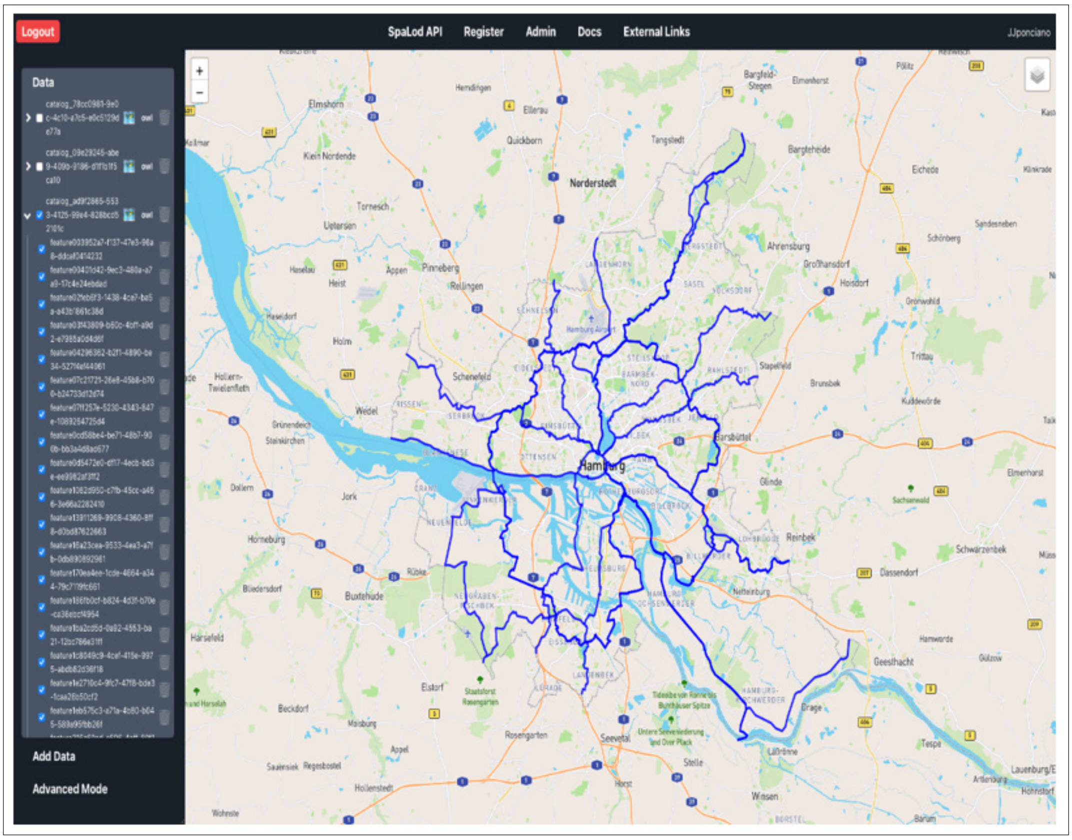

Figure 6: Example of Line Data

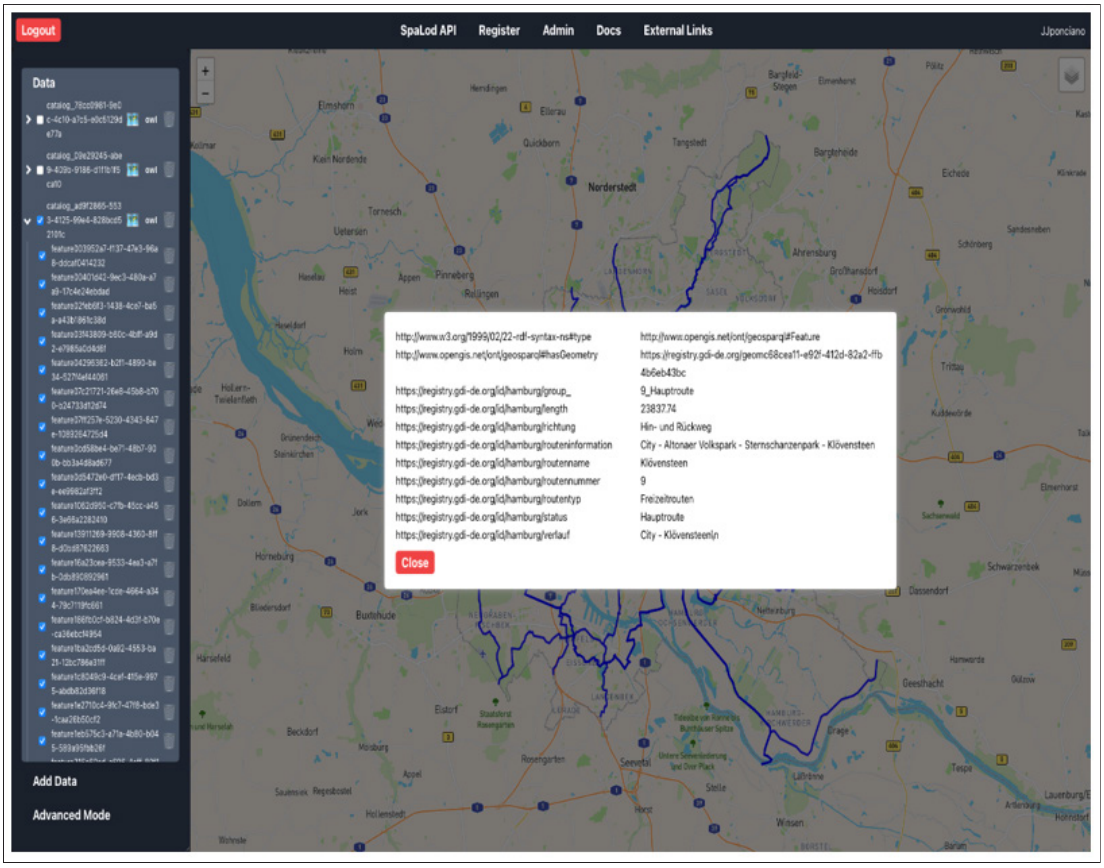

Figure 7: Example of Line Data Information

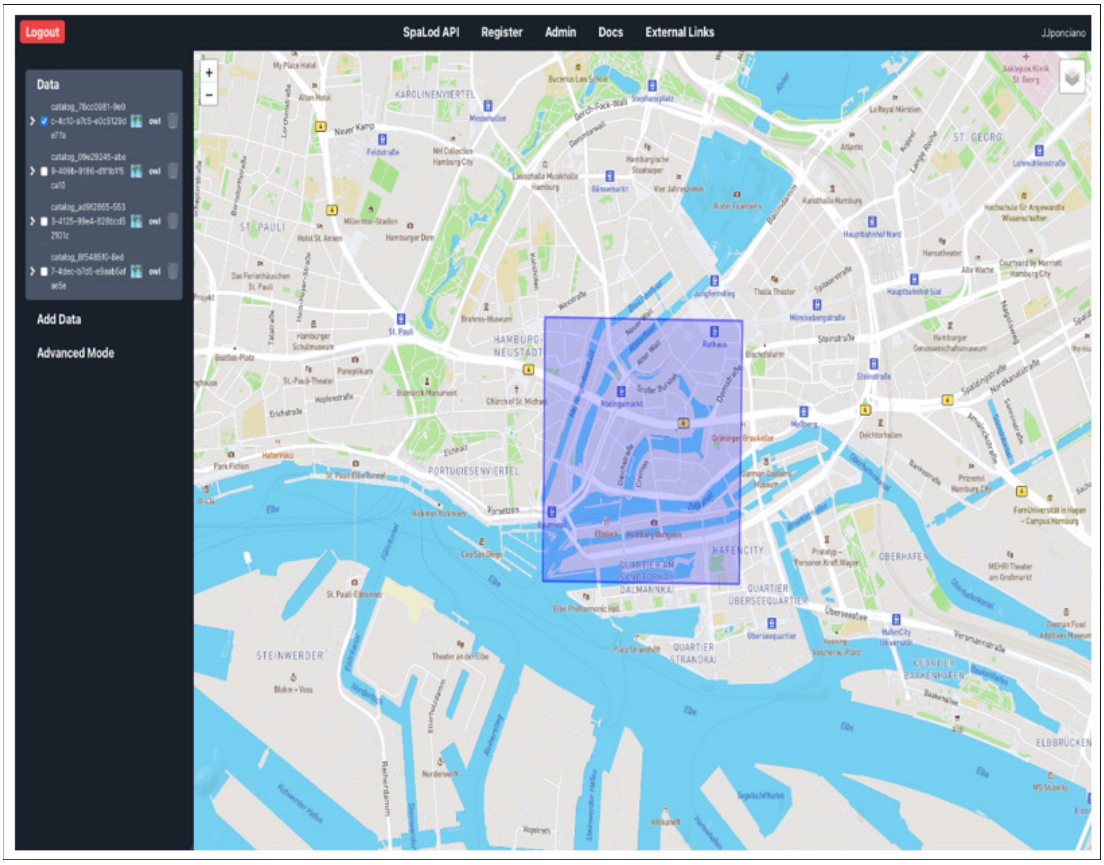

Figure 8: Example of Point Cloud Data

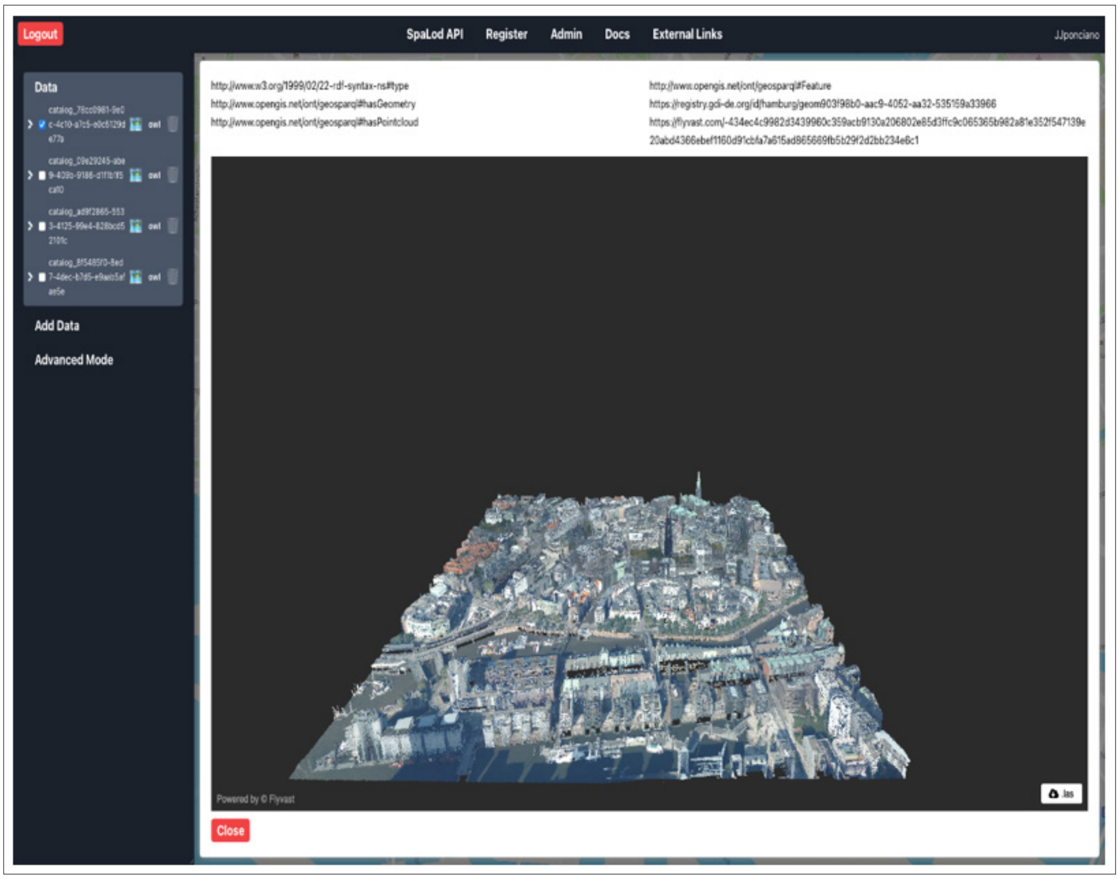

Figure 9: Example of Point Cloud Data Information

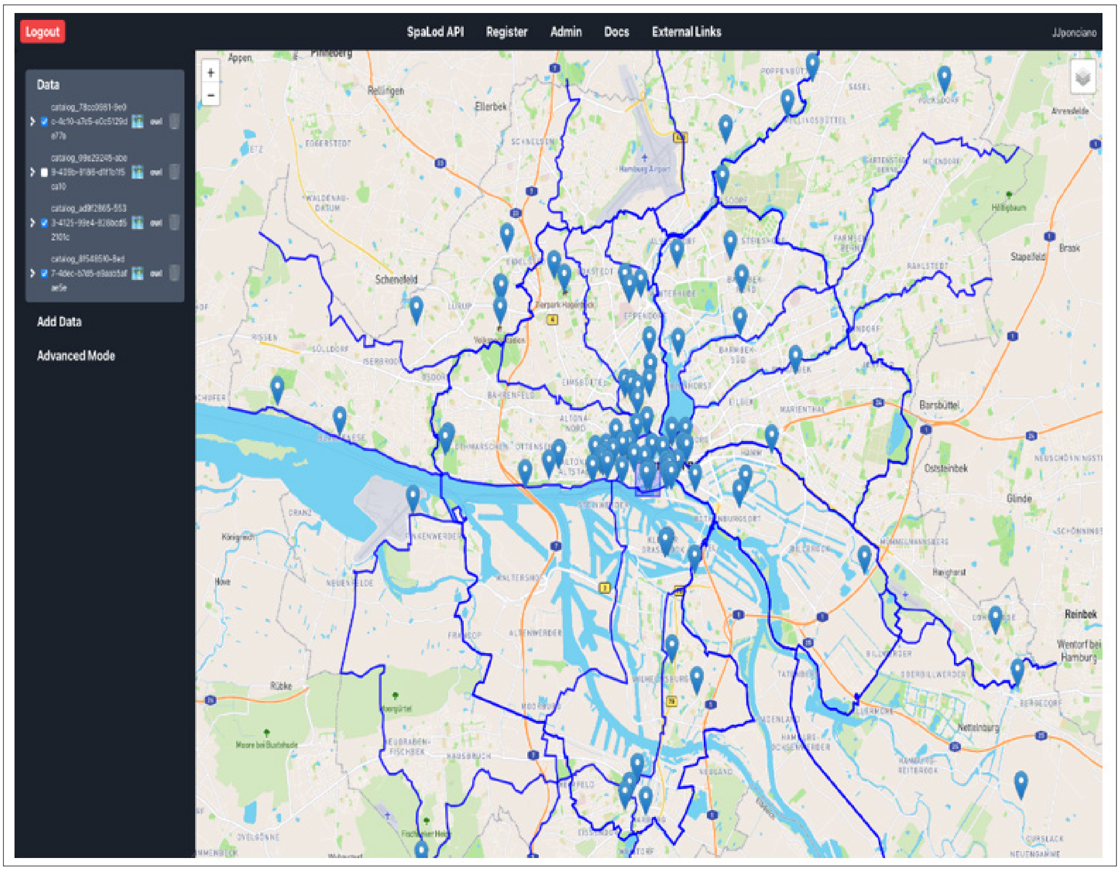

Figure 10: Overview of Heterogeneous Data Display

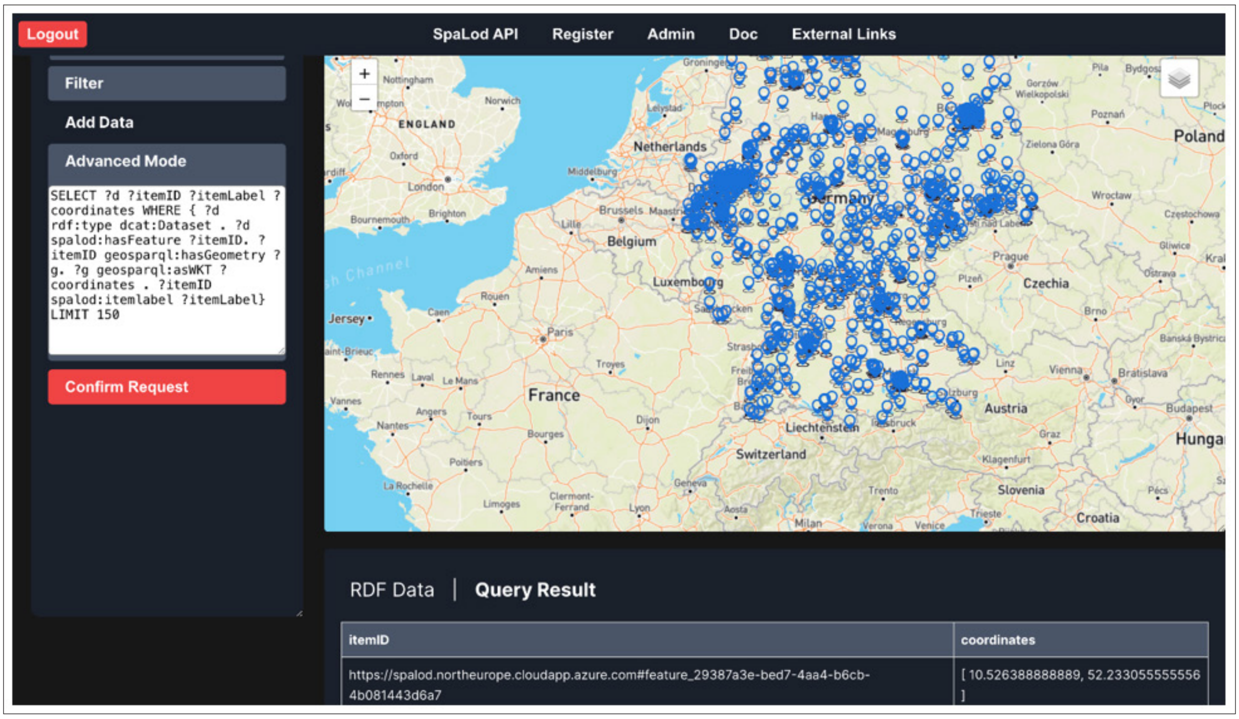

Figure 11: User interface of the SPALOD platform (Screenshots)

SPALOD aims to transform infrastructure management through:

- Metadata and Data Integration: It integrates various datasets, including geospatial data and infrastructure data (such as transportation networks, utilities, and environmental data), into a coherent framework. This integration allows for more comprehensive analysis and decision-making.
