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SYSTEM- AND DATA-INTEGRATED LINKING OF DIGITAL 3D MODELS OF EXISTING BRIDGE STRUCTURES WITH KNOWLEDGE GRAPHS OF NON-DESTRUCTIVE DIAGNOSTIC METHODS

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SUMMARY: *For a detailed analysis of damage to bridge structures, it is necessary to apply diagnostic methods. The results of these procedures are often complex results represented in heterogeneous and incompatible data formats. These are sometimes difficult to integrate with 3D Building Information Modelling (BIM) models. This article examines two system- and data-level integration methods for linking heterogeneous building diagnostic data with 3D digital bridge models in Industry Foundation Classes (IFC) format. At the beginning of the article, an ontology for non-destructive diagnostic methods (SODIA ontology) is developed and linked to other bridge ontologies. The first approach consists of transforming the diagnostic data and the data of the IFC model into the data schema of the Resource Description Framework (RDF), linking them together and integrating them into a graphical database (data integration). The second approach investigates system integration using information containers according to the ISO linking of ISO 21597. By validating the two approaches, it can be demonstrated that both methods provide a way to link heterogeneous diagnostic data to a 3D bridge model and achieve interoperability in maintenance management. The results can improve the use of data by bridge asset managers in the operation and maintenance management of bridges. At the same time, they serve as a basis for possible data analyses that lead to predictions about damage progression and changes in condition.*

KEYWORDS: *Ontology, Knowledge Graphs, BIM, Bridge Structures, 3D-Model, Semantic Web, ICDD, NDE, Non-destructive Testing, Linked Data.*

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1. INTRODUCTION

Bridges are known as complex, but durable structures (Hartung et al., 2020, Klemt-Albert et al., 2018). They are part of road and rail infrastructure systems and are important for a national economy and society (Jäkel et al., 2022). As a result, the usability and safety of the structure must be guaranteed during the operating phase (Jäkel and Klemt-Albert, 2023). For this purpose, the German standard DIN 1076 prescribes cyclical structural inspections (Deutsches Institut für Normung e.V., 1999).

In recent years, the number of damages occurring on bridge structures has increased. This can be attributed to many different factors, such as the increasing strain on the structure due to the increased volume of road and rail traffic and the ageing of the infrastructure (Zhou et al., 2021). In order to investigate the effects of the damage on the structure, the potential progression of further damage, and the influence on the overall condition, it is necessary to execute structural diagnostic procedures (Schacht et al., 2022). These procedures are conducted with destructive, semi-destructive or non-destructive methods directly on the structure (German Concrete and Construction Engineering Association, 2014). They are crucial for assessing the condition of existing bridges (Kang et al., 2024, Voigt et al., 2023). However, the work processes involved in structural diagnostics are resource-intensive and manual (Schacht et al., 2022). In addition, the procedures are barely standardized, making results challenging for third parties to interpret, and the knowledge acquisition process is time-consuming due to the use of heterogeneous data formats (Arndt et al., 2022, Schacht et al., 2022).

One possibility to address the named issues is the use of digital BIM models of bridge structures according to the Building Information Modelling method (BIM). In this context, all relevant diagnostic procedures can be visually located directly in the BIM model and other leading diagnostic data can be integrated into the semantics of the model (Morgenstern and Raupach, 2022, 2023). This provides the capability of centralized, consistent and transparent data management for all operational components (Arndt et al., 2022, Schickert et al., 2022).

Despite the possibilities of the BIM method using the open data exchange format "Industry Foundation Classes (IFC)", this data schema also has limitations in terms of data volumes, interoperability and data linking for comprehensive data evaluation. In addition, the transformation of the native formats of the diagnostic data into the IFC schema results in data loss (Farghaly et al., 2019, Hagedorn et al., 2023a, Rácz and Olofsson, 2009). To address these limitations, the Linked Data (LD) approach offers a solution by linking datasets in their native data formats with BIM models using knowledge graphs. This article aims to close this research gap by presenting two methods for linking digital bridge models with heterogeneous data from non-destructive inspection methods. The baseline for both approaches presented in the article is the use of openBIM standards in the operation of infrastructure assets based on the BIM strategy in the infrastructure sector in Germany (Bundesministerium für Verkehr und digitale Infrastruktur, 2015, Deutsche Einheit Fernstraßenplanungs- und -bau GmbH, 2023, Meister et al., 2021, Seitner et al., 2022, Singer and Borrmann, 2016). Thus, the standardized basis of the approach is a 3D building model in the format of the IFC. The use of model authoring software is not considered in the article. The article focuses on the use of the SODIA ontology (Jäkel et al., 2024) from the knowledge domain of non-destructive diagnostic methods in the context of bridge construction. Two different ways of ontology utilisation - (a) data integration with the Resource Description Framework (RDF) and (b) system integration with information containers - are considered, implemented and compared (Bonduel et al., 2019, Donkers et al., 2024).

2. RELATED WORKS

The related works present the results of a literature review on the topics of ontology in the construction industry, ontologies in the maintenance management of bridge structures and BIM in bridge diagnostics. The results are presented in the following three sub-sections. They form the foundation for the main section on developing the ontology and linking it to the BIM model using the LD approach.

2.1 General Ontologies in the construction industry

In the construction industry, ontologies and knowledge graphs are used in many different areas (Kamsu-Foguem and Abanda, 2015, Pauwels et al., 2022). Due to the existing limitations of the IFC data schema in its possible extensions and data integrations, interest in the possibility of linking further data in native formats with the BIM model has increased (Pauwels et al., 2022). Other articles present an initial approach for representing the IFC structure using the EXPRESS schema in an ontology, known as Industry Foundation Classes Ontology Web Language (ifcOWL) (Pauwels et al., 2017, Pauwels and Terkaj, 2016). Furthermore, the authors develop this approach and focus in their work on the representation of geometric data within an ontology. An alternative to ifcOWL is the Building Topology Ontology (BOT) for the standardized and simplified description of building topologies in structural engineering (Rasmussen et al., 2020).

There exist other ontologies along the value chain of construction projects. There are ontological approaches to represent the elementary framework conditions and requirements for the procedural and organizational structures of construction projects in building and infrastructure construction (El-Gohary and El-Diraby, 2010). Moreover, there are extensions to the ontologies considering the aspects of digitization towards the construction industry 4.0 (Zheng et al., 2021). Based on the subject area of structural diagnostics, there is the ontology of (Moreno Torres et al., 2021). This approach focuses specifically on the application of non-destructive inspection methods for materials science (MS) in a laboratory environment.

In contrast to the above-mentioned ontology for non-destructive evaluation (NDE) in the laboratory according to (Moreno Torres et al., 2021), the Structural Diagnostics Ontology (SODIA) focuses on the operative execution of the procedures in connection with a bridge structure in the field of structural diagnostics with a focus on NDE (Jäkel et al., 2024) .This forms the central aspect for the development of knowledge graphs and the subsequent linking with the digital 3D bridge model.

2.2 Ontologies for Bridge Maintenance

With the increasing attractiveness of the LD approach, more specific ontologies have been developed for individual sub-domains of the construction industry, such as bridge construction, road construction, dam construction and steel construction. Relevant ontologies and LD approaches for bridge structures are presented below.

