



ONTOLOGY-DRIVEN DATABASE FOR INTEGRATING BRIDGE DATA FROM MULTIPLE OPEN SOURCES

Samar Aqlan¹, Al-Hakam Hamdan², Steffen Marx¹, and Chongjie Kang¹

¹Institute of Concrete Structures, TU Dresden, Dresden, Germany

²A+S Consult GmbH, Dresden, Germany

Abstract

Bridges are associated with extensive data throughout their lifecycle, particularly during design and operational phases. Existing bridge data is stored in various national and international databases. This data can consist of geometric parameters, structural details, environmental conditions and is often available in non-machine-readable varying file formats. These inconsistencies hinder performance evaluations and AI applications. Ontologies based on the Web Ontology Language (OWL) could offer a solution for harmonizing this data. This paper proposes an ontology-driven approach that integrates open-source data for advanced semantic querying, enhancing consistency and enabling the potential of informed decision-making in bridge design through a harmonized, machine-interpretable model.

Introduction

Incompatible data formats and fragmented data storage present significant challenges in managing and utilizing bridge data. The diversity of file types and storage systems, ranging from simple tables to complex databases, introduces inconsistencies that hinder seamless data integration and fusion, especially when file structures are not machine-readable. However, managing infrastructure data (spanning multiple agencies, regions, and systems) inevitably involves some degree of data fragmentation, which can, in fact, be necessary to support flexibility, autonomy, and scalability across different data providers and stakeholders. Therefore, the goal is not to eliminate fragmentation entirely, but rather to develop a robust, ontology-based information model that enables semantic alignment, supports interoperability, and facilitates consistent interpretation of bridge data across diverse systems. The approach acknowledges the realities of decentralized data environments and the inconsistencies of different data sources while still enabling effective data integration and analysis.

National and international repositories like the Online Database (Structurae) and the bridge database of the Federal Highway Research Institute (Bundesanstalt für Straßenwesen) BAST contribute to the management of

bridge data. Structurae, is an online database for structural engineering, including a vast collection of bridge data from around the world. Similarly, the BAST in Germany provides valuable data on bridges and infrastructure, primarily focused on national standards.

Working with diverse open sources is challenging due to differences in data structures, languages, and a lack of standardization. As demonstrated by (Kang et al. 2024a) and (Kang et al. 2024b), digital twin systems rely on extensive bridge-related data. However, the variety of formats and sources could complicate effective integration and analysis, which highlights the importance of managing bridge data from multiple sources. The objective of developing machine-readable data model for bridges is to enable semantic linking and derive meaningful conclusions from data gathered across diverse repositories. By organizing the data into a coherent, standardized model, it becomes possible to extract valuable insights related to national and international bridge design practices. Existing bridge data documents design choices made for specific transportation needs, considering factors such as bridge type, materials, span layout, and cross-section. These decisions were influenced by various engineers across different countries, each working within their respective design codes and standards. Developing a structured data model is the first step toward establishing methodologies for analyzing and assessing bridge design based on documented bridge data.

An ontology-based approach can offer a robust solution for structuring bridge data offering several advantages. First, it facilitates easy integration with other existing ontologies, enabling the inclusion of additional relevant data from various domains. Second, it ensures that the model is easily extendable, allowing for the incorporation of new domain knowledge and terminology. This flexibility provides a unified framework for organizing, interpreting, and integrating bridge data from various sources, with a focus on bridge design-related data. This paper also aims to determine whether the collected bridge data can serve as a foundation for developing methods to extract and formulate conclusions on bridge design. The utilization of an ontology-based approach to create a comprehensive database for bridge data, aimed at

accelerating the ontology development process with a focus on targeting specific parameters related to bridge design, addressing challenges such as duplication and common concepts through a programmed mapping process.