- Enhanced Data Accessibility and Usability: By employing Semantic Web standards, Linked Open Data principles and implementing OGC API Records, SPALOD makes data more accessible and easier to use for infrastructure managers, decision-makers, and researchers.

As a web service, SPALOD is built to comply with OGC API standards. This compliance ensures interoperability with other geospatial data services and systems, facilitating broader data sharing and integration. The platform provides access to extensive catalogues, metadata, and spatial data, all conforming to OGC standards for maximum compatibility and usability in infrastructure management. This accessibility is not just about data retrieval; it's about providing a comprehensive understanding of data relationships and dependencies, which is essential for effective decision-making and the management of infrastructure networks.

Use Case Integration Results

The use case presented in this paper aims to illustrate the first four steps of the previously described process of data management to optimize completeness (c.f. section 4.4). It highlights missing information after the integration of datasets related to bicycle network from different sources. This use case is an initial step towards providing a comprehensive overview of national infrastructure networks, supporting decision-making processes in infrastructure management.

Results of step 1: Integration of cycling routes and segments from Hamburg and from the "Bicycle Network Germany"

Figure 11 shows the integrated data from two sources: Hamburg's dataset represented in blue and the "Bicycle Network Germany" in red.

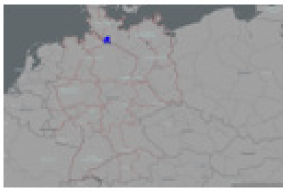

Figure 12: Overview of the integrated cycling network data (Screenshot)

Segments in red come from the dataset "Cycle Network Germany", whereas the blue segments come from the Hamburg dataset.

The data in the Hamburg dataset contains segments with information about the associated route: length, route name, direction, route type, route number, group, course, route information, status and geometry. The properties route name, route type, route number and route information are information relating to the route to which the segment belongs. Therefore, for each segment of the dataset, firstly, an instance of gdi: Route was created with the properties gdi: name for route name, gdi: routen-ID for route number and two newly added data properties for route type and route information. Secondly, an instance of gdi: Streckenabschnitt (Route segment) and geo: Feature was created. This instance is linked to the associated route via the object property gdi: hasRoute. The other properties relating to the section were added via the properties gdi: laenge for length, gdi: Richtung for direction and geo: hasGeometry for geometry, which is linked to a WKT via geo: asWKT. New properties have been added for the properties: group_, course and status (which do not correspond to the gdi: status properties in the ontology). Figure 12 shows an example of properties that belong to an integrated route section of Hamburg.