The Bridge Topology Ontology (BROT) including its extensions, serve as a comprehensive ontology for the superordinate description of a bridge structure, its components, spatial relationships and structural properties. In addition, it includes the characterization of the used materials (Hamdan, 2023, Hamdan and Kozak, 2022b). In other articles, Hamdan et al. present the Damage Topology Ontology (DOT) for the further description of damage to bridge structures and their further description and resulting maintenance measures (Hamdan and Bonduel, 2019). To describe the maintenance management of road bridges, Goebels and Beetz transform the existing standard of the Road Information Database for Engineering Structures (ASB-ING) from a relational database structure (SIB structures) into a machine-readable structure (Göbels and Beetz, 2021). With the Bridge Maintenance Ontology (BRMO), Ren et al. present another possible ontology for the operation of bridge structures. This primarily considers the procedural and organizational level of maintenance management and defines the operational (Ren et al., 2019). Additionally, with the Concrete Bridge Rehabilitation Project Management Ontology (CBRPMO), Wu et al. present the concept of handling, mapping and integrating dynamic and ever-changing project information into the operation of reinforced concrete bridge structures in conjunction with a BIM model (Wu et al., 2021).

In addition to the development and use of ontologies, there are also further approaches to LD approaches in bridge operation. Helmreich considers the storage, structuring and management of material science information with a LD approach for the inspection of bridge structures with a focus on steel bridges (Helmerich, 2012). Furthermore, Lui et al. and Hagedorn et al. present the systematic storage and management of data for the accompanying documentation of concrete work and inspections on infrastructure facilities using Information Container for Document Delivery (ICDD) (Hagedorn et al., 2023a, Liu et al., 2022).

2.3 BIM and NDE for bridges

In the last decade, the popularity of NDE has steadily increased due to the protection of the structure during measurements while providing the required information. Non-destructive testing methods have established themselves as a reliable means of maintenance management and determining the condition of bridge structures. Digitalization entered the field of NDE and the first approaches to linking complex NDE data with digital BIM models of the bridge structure using the BIM method were researched (Arndt et al., 2022, Niederleithinger, 2022, Schacht et al., 2022).

Niederleithinger present the non-destructive Engineering 4.0 approach in his article. NDE 4.0 serves as a framework for the further digitalization and standardization of the domain of non-destructive inspection methods. At the same time, NDE 4.0 highlights the possibilities of linking with digital BIM models or digital twins as well as other heterogeneous maintenance data for predictive maintenance management (Niederleithinger, 2022). Furthermore, Talebi et al. present in a case study the possibility of using NDE in the form of digital visual inspections and their vizualisation on a masonry railway bridge (Talebi et al., 2022). Moreover, Schickert et al. demonstrate an accurate approach to the further processing of NDE data for integration into a digital BIM models in IFC format. Established diagnostic procedures are analyzed and their data structure and the necessary data types are identified. In addition, the extension of the IFC data schema for the integration of diagnostic data is developed. Options for data visualization with various end devices are discussed. This is explained using two case studies (Schickert et al., 2022). Arndt et al. present an additional option for merging BIM model and building diagnostics data. A holistic approach from data acquisition and evaluation to user-friendly presentation via various end devices with an optimized front end with a focus on practicability is presented (Arndt et al., 2022). Another approach for condition assessment with diagnostic procedures and their visualization in the BIM model is presented by Chan et al. (Chan et al., 2016) and two articles of Morgensten et al. (Morgenstern and Raupach, 2022, 2023). This merely integrates the abstracted results of the condition assessment into the BIM model using different color scales. As a result, critical points can be quickly identified in the digital 3D-model. Each of the presented approaches provides an opportunity to demonstrate the possibilities and significance of digitizing the NDE domain and linking it with digital BIM models in the context of the BIM method.

Previous approaches to integrating NDE data into BIM models show value-enhancing results. Nevertheless, all approaches are primarily based on the IFC format. Although the IFC data schema is also considered an ontology due to its representation of classes and their relationships in the specific knowledge domain of building structures (Guarino et al., 2009), the data format has limitations, such as data loss during format conversion, problems when using heterogeneous databases and limited interoperability when using different IT systems. The possibility of using the RDF data schema needs to be investigated so that even complex and heterogeneous building diagnosis databases can be interoperably linked with data from the 3D model of a bridge structure. This research addresses the gap in integrating domain-specific ontologies with RDF-based representations of infrastructure models. It investigates how the SODIA ontology can structure the RDF representation of a 3D bridge model, ensuring interoperability and enabling structured queries. On the one hand, a data-integrated approach with a graph database and a system-integrated approach with ICDD infotmation containers are considered and compared in the article.

3. METHODOLOGY

In the last sections, the related works were reviewed to present the state of the art and the research problem addressed by this paper was derived. The main part of the paper is presented in two sections: (a) ontology development and (b) linking the ontology to the BIM model. The ontology development process follows the Linked Open Terms (LOT) methodology by Poveda-Villalón (Poveda-Villalón et al., 2022) , which is divided into six sub-steps: (i) ontology requirements specification, (ii) ontology implementation, (iii) ontology publication and (iv) ontology maintenance, (v) verification, and (vi) linking (see Fig. 1) (Poveda-Villalón et al., 2022).

In the first part, ontology requirement specification, the use case of the ontology is defined, followed by determining the purpose and scope, and identifying suitable data for capturing additional knowledge. The second main step involves transforming the BIM model into RDF format and integrating it into the knowledge graph. This ensures that the RDF-based representation of the BIM model can be queried and reasoned upon using the SODIA ontology. Thereby a data-integrated approach (a) and a system-integrated approach (b) are considered and compared. In the first scenario (a: data-integrated approach), the SODIA ontology is loaded into a graph database, and the BIM bridge model is converted into RDF to ensure semantic interoperability and seamless data integration. The digital bridge model is initially transformed from the IFC data schema into the RDF data schema using a converter, outlined by (Bonduel et al., 2018). For validation in this scenario, five queries are performed with SPARQL Protocol and RDF Query Language (SPARQL) in the graph database to evaluate existing links and demonstrate the potential of data utilization. In the second scenario (b: system-integrated approach), the ICDD approach, as defined by the ISO 21597 standard (ISO, 2020a), is employed. In this context, the BIM model is integrated into a decentralized web platform that runs using ontologies and is linked to additional datasets by creating link models. A special feature here is the ability to link the BIM model to various datasets (e.g. images, documents, etc.) without the need to transform native data formats. This approach is also validated by two queries within the ICDD platform. The first query verifies the linkage between IFC File and the Terse RDF Triple Language (TTL) file. The second query evaluates the utilization of the SODIA Ontology within the ICDD platform (P. Hagedorn, 2024). Finally, a direct comparison of the two approaches is conducted, along with the consolidation of the results. The comparison considers both the procedural and the information technology levels.

Both variants were chosen in the context of the article in order to compare two possible direct applications of ontologies in a specialized engineering knowledge domain in conjunction with digital 3D models. The aim is to determine which integration option (data or system) has a simpler process flow and thus achieves greater efficiency in the use of ontologies. At the same time, the main challenges for both approaches in the context of using BIM models will be identified. The comparison will show the addressed end users, e.g. commercial companies or scientific institutions, whether a practical integration approach of ontologies in the field of building diagnostics in bridge construction requires work at the data or system level.