Literature Review

Ontology Application in Bridge Engineering

Ontologies are progressively making their way into bridge engineering, with recent contributions demonstrating their potential in various aspects of the field. The contributions range from the basic definition of the bridge concept and its primary topology, inspired by the Industry Foundation Classes (IFC) standards, to the Bridge Topology Ontology (BROT) (Hamdan, A.-H., & Scherer, R. J. 2020). Other contributions focused on developing the ontological terminologies of the bridge in an object-based system where components of bridges in different spatial zones were addressed as classes and the relationships between these components are semantically described. In (Gobels, A., & Beetz, J. 2021) Göbels and Beetz discussed the automatic transmission of the German national bridge relational database SIB-Bauwerke to an object-oriented documentation structure, where bridges and their components are explicitly defined so damage information for could be assigned to the respective components. Similarly, in (Hamdan, A.-H., & Scherer, R. J. 2021) was the focus not only localizing the damages on components but also on specific selected surfaces of components regarded as area of interest (AOI). Ontologies in bridge engineering have also been developed to be task- or process-oriented for targeted use cases. For example, in (Wu et al. 2021) an ontology based framework for concrete bridge rehabilitation project management was developed to assign specific rehabilitation processes to the bridge components like deck system, superstructure and substructure. Similarly, bridge components were linked to repair and replacement actions for bridge inspection in (Erdene, K., Kwon, T. H., & Lee, S.-H. 2020). Beyond object-based and process-based ontologies, researches (Heise, I., & Borrmann, A. 2024)(Heise, I., Göbels, A., Borrmann, A., & Beetz, J. 2024) and (Göbels, A., & Beetz, J 2024) have investigated semantic spatial relationships in bridge engineering, emphasizing geospatial linkages over conventional object-based associations.

Despite these advancements, ontologies have not been as extensively utilized in bridge design as they have been in the domains of bridge rehabilitation and maintenance. Zhang (Zhang, P., Cui, C., Li, C., Zhang, C., & Liu, H. (n.d.). 2021) examined the use of the ontology editor Protégé software and Semantic Web Rule Language (SWRL) to develop an energy pile deicing system for bridge decks, considering multiple design parameters to achieve a holistic, multi-objective design approach. Hassan and Le (Hassan, F., & Le, T. 2020) implemented an ontology-based approach to automatically identify risks encoded in the prescriptive requirements in bridge

design codes. Currently, ontology-based methods for supporting bridge design are underexplored compared to their application in the design of building structures, e.g., (Carrara, G., Fioravanti, A., Loffreda, G., & Trento, A. 2009) and (Hou, S., Li, H., & Rezgui, Y. (n.d.). 2015). Existing ontologies do not include adequately defined bridge-specific geometric and design-related parameters. In (Kuhaneswaran, B., & Vasanthapriyan, S. 2020) the Bridge Category class encompasses only a limited range of bridge types, and the ontology was not specifically developed to address the detailed aspects of bridge types and classifications. The same applies to the Bridge Ontology (BRIDGE) (Hamdan, A.-H., & Kozak, T.) which covers limited types of bridges.

Ontology development in Bridge Engineering

Ontology development involves the creating of formal, structured representations of domain-specific knowledge, facilitating interoperability and effective knowledge sharing across systems (Enesi, F. A., Ishaq, O. O., Muhammad, B. A., & Muhammadu, S. 2020). In bridge engineering, ontology development methods have been applied differently across various use cases. Manual ontology developments have commonly been implemented through answering competency questions which define the use case or purpose of ontology, e.g., (Wu et al. 2021) and (Ren, G., Ding, R., & Li, H. 2019). In (Zhang, Y., Liu, Y., Lei, G., Liu, S., & Liang, P. 2022) Zhang et al. reviewed and analyzed existing ontologies in the field of bridge engineering, offering a comparative evaluation of their development processes. Zhang concluded that the majority of existing ontologies were developed manually and proposed an improved seven-step methodology for generating a bridge ontology, called BIONtology.

This approach introduces a more automated ontology development process by mapping relational databases stored in Bridge Management Systems (BMS), instead of relying solely on manual ontology creation or parsing complex models such as IFC. By focusing on database-driven ontology generation, this method enhances the automation of the ontology development process. However, in the development of BIONtology, only a single relational database was considered, with rules implemented for automatic mapping. Several challenges remain unaddressed, particularly when considering multiple relational databases or tabulated sources for automatic mapping. Key challenges include handling conflicts between datasets, managing unrelated columns and tables, and resolving overlapping concepts. Addressing these challenges requires the implementation of additional strategies to ensure the accurate integration and alignment of data from diverse sources.

Methodology

The ontology development methodology used in this paper is inspired by the Linked Open Terms (LOT) Methodology (Poveda-Villalón, M., Fernández-Izquierdo, A., Fernández-López, M., & García-Castro, R.