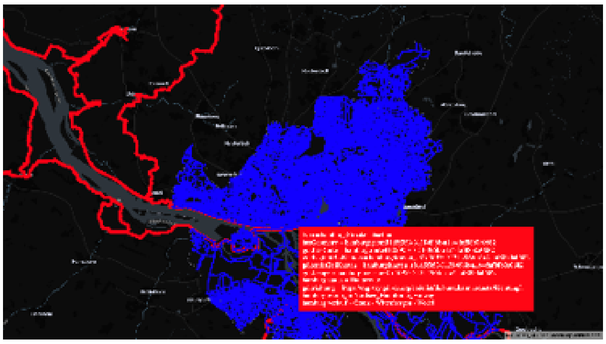

Figure 13: Display on the Map of an Integrated Route Section of Data from Hamburg

The dataset of "Bicycle Network Germany" contains segments with five properties: status, FID, layer, route number and geometry. Each of the segments contained in this dataset has been integrated as an instance of gdi: Streckenabschnitt (Route segment) and geo: Feature. Their geometry was added via the data property geo: asWKT, which is linked to an instance of geo: Geometry, which in turn is linked to its feature via the object property geo: has Geometry. For three of the other four properties, an equivalence was defined in the ontological structure: gdi: datum for status, gdi: quell-ID for FID, and gdi: d-Route for route number. The property layer was integrated as a new data property. Each of these properties has been linked to a segment, with the exception of the gdi: d-Route property, which is a property of a route instance created as the route to which the segment belongs. Figure 13 shows an example of properties that belong to an integrated route segment of "Bicycle Network Germany".

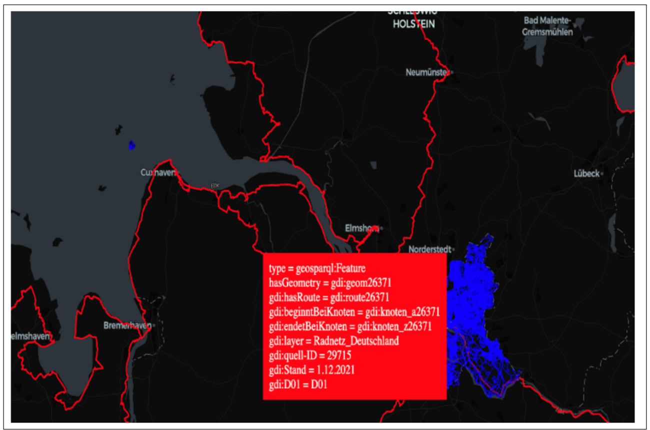

Figure 14: Display on the Map of an Integrated Route Section of Bicycle Network Germany

Results of Step 2: Integration of Wiki data Instances

The queries applied on Wiki data to retrieve the instances in Germany of the defined classes of the process step 2 have provided the following results:

- long-distance cycling route (Q353027): 118 instances,
- cycling route (Q102307360): 4 instances,
- bike path (Q221722): 37 instances,
- urban cycling route (Q2512606): no instances,
- bike lane (Q1378400): 2 instances (Zick-Zack-Weg Q56273580 and cycle lane in Leo-Baeck-Straße Q56273580,
- cycling infrastructure (Q5198662): 1 instance (Emmy-Lanzke-Weg Q98951201).

The chosen classes from Wiki data have been added in the ontology as subclasses of gdi: Route. Their instances have been added related to their Wiki data class and as instances of geo: Feature. Their point geometry has been added similarly to the previously integrated data through an instance of geo: Geometry with the property geo: as WKT.

Results of step 3: Inference

The third step has been applied through two sub steps. The first sub step aims at matching existing instances inside the ontology by using following rules:

- two instances are equivalent, if they have the same label or same name (for routes). In SWRL, it corresponds to the three following rules:

rdfs: label (?x,?l) ∧rdfs: label (?y,?l) → owl: sameAs (?x,?y) (1)

gdi: name (?x,?l) ∧gdi: name (?y,?l) → owl: sameAs (?x,?y) (2)

gdi: name (?x,?l) ∧rdfs: label (?y,?l) → owl: sameAs (?x,?y) (3)

•A route integrated from Wiki data is equivalent to a route integrated from one of the two use case datasets, if the (point) geometry of the Wiki data route intersects the segment (line) geometry of an instance of gdi: Route. This rule is based on the GeoSPARQL functionality geof: sfIntersects. In SWRL, it corresponds to the following rule:

rdf:type(?x,gdi:Streckenabschnitt)∧gdi:hasRoute(?x,?r)∧geo:hasGeometry(?x,?geom1)∧wdt:P31(?y,?c)∧rdfs:subClassOf(?c,gdi:Route)
∧wdt:P625(?y,?geom2)∧geof:sfIntersects(?geom2,?geom1)
→owl:sameAs(?r,?y)

An equivalence have been defined between an instance of bike path (Q221722) and a route (called Magdeburger Bruecke in German) from the Hamburg dataset. Some equivalences have been created between route instances from the dataset "Cycle Network Germany" and the instances of long-distance cycling route (Q353027), bike path (Q221722), bike lane (Q1378400) thanks to the second rule (as route instances from the dataset "Cycle Network Germany" have no defined name).