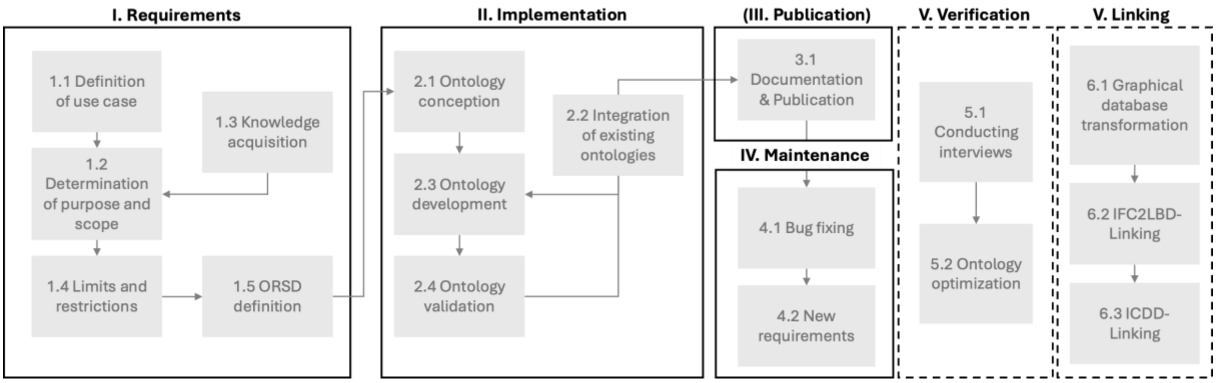

Figure 1: Methodolgy of the article (based on Guarino et al. (2009)).

4. SODIA ONTOLOGY

4.1 Ontology Requirements Specification

The requirements specification for the SODIA ontology is detailed in this section. These are converted into an Ontology Requirements Specification Document (ORSB) at the end of the sub-step. The requirements profile includes the definition of the specific purpose and the target end user of the ontology. Furthermore, the knowledge sources are characterized, and the functional and non-functional requirements for the ontology are determined.

The specific requirements for the ontology focus on the area of NDE methods in the context of the bridge structures maintenance management. NDE methods are emphasized due to their advantage of avoiding direct impact on the structure, unlike low-destructive and destructive diagnostic methods, making them particularly valuable in both research and practical applications. To define the ontology, relevant normative and structural engineering principles, such as DIN EN 1076, are used (Deutsches Institut für Normung e.V., 1999). Furthermore all NDE methods relevant to bridge construction are considered (German Concrete and Construction Engineering Association, 2014).

The domain area of the ontology considers the planning and execution of NDE procedures on bridge structures in the operational phase for optimal maintenance management. The primary user group addressed by the ontology is all those involved in the maintenance management of bridge structures, such as engineering offices for structural testing and diagnostics, plant operators and construction supervisors. Secondarily, construction companies are also regarded as potential users.

The ontology development adopts a top-down approach, built on existing knowledge. On the one hand, this existing knowledge includes current standards, regulations, and technical specifications as explicit knowledge. On the other hand, implicit knowledge is acquired from experts in the field of structural diagnostics as part of a series of interviews. The focus is on German standards and regulations, with the input from experts who have expertise in the structural diagnostics sector. The published standards (e.g. DIN 1076, DIN 12504-2, etc.), the regulations of the Deutscher Beton- und Bautechnik-Verein e.V. (DBV) and the Deutsche Gesellschaft für zertörungsfreie Prüfung e.V. (DGZfP) in the field of NDE methods are used as an explicit source of knowledge (German Concrete and Construction Engineering Association, 2014). Furthermore, 10 technical bulletins, such as the DBV documentation "Application of Non-Destructive Inspection Methods in Construction" (German Concrete and Construction Engineering Association, 2014), are used. The implicit knowledge is derived from the results of five expert interviews with a total of 6 experts in the field of structural diagnostics in Germany. One interview was conducted with two experts from the same company.

The functional ontology parameters are defined based on the overall purpose and the defined target group. These are represented by 13 competency questions for the development of the SODIA ontology development (Fernández-López and Gómez-Pérez, 1997):

1. Which inspection method is directly linked to an inspection task in the diagnostic procedure?
2. Which measurement method is used in each inspection method?
3. Which inspection method requires access to only one side of the bridge component?
4. Which parties or groups of people are involved in an inspection?
5. What qualifications does the inspector have?
6. What is the inspection date of the inspection method?
7. Which component is being inspected and how many inspection points are there?
8. To which category can the inspection task be assigned (Condition, Geometry, or Material)?
9. Which regulations are relevant for the inspection methods?
10. Which inspection tool is used for the inspection method?
11. How is the condition of the structure assessed in terms of durability, stability, and traffic safety?
12. What is the inspection direction of the inspection methods (longitudinal or transverse)?
13. What is the inspection area (point-based, linear, surface-based, or volumetric)?

In addition, six non-functional parameters were defined as requirements for ontology development and subsequent subjective validation. These parameters include (i) coverage, (ii) consistency, (iii) clarity, (iv) conciseness, (v) usability, (vi) extensibility and (vii) reusability. They are based on existing studies in the field of ontology development in civil engineering (Costin and Eastman, 2019, El-Gohary and El-Diraby, 2010, Seiß et al., 2023, Zhou et al., 2016). The SODIA ontology is designed as a top-level ontology for the planning of structural diagnostic processes in the maintenance management of bridge structures. All inspection methods and relevant parameters of the NDE domain used in practice are integrated into this ontology.

The ontology establishes connections between individual NDE methods and essential relations between these methods and bridge structures, possible damage patterns, and the necessary personnel. In addition, it serves as a basis for the further specification of all individual inspection methods in the field of non-destructive and low-damage diagnostic technology. Due to the scope and complexity, the specifications of all individual inspection methods are not included in the SODIA ontology, but are represented as individual, superordinate classes.

4.2 General Structure of the SODIA Ontology

The structure of the SODIA ontology is divided into four main topics - inspection, standardization, formal specifications and influencing factors in the field of non-destructive diagnostics (see Fig. 2). The basic structure of the ontology is based on the formalised and structured knowledge of hybrid knowledge sources. Existing standards, guidelines and codes of practice in the field of non-destructive structural diagnostics on bridge structures (explicit knowledge base) and expert knowledge from science and industry (implicit knowledge) were used to generate a holistic ontology. The development process of the SODIA ontology is described in detail in the article (Jäkel et al., 2024). This serves as the basis for the following implementation steps.

The concept of inspection is the most comprehensive component of the ontology. At the center of the inspection are the NDE methods and the associated inspection tasks. The concept is based on the german national guideline, “Application of Non-Destructive Inspection Methods in Construction” (German Concrete and Construction Engineering Association, 2014). At the same time, DIN 1076 with focus on maintenance management and the inspection of bridge structures (Deutsches Institut für Normung e.V., 1999) is used as a source of knowledge for the integration of suitable content in relation to the subject areas of bridge construction, structural inspection and damage management. In addition to the classes of inspection methods and inspection tasks, the inspection concept also includes other aspects such as inspection equipment, inspection areas, and inspection results. The second concept considers objects for the “standardization” of the domain. These characterize the framework conditions. This includes existing regulations as well as necessary and standardized qualifications for the planning and execution of diagnostic projects (German Concrete and Construction Engineering Association, 2022). The third and fourth concepts contain classes for the documentation or evaluation of inspection methods in the area of NDE: "Formal Requirements" and "Influencing Factors".

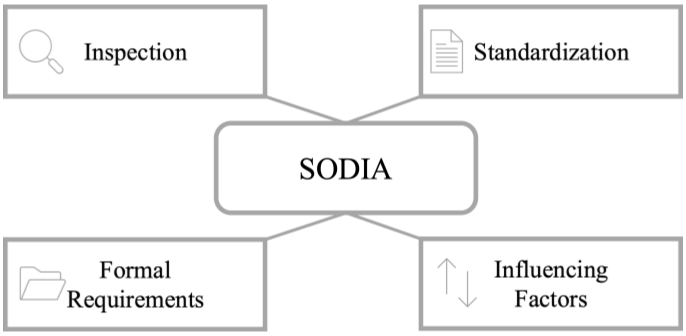

Figure 2: Core Domains of the SODIA Ontology.