2022), following a structured, phased approach. It begins with the *Ontology Requirements Specification Phase*, where the goals, scope, and competency questions are identified to ensure alignment with the intended objectives. This is followed by the *Ontology Implementation Phase*, which includes several key activities: the reuse of existing ontologies and vocabularies to maximize interoperability, the iterative development of the ontology, and the processes of conceptualization and encoding using formal languages such as Resource Description Framework (RDF) format or OWL. Finally, the *Ontology Evaluation Phase* is ensuring that the ontology meets its predefined requirements.

Ontology Requirements Specification

The developed ontology provides a structured framework for organizing bridge design data by integrating multiple open sources into a consistent, machine-interpretable model. The main goal is to merge and structure this data by identifying key relationships and attributes relevant to bridge design. The scope covers general bridge information, classification, obstacles crossed, and structural parameters (e.g., span length, lanes, tracks). A set of general and detailed competency questions—based on domain knowledge—was formulated to define the ontology’s requirements. Table 1 lists the core questions identified.

Table 1: Competency questions for the developed ontology

Competency Questions	
»	What are the geometrical parameters of a given bridge (e.g., length, height, width)?
»	What are the types of bridges in a specific region or country?
»	What types of obstacles do a given bridge cross (e.g., rivers, roads, valleys)?
»	Which bridges are made primarily of steel, concrete, or composite materials?
»	Who were the key participants involved in the design, construction, or maintenance of a specific bridge?
»	What is the slenderness ratio of a specific bridge or bridge component?
Additional Competency Questions	
»	How can bridges be classified based on their slenderness ratios (e.g., slender, moderate, robust)?
»	How does the slenderness ratio of a specific bridge compare to others of the same type or in the same region?
»	What are the typical environmental conditions associated with bridges of a specific bridge type?
»	What are the trends in bridge construction across different countries and different time spans?
»	How do bridges in one country compare to those in another in terms of type, size, or materials?

Ontology Implementation

The ontology implementation process combines top-down and bottom-up approaches (Noy, N. F., & McGuinness, D. L. 2001). The top-down approach is guided by bridge engineering and bridge design literature,

as well as competency questions, while the bottom-up approach leverages detailed data extracted from multiple open databases. Given the heterogeneity of data sources, preprocessing steps were implemented to structure and harmonize the data. To accelerate the ontology construction process and maintain compatibility across diverse data source. The implementation process was automated with programmed scripts utilizing the RDFlib¹ package that convert relational databases and tabulated data to the RDF format.

Top-down Method

In a top-down approach, the ontology development process starts with the definition of broad, high-level concepts or classes, which are then progressively refined into more specific subclasses or relationships. For this ontology, the top-down method was initially applied by collecting terminologies and concepts related to bridge infrastructure from the literature. These terminologies served as the foundation for a generic data framework, shaping the overarching structure of the ontology and establishing its core concepts and classes.

Bottom-up Method

The bottom-up approach, in contrast, begins with specific data and works upward to identify patterns, relationships, and general concepts. In this case, data from two sources - data source A (BAST) and data source B (Structurae) - were integrated using a bottom-up methodology. This approach enabled the creation of specific classes, relationships, and data structures based on the detailed, real-world data collected from these sources.

To automate ontology development, existing tabulated data were processed using a Python-scripted workflow that reads tabular data and automatically generates classes and properties in RDF format. By analyzing these datasets, the ontology was refined to ensure that its structure accurately reflects domain-specific terminology and concepts. The predominantly manual top-down process provided a broad framework, while the bottom-up approach ensured that the ontology was tailored to the existing data in an automatic process. The overall ontology implementation process is illustrated in figure 1.

Re-use existing Ontologies

The existing ontologies do not include all the necessary classes and properties to effectively manage the gathered data, as they consist of very broad and general semantic structures. This highlights the need to develop a more suitable ontology tailored specifically to the characteristics of the collected data. The developed ontology was enriched by reusing several established and online published ontologies: The Bridge Topology Ontology (BROT) (Hamdan, A.-H., & Kozak, T.), Bridge Component Ontology (BRCOMP) (Hamdan,A.-H., & Kozak, T.), (BRIDGE) (Hamdan, A.-H., & Kozak, T.). Additionally the Digital Construction Building Material