The second substep consists in checking the consistency of the ontology to identify required missing information. The results of this second substep is detailed in the next subsection.

Results of Step 4: Missing Information

From the inconsistency checking, we have identified the following missing information:

• from the Hamburg dataset:

- missing required information for routes: d-route, eurovelo, radnetz_D, landesnetz, kommunetz, ergNetze, lebenszeitintervalAnfang, and lebenszeitintervalEnde.
- missing required information for segments: quell-ID, strecken-ID, GeometrieAbschnitt, fuehrung, belag, datum, lebenszeitintervalAnfang, and lebenszeitintervalEnde.

• from the dataset "Cycle Network Germany":

- missing required information for route: name, routen-ID, eurovelo, radnetz_D, landesnetz, kommunetz, ergNetze, lebenszeitintervalAnfang, lebenszeitintervalEnde.
- missing required information for segments: strecken-ID, GeometrieAbschnitt, fuehrung, richtung, belag, laenge, lebenszeitintervalAnfang, and lebenszeitintervalEnde.

Missing information for routes from Wikidata varies from instances of the different classes and also from one instance to another one of the same class.
The initial results from the SPALOD platform and the use case demonstrate the potential of the proposed method to support infrastructure management by identifying data gaps. This identification of missing information can guide efforts to improve dataset completeness, which is essential for better decision-making and more accurate infrastructure planning.

Discussion

Missing Information Highlighted by the Application of the First Four Steps of the Process

By leveraging Semantic Web technologies and Linked Open Data, SPALOD enables intelligent data integration and management, effectively identifying incomplete data that is critical for improved infrastructure decision-making.

In the presented use case, we identified significant gaps in the datasets. The Hamburg dataset provides only 2 out of 10 of the required pieces of information for routes and 2 out of 10 for segments. Similarly, the "Infrastructure Network Germany" dataset supplies only 1 out of 10 of the necessary information for routes and 2 out of 10 for segments. These findings offer a strong starting point for data providers to enhance the completeness of their data, which is crucial for supporting informed infrastructure management and planning.

Furthermore, through the integration of Wikidata (and the inference from step 3), we were able to identify road instances with no associated segments. These instances provide valuable leads for further dataset integration, helping to complete the broader German infrastructure network.

Impact and Future Implications of SPALOD in Infrastructure Management

The SPALOD platform addresses the majority of challenges, offering numerous advantages for infrastructure management:

• **Robust Data Integration and Management**: SPALOD integrates and manages diverse datasets, including spatial, temporal, and infrastructure data, enabling efficient handling of large and complex datasets. Its advanced processing capabilities support comprehensive infrastructure analysis.

• **Comprehensive Ontological Framework:** The platform implements comprehensive ontologies that represent infrastructure concepts and relationships, facilitating the management of spatial datasets, metadata, and infrastructure elements like roads and utilities. These ontologies are adaptable, allowing customization for different infrastructure management needs.

• **Standardized Semantic Web Technologies:** SPALOD utilizes standardized Semantic Web technologies such as RDF, OWL, and SPARQL, ensuring seamless data interoperability and accessibility. It remains up-to-date with the latest standards and best practices, ensuring the platform's technological relevance.

• **User-Friendly Interface and Tools:** The platform offers an intuitive interface, making it accessible to infrastructure managers and decision-makers without requiring extensive technical expertise. It includes tools for data integration, management, visualization, and spatial analysis, streamlining infrastructure management workflows.

• **Privacy and Security Measures:** SPALOD incorporates strong data privacy and security measures, protecting sensitive infrastructure data while ensuring compliance with data protection regulations. This fosters user trust and ensures legal compliance.

• **Scalability and Performance Optimization:** The platform is designed for high scalability, enabling it to handle increasing data volumes and complex queries without compromising performance. Its performance optimization ensures fast response times and efficient data processing.