4.3 Integration of Existing Ontologies and Expert knowledge

The ontology development approach includes the use and integration of existing ontologies relevant to bridge construction, maintenance management, damage management, materials, and personnel, which are crucial for the SODIA ontology. A total of seven ontologies are used in the development process of the SODIA ontology (see Table 1). These integrated ontologies are adapted as required, with new links between individual classes defined to ensure there are no contradictions or redundancies, thereby guaranteeing practicable usability.

Table 1: List of integrated ontologies.

No.	Description	Abbreviation	Source
1.	Bridge Topology Ontology	BROT	(Hamdan and Kozak, 2022b)
2.	Bridge Components Ontology	BRCOMP	(Hamdan and Kozak, 2022a)
3.	Bridge Ontology	BRIDGE	(Hamdan and Kozak, 2019a)
4.	Bridge Structure	BRSTR	(Hamdan and Kozak, 2019b)
5.	Damage Topology Ontology	DOT	(Hamdan and Bonduel, 2019)
6.	Building Material Definitions	BMAT	(Hamdan and Kozak, 2019c)
7.	Friend-of-a-Friend Ontology	FOAF	(Brickley and Miller, 2014)

The integration of existing ontologies lays the foundation for subsequent linking with digital BIM models. For the development and representation of the SODIA ontology, basic principles of the Semantic Web and LD are considered, with the RDF standard being used as the data model (Schneider et al., 2024). In addition, the ontology is extended with further implicit knowledge gathered from a series of qualitative interviews with six experts in structural diagnostics for bridge construction. The first concept of the SODIA ontology is also discussed during these interviews.

The experts were selected according to a predefined expert profile. Each expert must have more than three years of professional experience in structural diagnostics. A total of six experts were interviewed. To ensure diverse perspectives, the interviewees included three experts from academia and three from the construction industry. This balance of experts means that the ontology can be evaluated from different perspectives and structured in such a way that it is valid for research and business. The individual interviews were analyzed using Mayring's content analysis method (Mayring, 2012). The insights gained from the expert interviews are then used in the following section for a qualitative expansion and specification of the SODIA ontology, while also verifying its basic structure. The expert interviews provide valuable insights into two key areas (s. Tab. 2).

Table 2: Insights of the expert interviews.

Key Area	Topic	Insights
Key Area 01	Diagnostic procedure	The experts were able to evaluate and supplement the existing types of diagnostic procedures within the ontology. In addition, further insights were gained into the individual process steps, existing dependencies between the diagnostic procedures, existing restrictions and influencing factors, as well as the equipment required and the qualifications of the personnel carrying out the procedures. In addition, the data types of the process results and the software applications used were determined.
Key Area 02	Further relations Diagnostic methods for damage and structures:	The experts were able to present relevant basic conditions for the condition of the bridge structure for individual diagnostic procedures. Furthermore, relevant dependencies of the constellation of structure, damage and resulting diagnostic procedures could be identified, which are absolutely necessary for a qualitative use of the ontology in maintenance management.

Figure 3 shows the final result of the SODIA ontology with the linked ontologies, based on (Akbarieh et al., 2023, Jäkel et al., 2024) as a generic visualization. The next step is to describe the schema of the ontology.

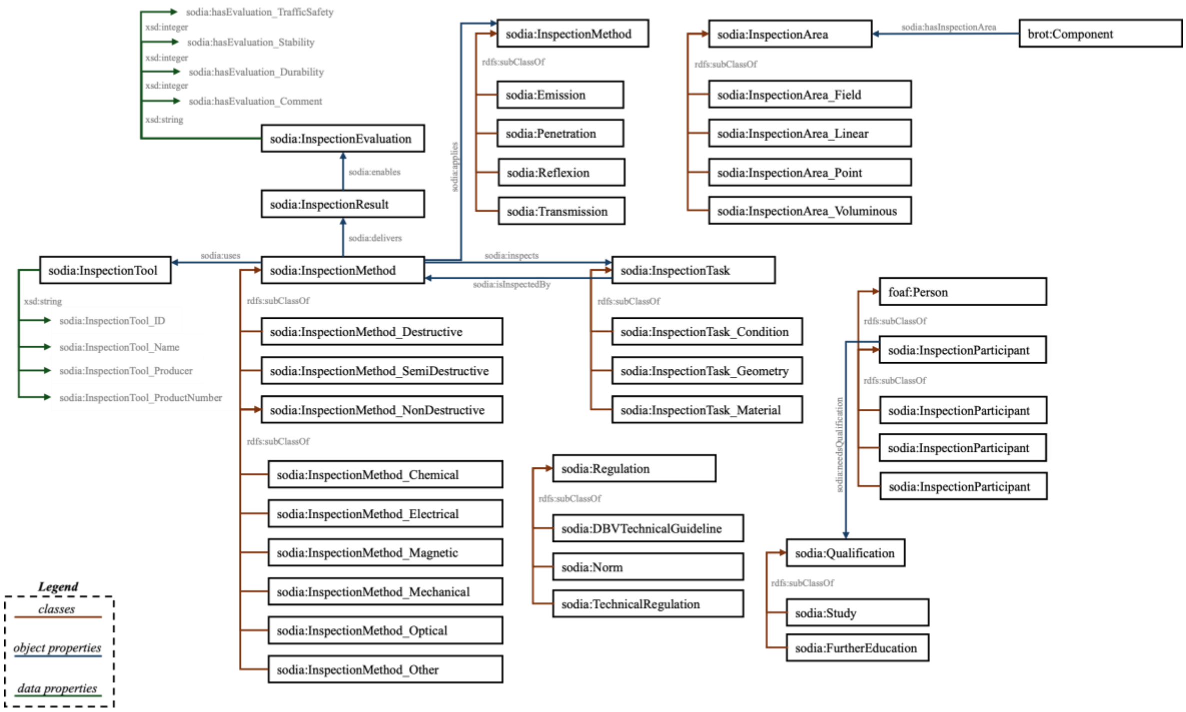

Figure 3: Conceptual overview of the SODIA ontology (inspired by Akbarieh et al. (2023)).

First, the relevant classes are defined and described. Then the object properties and data properties of the ontology are presented in the context of the article. The SODIA is also illustrated in the appendix (see Figure 11) with the included classes and all properties using the visualization tool for ontologies WebOWL (Lohmann et al., 2015).

4.3.1 Classes

In this step, the terms relevant to the domain of structural diagnostics, obtained from literature and expert interviews, are sorted into classes and hierarchically arranged. It is determined which terms represent independent concepts and which merely describe them further (Noy and McGuinness, 2001). Additionally, the question of existing subsumption relationships must be addressed. This is accomplished by checking whether a class is a subset of another class, possessing the same properties as its superclass (H. Stuckenschmidt, 2011). During the design phase, class hierarchies are primarily established using a top-down approach, although a combination of methods is occasionally employed.

Based on the main components of the SODIA ontology presented in section 4.2, some classes of the SODIA ontology are presented as examples. The main components themselves do not necessarily represent classes, but are merely used to represent the classes in a bundled form.