¹ <https://rdflib.readthedocs.io/en/stable/>

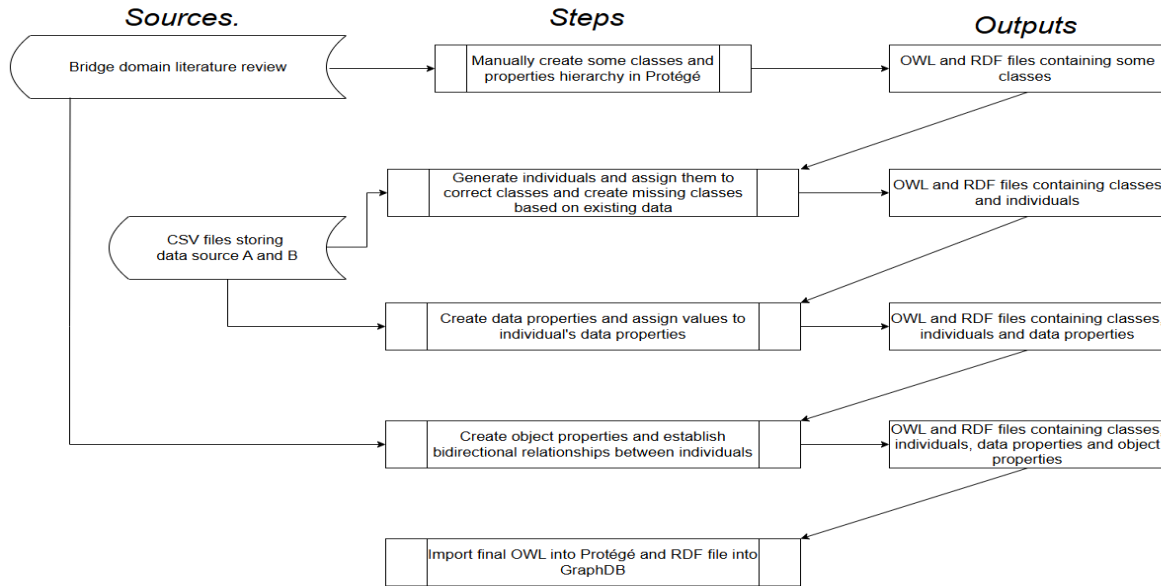


Figure 1: Ontology Development Process

Ontology (DICBM) (Karlupudi, J., & Valluru, P. 2024) which standardize material definitions, including those for bridges and the ASB-ING Ontology (Göbels 2022) which is developed based on German national standards that manages and standardizes data for infrastructure projects and represents the guidelines for the structure of the BAST database. Table 2 lists the used ontologies in this work.

Table 2: Namespace Prefixes and IRIs used

Ontology	Prefix	IRI
Managing Bridge Data Ontology	MBDO	* https://w3id.org/mbdo
Bridge Topology Ontology	brot	https://w3id.org/brot#
Bridge Component Ontology	brcomp	https://w3id.org/brcomp
Digital Construction Building Material Ontology	BMO	https://w3id.org/digitalconstruction/0.3/BuildingMaterials
Digital Construction Agents Ontology	Dica	https://w3id.org/digitalconstruction/0.3/Agents
Schema.org	ImageObject	https://schema.org/ImageObject
ASB-ING	abs	https://w3id.org/asbingowl/core

*The developed ontology in this work Managing Bridge Data Ontology (MBDO) will be online accessible soon.

Knowledge Representation

The developed ontology is based on OWL. The Protégé ontology editor was used to create the classes for this ontology. After clarifying the scope and identifying the domain, the first steps were taken to model and define the classes, and their hierarchical relationships. The developed Ontology includes eight main classes. The following description will illustrate each main class and its content.

Bridge

The *Bridge* class, originated from BROT (Hamdan, A.-H., & Kozak, T.) represents the central concept within the Bridge Engineering domain, and serves as the conceptual model for the bridge structure itself. The attributes related to the bridge will be assigned to this class, making the Bridge class the domain for these bridge-related properties as attributes can be assigned to bridges. The *Bridge* class is then linked to other important classes such as *Bridge Classification*, which categorizes the bridge, *Bridge Component* which defines its physical elements, and *Building Material*, which lists the materials used in its construction. Overview of the classes are demonstrated in figure 2.