• **Cost-Effective and Resource-Efficient Design:** SPALOD's design is cost-effective, minimizing resource requirements and leveraging open-source technologies to reduce costs. This approach fosters collaboration and lowers barriers to entry for users and developers.

• **Training and Support:** The platform offers training resources and continuous support to help users effectively utilize its features. Updated documentation ensures that users stay informed about new features and best practices.

• **Sustainability and Future-Proofing:** SPALOD is built with adaptability in mind, ensuring that it can accommodate future technological advancements and evolving infrastructure management needs. Its sustainability and forward-looking design ensure long-term relevance and utility.

Testing the SPALOD Platform with a Hackathon

SPALOD platform has been tested during a Hackathon in November 2024. During this Hackathon, SPALOD demonstrates several valuable contributions:

- Integration of Semantic Web Technologies: SPALOD combines Semantic Web technologies, Linked Open Data, and ontological frameworks to provide a structured approach to managing diverse spatial datasets. While still at an early stage, this integration offers potential for more coherent infrastructure data management.
- Improving Data Completeness: The platform's ability to detect missing data and highlight gaps in infrastructure datasets is a positive first step toward improving data quality. However, there is room for further development in making these processes more comprehensive and efficient.
- Interoperability and Accessibility: SPALOD's adherence to Semantic Web standards and OGC APIs promotes data interoperability and accessibility. This has the potential to facilitate collaboration among stakeholders, though continued efforts are needed to enhance the platform's usability.
- Scalable and Adaptable Design: The platform's scalable architecture positions it to handle increasing data volumes and complexity, but further refinement is required to fully realize its potential in diverse infrastructure contexts.

- The Hackathon has also allowed to identify some useful and missing functionalities of the SPALOD platform for collaborative work in the data integration. These identified useful functionalities are considered as our future work on the platform and are the following:
- Although the metadata are integrated into the ontology and available via the OGC API, it is not currently viewable on the platform interface. One of our future works will be to add functionalities enabling metadata to be viewed, modified and enriched, in order to improve collaborative working on the platform, which is essential for infrastructure management.

- When integrating heterogeneous data and working collaboratively, information on the quality of integrated data plays an essential role in decision-making. The SPALOD platform has made it possible to address data completeness, but completeness is only one aspect of data quality. That is why we are planning to implement a data quality assessment system based on the FAIR reference principles: Findability, Accessibility, Interoperability, and Reuse.

Conclusion

This paper has investigated the integration of heterogeneous geospatial datasets in the context of infrastructure management, with a focus on the development and application of the SPALOD platform. Through the use case of cycling infrastructure, we identified substantial gaps in data completeness, highlighting the persistent challenges associated with managing and integrating infrastructure datasets. Despite these challenges, SPALOD shows promise as a tool for addressing data fragmentation and supporting more informed infrastructure planning and decision-making.

While SPALOD provides a useful starting point for infrastructure management. There is still significant room for improvement, particularly in areas such as data integration and usability. Nevertheless, the platform offers a promising foundation for supporting more complete and reliable data-driven decision-making in infrastructure planning.

Looking forward, further research and development are needed to fully exploit SPALOD's potential. Integrating additional datasets, refining the ontologies, and improving user interaction will be critical to make SPALOD more robust and applicable in broader infrastructure contexts. As infrastructure planning continues to face increasing complexity, tools like SPALOD could contribute meaningfully, though it will require ongoing adaptation and refinement to meet future demands.

Author Contributions

Conceptualization: C.P. and J.-J.P.; Methodology: C.P.; Software: C.P.; Validation: C.P., J.-J.P. and H.M.; Formal Analysis: C.P.; Investigation: C.P.; Resources: F.W.; Data Curation: F.W.; Writing—Original Draft: C.P. and F.W.; Writing—Review and Editing: M.S., H.M., and J.-J.P.; Visualization: C.P.; Supervision: J.-J.P. and M.S.; Project Administration: M.S.; Funding Acquisition: F.W.

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Data Availability

The use case presented in this paper is based on two datasets:

- Verkehrsentwicklungsplanung — Available at: https://geodienste.hamburg.de/download?url=https://geodienste.hamburg.de/HH_WFS_Freizeitrouten f=json
- Bicycle Network Germany — Available at: https://www.radroutenplaner-deutschland.de/veraDaten_DE.asp

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Conflicts of Interest

The authors declare no conflicts of interest.

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