The first concept includes all classes relevant to an inspection. The class *sodia:InspectionMethod* represents the inspection methods. In addition to non-destructive inspection methods, there are also destructive and semi-destructive methods in structural diagnostics (German Concrete and Construction Engineering Association, 2014). Although these methods are not further subdivided in the SODIA ontology, they are still represented as classes. The non-destructive inspection methods are further specified by their measuring principle, for example, into mechanically induced, electrical, or magnetic methods (German Concrete and Construction Engineering Association, 2014). Classification is done by creating subclasses with the introduced feature of the measuring principle. Thus, the class *sodia:InspectionMethod_NonDestructive* has, for example, the subclass *sodia:InspectionMethod_Magnetic*. Following these classes are the inspection methods, such as the classes *sodia:ReboundHammer* or *sodia:RadarMethod*.

Inspection methods are used in structural diagnostics to fulfill inspection tasks (German Concrete and Construction Engineering Association, 2014). For this purpose, the class *sodia:InspectionTask* was introduced. This is linked to the class *sodia:InspectionMethod* through appropriate properties. Inspection tasks can be further subdivided into the triad Condition, Geometry and Material.

Additionally, other inspection-relevant classes such as *sodia:InspectionResult* or *sodia:InspectionTool* are created. The class *sodia:InspectionResult* is a generic class not further subdivided, as the results of inspection methods are difficult to generalize.

To locate the recorded inspection results, the class *sodia:InspectionArea* is created. To remain as generic as possible and follow the top-down approach, this class is divided into non-further restricted subclasses:

- *sodia:InspectionArea_Field,*
- *sodia:InspectionArea_Linear,*
- *sodia:InspectionArea_Point,*
- *sodia:InspectionArea_Voluminous*.

The concept of standardization aims to represent all objects that define or influence the framework conditions of structural diagnostics. To initially consider the regulations for structural diagnostics, the class *sodia:Regulation* is created, which includes norms, guidelines, and technical regulations through subclasses. The class *sodia:InspectionParticipant* includes the subclasses *sodia:EngineeringOffice*, *sodia:PlantOperator* and *sodia:PublicAdministration*. The imported FOAF ontology enables the description of individuals and the representation of their relationships. This allows, for example, the semantic depiction of the class *sodia:InspectionParticipant* and its interactions. The class *sodia:Qualification* includes the qualifications required for inspection personnel as per DIN EN ISO 9712 (German Concrete and Construction Engineering Association, 2022).

The execution of structural diagnostics must be constantly documented and later evaluated. Therefore, the classes *sodia:Documentation* and *sodia:Evaluation* are introduced. The class *sodia:Documentation* is further subdivided into the classes *sodia:Description*, *sodia:DocumenationExternal*, *sodia:DocumenationGenerating* and *sodia:DocumentationNecessary* to allow a structured documentation of the diagnostic process.

4.3.2 Object Properties

To establish relationships between instances of the previously created classes, object properties are created and exemplarily introduced in this step.

A core area of the SODIA ontology is the relationship between inspection methods and inspection tasks. A connection must be established between these. For this purpose, the object property *sodia:inspects* and its inverse *sodia:isInspectedBy* are created.

To integrate the class *sodia:InspectionParticipant* into the diagnostic process, the object property *sodia:isParticipantOf* is introduced. The SODIA ontology incorporates concepts from the FOAF ontology by referencing the class *foaf:Person*, enabling the use of properties to describe individuals and their relationships. This allows the organization of various project participants through well-defined connections, which establish and structure relationships between different actors. For future projects, task assignments can also be considered based on the inspection method. Additionally, a connection between the class *sodia:InspectionParticipant* and the class *sodia:Qualification* is established via the object property *sodia:needsQualification*, indicating required qualifications.

The class *sodia:InspectionMethod* is linked to the class *sodia:InspectionTool* through the object property *sodia:uses*. The inverse *sodia:isUsedBy* is also created for the opposite connection. Thus, the inspection tool can be selected depending on the inspection method, or the inspection method can be determined based on the inspection tool.
The connection between inspection methods and regulations is established using the object properties *sodia:regulates* and *sodia:isRegulatedBy*.

4.3.3 Data Properties

Data properties are used in ontologies to establish connections between subjects and datatype values. In the SODIA ontology, they primarily serve documentation purposes within the diagnostic project by structuring and formalizing key attributes of inspection methods, evaluation criteria, influencing factors, and inspection tools.
To document inspection processes, *sodia:inspectionDate* records the date of an inspection, while *sodia:numberOfReadings* captures the number of measurement points collected during an inspection. To verify the qualifications of inspection personnel, *sodia:isQualified* is defined with a range of *xsd:boolean*, allowing for a simple true/false validation.
The class *sodia:InspectionTool* is further described using data properties that define its attributes. These include *sodia:InspectionTool_Name*, *sodia:InspectionTool_ID*, *sodia:InspectionTool_ProductNumber* and *sodia:InspectionTool_Producer*, ensuring a structured representation of the tools used in inspections.
Based on the results of a structural inspection, an evaluation can be conducted regarding traffic safety, structural safety, and durability conducted (Bundesministerium für Verkehr, Bau und Stadtentwicklung, 2013). This assessment is formalized through *sodia:hasEvaluation_Durability*, *sodia:hasEvaluation_StructuralSafety*, and *sodia:hasEvaluation_TrafficSafety*, all of which have a range of *xsd:integer* to allow numerical evaluation. Additionally, *sodia:hasEvaluation_Comment* enables the inclusion of qualitative remarks from the inspector.
Influencing factors affecting an inspection are represented using *sodia:hasInfluencingFactor*, which captures relevant conditions that may impact the inspection process. This property is further refined into *sodia:hasInfluencingFactor_Chemical*, *sodia:hasInfluencingFactor_Constructive*, and *sodia:hasInfluencingFactor_Other*, which categorize different types of influencing factors. Within *sodia:hasInfluencingFactor_Constructive*, the sub-property *sodia:hasAccess* represents the number of access points available for an inspection. All influencing factor properties share the domain *sodia:InspectionMethod*, ensuring they are directly associated with the respective inspection methods.

4.4 Ontology Implementation

The implementation of the SODIA ontology is conducted using the open source software Protégé, in compliance with the standards of the World Wide Web Consortium (W3C) (T. Tudorache et al.). All concepts, classes, dependencies and restrictions defined in the previous sections are applied. The SODIA ontology, including the ontologies imported and adapted in Section 4.3, comprises a total of 225 classes, 78 object properties, and 137 data properties. These include 121 classes, 19 object properties and 37 data properties developed specifically within the SODIA ontology to meet the special requirements of structural diagnostics.

Figure 3 shows an abstracted excerpt from the SODIA ontology. In this representation, only the classes at the first hierarchical level are illustrated. The focus of the illustration is on the NDE methods and the associated inspection tasks. In addition, the connections to this central area of the ontology and the integrated ontologies are depicted. The validation of the ontology is confirmed building upon the results of (Jäkel et al., 2024). The final SODIA ontology is published open-access and and can be accessed via the permanent link *"http://purl.org/sodia*" (Jäkel and Heinlein, 2025).

5. VALIDATION (CONNECTION TO A BIM MODEL)

Once the SODIA ontology has been developed and successfully verified, their validation is the next step. This step focuses on ensuring that the ontology enables the integration and semantic alignment of associated datasets with a 3D bridge model. The implementation and validation are conducted using two different approaches: (a) data-integrated approach with linking to a graph database (see Section 5.2) and (b) the system-integrated approach with the use of ICDD information container (see Section 5.3). The chapter concludes with a consolidation of both results, highlighting the approach-specific added value and challenges. In addition, a generic comparison is conducted.