Bridge Classification

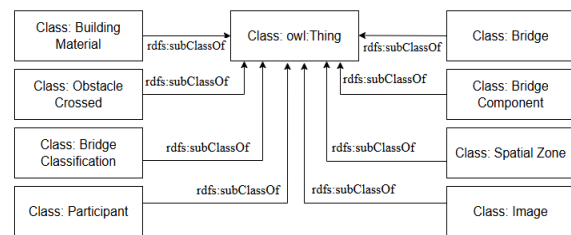


Figure 2: Main Classes

The ontology implementation followed a hybrid approach, within the top-down method initial general bridge classifications were identified based on established literature in the bridge domain. As the process evolved, the bottom-up method, supported by the automated transformation of existing bridge data, allowed for a more detailed and refined classification system that incorporated real-world bridge design experience. For example, hybrid-designed bridges, which might not fit traditional categories found in literature, are classified differently, and new superstructure configurations can be introduced as additional subclasses within the *Bridge*

Classification class, which were not originally considered in the top-down approach. To maintain a clear and scalable structure, bridge classification and its subclasses are represented as a class in the ontology, rather than using object properties as illustrated in figure 3. This class-based approach ensures a hierarchical structure that facilitates flexibility in adding new classifications or adapting to changes, while also providing semantic clarity and ease of management as the classification system evolves, allowing the ontology to dynamically evolve based on the data it incorporates.

Bridge Component

The *Bridge Component* class originated from BRCOMP

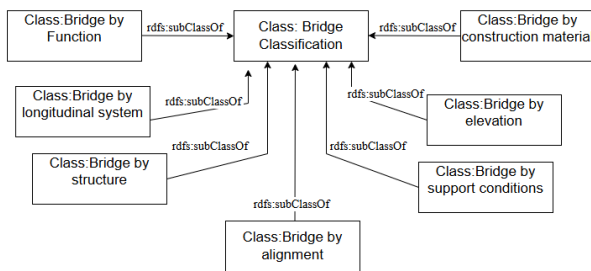


Figure 3: Subclasses of the Bridge Classification class

(Hamdan, A.-H., & Kozak, T.) focuses on the various structural elements that make up a bridge, following as well ASTM Standards for Bridge Element Classification with some extensions. It includes components like the *Deck*, represents the surface for vehicles and pedestrians. It reuses the *Superstructure* and *Substructure* from BROT, which form the main structure of the bridge, and specialized elements like Bearings and Expansion. Each component, along with its corresponding hierarchical components subclasses, allows for easier assignment of data properties and precise use of object properties. This structure also facilitates spatial relationships between the components.

Building Material

The *Building Material* class identifies the different materials used in the construction of bridges. Subclasses under this class include *Composite Material*, which refers to materials like Steel Concrete Composite, *Concrete*, which includes various types like reinforced or pre-stressed concrete, and *Metal*, which refers to *Steel*, *Aluminum*, *Iron* and other metals used in structural components. These materials are chosen based on the specific needs of each bridge and the requirements of bridge engineering. Some of the classes and properties have been reused from Digital Construction Building Material Ontology (DICBM).

Spatial Zone

The *Spatial Zone* class provides geographical context to each bridge by linking it to its region, country, and city. This class organizes the location information into categories such as *Continent*, which identifies the broad landmasses (e.g., Asia, Europe), *Country*, which specifies

the nation where the bridge is located, *Region*, which could be a state, province, or district, and *City*, which pinpoints urban areas where bridges are situated. It also supports better data organization and retrieval by associating each bridge with specific geographic entities.

Obstacle Crossed

The *Obstacle Crossed* class identifies the natural and man-made obstacles that a bridge is designed to span. It includes subclasses like *River*, for bridges that cross water bodies, *Valley*, for those spanning deep ravines or gorges, and *Sea*, for bridges that span large bodies of water. In addition, the class includes obstacles like *Road*, for bridges built over highways or roads, and *Railway*, for bridges that pass over or under rail tracks. This classification helps understand the environmental context of the structure.

Image

The *Image* class holds visual records of bridges, including photographs, design drawings, and other visual materials. The visual records are categorized into three distinct groups, images of the bridge in its entirety, images of specific bridge components, and images of particular sets of bridge components. The images are linked to the corresponding bridges or bridge components, ensuring a structured association. Beyond the visual content, additional attributes such as metadata, including the capture time, the creator, copyright information, and comprehensive quality assessments, will be incorporated in the future to enhance the richness of the dataset. Further concepts from ImageObject (Schema.org) can be reused.