5.1 Description of the BIM model

The validation of the two approaches is based on a digital BIM model of a real-world demonstrator. A pedestrian bridge in the city of Aachen is used for this purpose. The digital BIM models of the existing bridge is stored in IFC data format and has three submodels: substructure, superstructure, and structural equipment. In addition, a submodel for structural diagnostics is used, focusing on the diagnostic methods (i) rebound hammer and (ii) radiography. The approach of using submodels based on BIM use cases in operation complies with the method decribed by (Jäkel and Klemt-Albert, 2023).

Within the structural diagnostics submodel, each inspection area of an inspetion method is assigned its own object. The rebound hammer method is represented as an object in the form of a cylinder. In contrast, the radiography method is represented as a volumetric rectangle in its linear orientation. In total, there are 15 rebound hammer inspection points (shown as cylinders) and two opposite inspection points of radiography procedure in the submodel "diagnostics" (see Fig. 4).

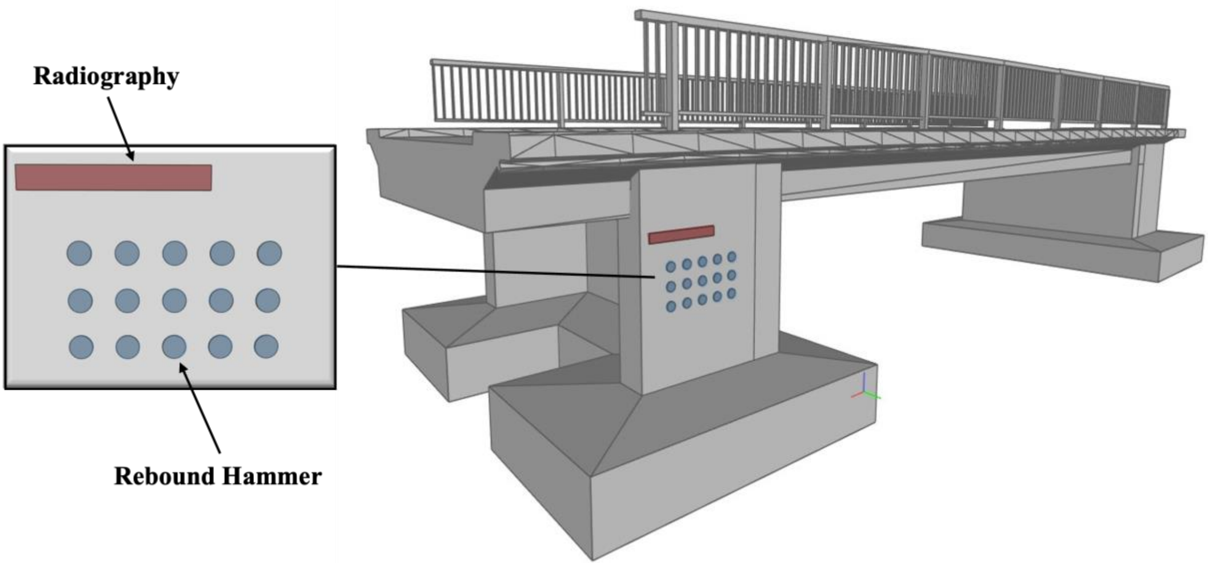

Figure 4: BIM Model with inspection methods (red: radiography; blue: rebound hammer).

5.2 Connection to a Graph database

5.2.1 Workflow

In the data-integrated approach, the SODIA ontology provides the conceptual framework for structuring the knowledge graph. The graph database Stardog is used for this purpose in this article (2024 Stardog Union). The aim of the first validation approach is to generate an RDF-based representation of a digital BIM model of an existing bridge structure. Figure 5 illustrates the process of using BIM models in the context of LBD (M. Bonduel, M. Vergauwen, R. Klein, M.H. Rasmussen, P. Pauwels, 2018). In the first process step, the export of the BIM model to the open IFC format is required. Next, the IFC file is converted into a LBD graph, which constitutes the ABox (M. Bonduel, M. Vergauwen, R. Klein, M.H. Rasmussen, P. Pauwels, 2018). The generation of LBD graphs can be achieved in different ways using different converters. In this research project, the IFCtoLBD converter was chosen as the tool to convert IFC models into RDF graphs. The W3C Linked Building Data ontologies used in this research include BOT, PRODUCT (Classification of Building Elements), and PROPS (Building-Related Properties).

The IFCtoLBD converter has several advantages over other converters. One significant advantage is its clear graph structure, which results in a smaller file size. In addition, the converter facilitates data querying. These features are particularly beneficial when processing large BIM models, as they improve data processing speed and analysis results (Bonduel et al., 2018). Each instance of the TTL file generated by the LBD converter corresponds to an IFC object. An example of such an instance extract is shown in Table 3.

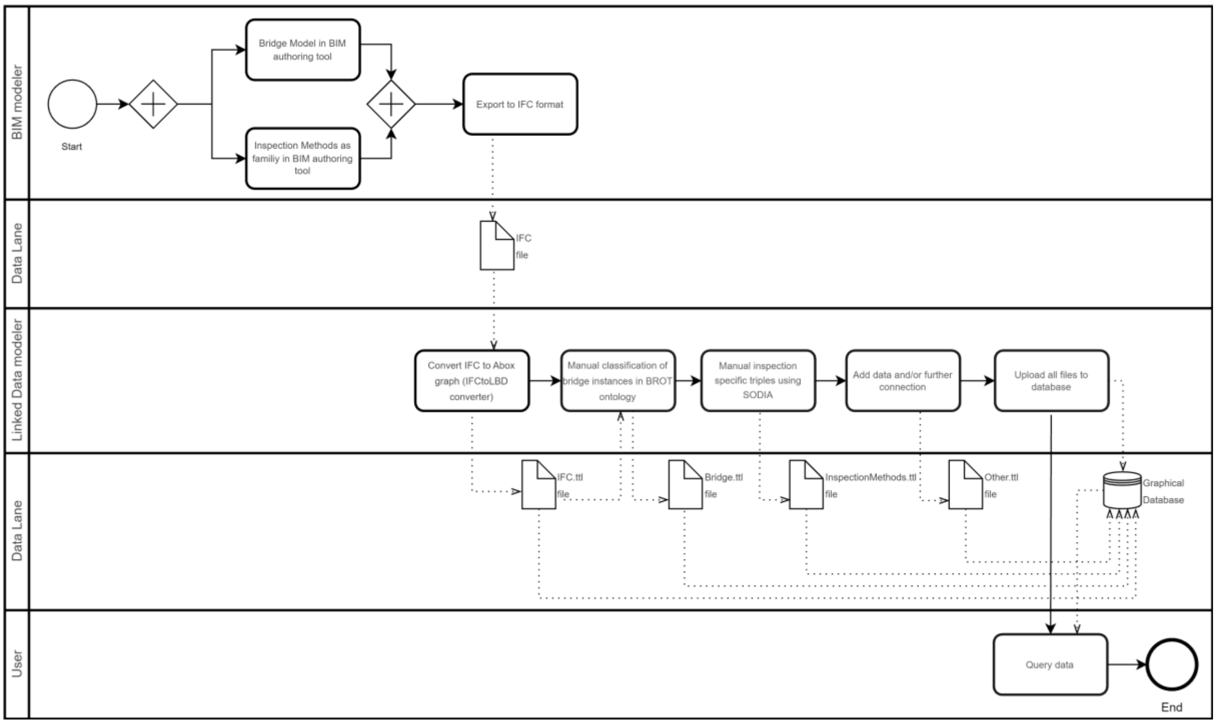

Figure 5: Workflow of Graph database Approach (based on (M. Bonduel, M. Vergauwen, R. Klein, M.H. Rasmussen, P. Pauwels, 2018)).