Participant

The *Participant* class identifies the various entities involved in the design, construction, and ownership of a bridge. This class contains subclasses such as *Designer*, which includes architects and engineers responsible for the bridge's design, *Contractor*, who builds the bridge, and *Asset Owner*, the individual or organization that owns and is responsible for the maintenance and operation of the bridge. The Digital Construction Agents Ontology (Törmä, S., & Zheng, Y.) provides more concepts for further participants. When extending the current data collection, additional concepts can be adopted.

Data Properties

Class: Bridge	Class: Bridge Component	Class: Image
+ Construction Method xsd:String	+ Cross-section type xsd:String	+ URL xsd:String
+ Status xsd:String	+ Type xsd:String	+ Format xsd:String
+ Construction Start xsd:dateTime	+ Surface Area xsd:decimal	+ Resolution DPI xsd:decimal
+ Construction End xsd:dateTime	+ Concrete volumn xsd:decimal	+ Copy Right xsd:String
+ Coordinates xsd:decimal	+ Length xsd:decimal	+ Capture Date xsd:String
+ Span Number xsd:Integer	+ Height xsd:decimal	+ Photographer xsd:String

Figure 4: Data properties in the developed ontology

Data properties are used to associate literal values (such as strings, numbers, or dates) with instances of classes. These properties facilitate the representation of attributes or characteristics of the entities within the ontology. The

data properties used in the developed ontology are based on the existing data sources. The restrictions on domain and range of data properties were developed based on the of bridge engineering domain knowledge. Figure 4 illustrates a selection of adopted data properties utilized in this work.

Object Properties

In the developed ontology, object properties help in establishing relationships between different instances of classes. For example, the *Spatial Zone* class adopted from BROTON could be linked to the *Bridge* class using the object property *containsStructure*. This relationship could represent the connection between a specific location and the bridges. Similarly, the object property *containsComponent* could also be used to link the *Bridge* class to the *Bridge Component* class, defining the various components that make up a bridge. Additional object properties can provide further relational details, such as indicating that one bridge replaces another, or that a specific bridge component is adjacent, below, or above another component. Example of linking spatial zones with bridges considering the bridge as structure and its components as individual components is illustrated in Figure 5.

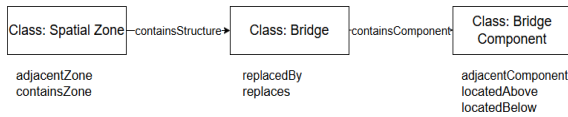


Figure 5: Object properties used in the developed Ontology

Ontology-Based Data Harmonization

To harmonize and integrate bridge data from multiple open sources, an ontology-based standardization approach was employed. This process used ontologies to unify and structure data from BAST and Structurae. However, before automating the generation of classes and properties from these sources, preprocessing phase was implemented.

Data Classification and Preprocessing

The data for implementation was sourced from two primary origins: Bridge data from source A are organized into multiple tables, which are named according to the ASB-ING standard and are stored in tabulated format. Bridge data from source B are available upon request from the provider of Structurae website as relational database format, and bridge images are stored in a local drive as multiple image format. The primary focus of the data collection was on parameters related to bridge design, with less emphasis on tabulated data concerning the administration and maintenance of bridges. A preprocessing step was implemented by defining target superclasses and attributes after initializing the top-down method. A programmed class-based search filtered data sources A and B, retaining only tables for the relevant classes and attributes (e.g., bridge components like superstructure and substructure).

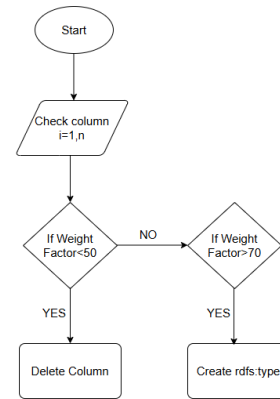


Figure 6: Class-based Search Algorithm

A Python script was then employed to apply fuzzy matching (Cayrol, M., Farnery, H., & Prade, H. 1982) to weigh word-to-word similarity, assigning higher factors for exact matches and lower ones for partial matches. Figure 6 illustrates that column with a weight factor below 50 are deleted, and those above 70 are automatically classified as classes or properties. Columns with a weight factor between 50 and 70, however, require manual review before transformation. Table 3 presents the similarity scores for words compared to "Cable."

Table 3: Example of string similarity scores

String to Compare with the word "Cable."	Similarity Score
Cable diameter	100
Cable Material	100
Diameter of cable	71
Bridge height	33
Bridge type	30
Support condition	18

Data Mapping and Harmonization

In the process of data mapping and harmonization, data from different sources are mapped to a unified ontology structure. For the data from source A, which follows the ASB-ING system. To efficiently align the two data sources, the existing ASB-ING ontology was reused to integrate necessary terminology and concepts. Initially, both data sources were thoroughly reviewed to understand their respective classes, properties, and relationships. Conceptual matches were identified, and discrepancies, such as differing naming conventions or representations, were addressed through the establishment of equivalent terms and mapping rules. A mapping framework was then created, incorporating direct mappings for matching concepts and defining transformation rules for those requiring adjustment. Data transformations were implemented to align the structures of Data Source A and Data Source B, with necessary adjustments made to formats, units, and categories. Finally, consistency rules were applied across both datasets to ensure uniformity in naming conventions, data types, and relationships, thereby facilitating a coherent integration of the two data sources. This integration process enriched the ontology

with additional classes and properties specific to the ASB-ING system. The utilization of *owl:equivalentClass* facilitates the declaration of classes, while *owl:equivalentProperty* enables the designation of object properties as equivalent to other object properties. Table 4 illustrates examples of mapping common concepts.

Table 4: Examples of mapping common concepts

Subject	Predicate	Object (acc. to ASB)
Building Material Class	owl:equivalentClass	Baustoff
Has bridge classification	owl:equivalentProperty	Bruecke_Bauwerksart
Total length	owl:equivalentProperty	Bruecke_Gesamtlaenge
Construction duration	owl:equivalentProperty	Dauer_Jahre

Data Integrity Verification

Data integrity verification was carried out to ensure that instances and relationships were correctly structured and logically consistent. Reasoning engines, such as Hermit or Pellet, were implemented to check for logical errors. Verification also involved cross-checking imported data against the original sources to ensure no information was lost or misrepresented during the import and conversion process. This step guaranteed the ontology's integrity and prepared it for further use in analysis, reasoning, or querying.

SPARQL-Based Querying

The ontology-based database can be stored in triple stores like GraphDB, which allows for visualizing the knowledge graph structure allowing users to query the data using Protocol and RDF Query Language (SPARQL). Figure 7 demonstrates an example for a query, which facilitates the analysis of the distribution of bridge types across different countries, span lengths and years.

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PREFIX MBDO: <http://www.mbdo.org/ontologies/MBDO#>
PREFIX DICBM: <http://www.mbdo.org/ontologies/DICBM#>
PREFIX BROT: <http://www.mbdo.org/ontologies/BROT#>
PREFIX DICAQ: <http://www.mbdo.org/ontologies/DICAQ#>
PREFIX SCHEMA: <https://schema.org/>
PREFIX BRCOMP: <http://www.mbdo.org/ontologies/BRCOMP#>
PREFIX ASBING: <http://www.mbdo.org/ontologies/ASB-ING#>
PREFIX RDF: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>

SELECT ?country ?year ?bridgeClassification ?spanLength (COUNT(?bridge) AS ?bridgeCount)
WHERE {
  ?bridge a BROT:Bridge ;
    MBDO:located_in ?country ;
    MBDO:constructedInYear ?year ;
    MBDO:hasBridgeClassification ?bridgeClassification ;
    MBDO:hasSpanLength ?spanLength .
}
GROUP BY ?country ?year ?bridgeClassification ?spanLength

```

Figure 7: SPARQL-based query

Conclusion

Implementing an ontology for managing open-access bridge data supported the reuse of common domain concepts and existing bridge-related ontologies. This enabled the creation of a flexible, ontology-based

database where new concepts and more specific relationships could be easily added. The integration of data from multiple sources was implemented using string matching and automatic conversion of tabular data into ontology format. Concept mapping and the addition of explicit definitions were also automated using RDFS commands and Python scripts, ensuring that all information was stored in a centralized RDF graph and the structure of the ontology is processed as OWL graph to further validate the ontology. This approach eased data integration, unlike relational databases that need restructuring to accommodate new data sources. The future work could explore the use of rules such as SWRL (Semantic Web Rule Language) to support bridge design through a use-case-driven approach.

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