Table 3 illustrates the instance of the abutment IFC object converted by the LBDtoIFC converter. This instance has connections and properties in triple form. For example, the attribute compressive strength "C35/45" is linked to the literal via the property *props:strengthClass_simple* (line 221). Furthermore, an automatic assignment to the class *bot:Element* by the converter can be observed (line 232). The BOT ontology is designed for building construction and thus does not apply to the infrastructure sector (Hamdan and Kozak, 2022b). Therefore this assignment is not suitable, due to the focus on a bridge structure.

The assignment of the bridge model to thematically appropriate classes is performed manually using the BROT and BRCOMP ontologies. These ontologies adopt the concept of the BOT ontology but have been tailored for the semantic representation of bridge structures. The BRCOMP ontology extends the class *brot:Component* and categorizes the individual bridge components based on their static function (Hamdan, 2023).

During the manual mapping process, instances in the RDF schema are assigned to the individual classes of the BROT ontology using the *rdf:type* property, as defined in the RDF 1.2 Schema (Tomaszuk and Haudebourg, 2024). An illustrative example of this is the following triple, where the instance is initialized as a bridge abutment: *"inst:buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10 rdf:type brcomp:Abutment".*

The IFC families of the inspection methods radiography and rebound hammer are converted analogously to the bridge model. The instances are then categorized into the corresponding classes of the non-destructive inspection methods in the SODIA ontology.

In the subsequent phase, additional relationships are established in accordance with the SODIA ontology. For instance, relationships between the inspection methods and bridge components are created, or the inspection date is specified using a data property.

To validate the SODIA ontology across multiple domains, structured RDF data was manually generated using RDFLib, a Python library for constructing and processing RDF graphs. For this purpose, six datasets were created, each covering different aspects of structural diagnostics, including inspection methods, inspection tasks, evaluation results, inspection participants, inspection tools, and applicable regulations. These datasets were transformed into RDF graphs, where instances, relationships, and properties were defined in accordance with the SODIA ontology. By creating these RDF graphs in a controlled manner, the validation process ensures that all relevant aspects of the ontology can be tested systematically.

Table 3: Converted IFC object as an instance.

```
inst:buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10
        rdf:type owl:NamedIndividual ,
        beo:BuildingElement ,
        beo:BuildingElement-NOTDEFINED
        bot:Element ;
        props:batid_attribute_simple "3163850" ;
        props:exposureClass_simple "XC 3" ;
        props:globalIdIfcRoot_attribute_simple "3ca4umfFD1SRcBJ94m9rqG" ;
        props:isExternal_simple "false"^^xsd:boolean ;
        props:nameIfcRoot_attribute_simple "Widerlager_Ost:Widerlager_Ost:3163850"
        props:objectTypeIfcObject_attribute_simple "Widerlager_Ost:Widerlager_Ost" ;
        props:reference_simple "Widerlager_Ost" ;
        props:reinforcementVolumeRatio_simple 500;
        props:strengthClass_simple "C35/45" ;
        geo:hasGeometry inst:buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10_geometry ;
```

5.2.2 Validation

After uploading the converted IFC files, the manually created triples, and the ontologies into the graph database. SPARQL queries are executed on the generated RDF dataset to validate whether the ontology enables the retrieval of relevant information (P. Hitzler, 2010). As part of the validation process, ten queries are selected. The individual queries are described below and presented in abstract form in the respective tables for the query. Illustrations directly from the application system are shown in the appendix to further support the validation (s. Figure . 12 – 21)

Query01 Inspection:

This query (see Table 4) is designed to examine the connections between inspection methods and the inspected bridge components. The relationships between the converted inspection methods and IFC files were established using the SODIA ontology. The results (see Table 5) of the query present the two instances of the respective inspection methods, namely radiography and rebound hammer, as well as the inspected bridge components (abutments).

Table 4: Structure of Query 01.

```
SELECT
   (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionInstance)
   (STRAFTER(STR(?inspectionType), "#") AS ?InspectionMethodName)
   (STRAFTER(STR(?abutment), "#") AS ?BridgeInstance)
   (STRAFTER(STR(?abutmentType), "#") AS ?BridgeComponent)
WHERE {
   ?InspectionMethod sodia:inspects ?abutment.
   ?InspectionMethod rdf:type ?inspectionType.
   ?abutment rdf:type ?abutmentType.
   FILTER(?inspectionType IN (sodia:ReboundHammer, sodia:Radiography))
   FILTER(?abutmentType IN (brcomp:Abutment))
}
```

Table 5: Results of Query 01.

InspectionInstance	**InspectionMethodName**	**BridgeInstance**	**BridgeComponent**
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"Radiography"	"buildingelement_593659d2-1e06-415e-8603-93c28d83a203"	"Abutment"
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"ReboundHammer"	"buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10"	"Abutment"

Query 02 Access:

The accessibility of the component to be inspected is a critical factor in determining the most appropriate inspection methods. Therefore, query 02 evaluates the accessibility of the component. The query and results in Table 6 and Table 7 illustrate the inspected object, the inspection methods used as well as the number of available access points. Radiography requires two access points due to its transmission method (A. Walther and A. Hasenstab, 2012). Consequently, if a component has only one access point, the SPARQL query generates an error message.

Table 6: Structure of Query 02.

```
SELECT
   (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionInstance)
   (STRAFTER(STR(?TypeName), "#") AS ?InspectionMethodName)
   ?AccessCount
   ?errorMessage
WHERE {
   {
      ?InspectionMethod sodia:inspects ?Abutment.
      ?InspectionMethod sodia:hasAccess ?AccessCount.
      ?InspectionMethod rdf:type sodia:Radiography.
      FILTER(?AccessCount = 1)
      BIND("Error: Radiography requires 2 accesses" AS ?errorMessage)
      BIND(sodia:Radiography AS ?TypeName)
   }
   UNION
   {
      ?InspectionMethod sodia:inspects ?Abutment.
      ?InspectionMethod sodia:hasAccess ?AccessCount.
      ?InspectionMethod rdf:type sodia:ReboundHammer.

      BIND("" AS ?errorMessage)
      BIND(sodia:ReboundHammer AS ?TypeName)
   }
}
```

Table 7: Results of Query 02.

InspectionInstance	InspectionMethodName	AccessCount	errorMessage
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"ReboundHammer"	1	""
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"Radiography"	1	"Error: Radiography requires 2 accesses"

Query 03 Inspection Participant:

Query 03 is designed to determine the qualifications of the inspection personnel. The query accesses the file generated by the LLM model. Table 8 shows the query code and Table 9 the results of the query, which includes the name of the inspector, the title of the qualification, the date of issue, and a description of the training. The query verifies that the person has the required qualification, ensuring that only certified personnel perform inspections according to DIN EN ISO 9712 (German Concrete and Construction Engineering Association, 2022).

Table 8: Structure of Query 03.

```
SELECT ?ParticipantName ?QualificationTitle ?IssueDate ?TaskDescription
WHERE {
  ?participant a sodia:InspectionParticipant ;
          foaf:name ?ParticipantName ;
          sodia:hasQualification ?certificate .
  ?certificate a sodia:Qualification ;
          dcterms:title ?QualificationTitle ;
          dcterms:issued ?IssueDate .
  ?task a foaf:Project ;
      dcterms:description ?TaskDescription ;
      sodia:needsQualification ?certificate .
}
```

Table 9: Results of Query 03.

ParticipantName	QualificationTitle	IssueDate	TaskDescription
"Eva Heinlein"	"Training Certificate"	2023-11-13	"Training on non-destructive testing of structures"

Query 04 Information about ReboundHammer Inspection:

The fourth query (see Table 10 and Table 11) provides detailed information about the rebound hammer. This information is relevant for the documentation of conducted inspections. Table 11 depicts the rebound hammer, accompanied by the inspection date and the inspected component. Furthermore, the number of measurement points is displayed. The rebound hammer operates on a point-based inspection method and requires at least 12 measurement points, in accordance with DIN EN 12504-2 (Deutsches Institut für Normung e.V., 2021).

Table 10: Structure of Query 04.

```
SELECT
  (STRAFTER(STR(?ReboundHammer), "#") AS ?ReboundHammerInstance)
  ?InspectionDate
  (STRAFTER(STR(?AccessPoint), "#") AS ?AccessPointInstance)
  (COUNT(?InspectionArea) AS ?InspectionAreaCount)
WHERE {
  ?ReboundHammer a sodia:ReboundHammer ;
          sodia:inspects ?AccessPoint ;
          sodia:inspectionDate ?InspectionDate ;
          sodia:hasInspectionArea ?InspectionArea .
}
GROUP BY ?ReboundHammer ?InspectionDate ?AccessPoint
```

Table 11: Results of Query 04.

ReboundHammerInstance	InspectionDate	AccessPointInstance	InspectionAreaCount
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"2023-11-21"	"buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10"	15

Query 05 Inverse Relationship:

Query 05 is designed to ascertain the correctness of the inverse relationships between two object properties defined in the SODIA ontology. The query (see Table 12) determines which component is subject to inspection by a specific inspection method, namely *sodia:isInspectedBy*. In the manually written triples, only the relationship "InspectionMethod inspects component" was created. The object property *sodia:inspects* has an inverse relationship with the property *sodia:isInspectedBy*. The query results (see Table 13) confirm that the inverse property correctly derives the relationship to *sodia:isInspectedBy*. Additionally, the number of access points to the component is displayed, illustrating the utility of the characteristics defined in the SODIA ontology.

Table 12: Structure of Query 05.

```
SELECT ?BridgeComponent ?AccessCount
WHERE {
  ?BridgeComponent sodia:isInspectedBy bot:ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252;
              sodia:Access ?AccessCount.
}
```

Table 13: Results of Query 05.

BridgeComponent	AccessCount
https://pi.pauwel.be/voc/buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10	1

Query 06 Inspection Task:

This query 06 (see Table 14) identifies the relationship between inspection methods and specific inspection tasks. The results in Table 15 show the tasks associated with different methods, such as determining compressive strength or detecting voids. These results provide essential information for planning inspections efficiently and matching inspection methods to specific diagnostic objectives.

Table 14: Structure of Query 06.

```
SELECT DISTINCT (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionMethodName)
            ?InspectionTask
            ?TaskType
WHERE {
   ?InspectionMethod sodia:inspects ?InspectionTask .
   ?InspectionTask rdf:type ?TaskType .

   VALUES ?TaskType { sodia:CompressiveStrength sodia:Void }
}
```

Table 15: Results of Query 06.

InspectionMethodName	InspectionTask	TaskType
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	http://example.org/synthetic_data/inspection_task_void	sodia:Void
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	http://example.org/synthetic_data/inspection_task_compressive_strength	sodia:CompressiveStrength

Query 07 Regulation:

Query 07, shown in Table 16, retrieves regulatory information relevant to specific inspection methods. The results in Table 17 list regulations, such as DIN 1076 and DIN 12504-4, and their association with the corresponding inspection methods. DIN 12504-4 applies to the rebound hammer method, while DIN 1076 provides general guidelines for structural diagnostics (Deutsches Institut für Normung e.V., 1999, 2021). This query ensures compliance with applicable standards by linking regulatory requirements directly to inspection methods.

Table 16: Structure of Query 07.

```
SELECT
   (STRAFTER(STR(?Regulation), "#") AS ?RegulationName)
   (STRAFTER(STR(?x), "#") AS ?RegulatedInstanceName)
WHERE {
   ?Regulation sodia:regulates ?x .
}
```

Table 17: Results of Query 07.

RegulationName	RegulatedInstanceName
" DIN12504-2"	"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"
"DIN1076"	"structural_diagnostic"

Query 08 Inspection Tool:

This query provides information regarding the inspection tools used within each inspection method (see Table 18). The results in Table 19 list the tools alongside their respective manufacturers and model names. For example, the radiography method employs the "X-Ray Inspection System 2000" from YXLON International, whereas the rebound hammer method utilizes the "Schmidt Rebound Hammer Type N" from Proceq.

Table 18: Structure of Query 08.

```
SELECT DISTINCT
   (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionMethodName)
   ?ToolName ?ToolProducer ?ToolID
WHERE {
   ?InspectionMethod sodia:uses ?InspectionTool .
   ?InspectionTool sodia:inspectionTool_Name ?ToolName ;
              sodia:inspectionTool_ID ?ToolID;
              sodia:inspectionTool_Producer ?ToolProducer .
}
}
```

Table 19: Results of Query 08.

InspectionMethodName	ToolName	ToolProducer	ToolID
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"X-Ray Inspection System 2000"	"YXLON International"	"RT-200"
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"Schmidt Rebound Hammer Type N"	"Proceq"	"RH-001"

Query 09 Evaluation:

Query 09 evaluates the inspection results based on predefined evaluation criteria, including durability, structural stability, and traffic safety (see Table 20). The results in Table 21 provide a rating for each criterion along with a descriptive evaluation comment. For example, an inspection result indicating localized spalling with exposed reinforcement on an abutment may receive a low stability rating.

Table 20: Structure of Query 09.

```
SELECT DISTINCT
   (STRAFTER(STR(?InspectionResult), "#") AS ?InspectionResultName)
   (STRAFTER(STR(?Evaluation), "#") AS ?EvaluationName)
   ?Durability ?Stability ?TrafficSafety ?EvaluationComment
WHERE {
   ?InspectionResult sodia:enables ?Evaluation .
   ?Evaluation sodia:hasEvaluation_Comment ?EvaluationComment ;
            sodia:hasEvaluation_Durability ?Durability ;
            sodia:hasEvaluation_Stability ?Stability ;
            sodia:hasEvaluation_TrafficSafety ?TrafficSafety .
}
```

Table 21: Results of Query 09.

InspectionResultName	EvaluationName	Durability	Stability	TrafficSafety	EvaluationComment
"inspection_result"	"evaluation_instance"	2	1	0	"Abutment West, concrete, localized spalling with exposed reinforcement at the side surfaces and undersides"@en

Query 10 Measurement Method:

The final query 10 determines which measurement methods are used within each inspection procedure (see Table 22). The results in Table 23 establish connections between an inspection method and its corresponding measurement method. For instance, radiography applies the transmission method, while the rebound hammer applies the penetration technique.

Table 22: Structure of Query 10.

```
SELECT DISTINCT
   (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionMethodInstance)
   (STRAFTER(STR(?MeasurementMethod), "#") AS ?MeasurementMethodName)
WHERE {
   ?InspectionMethod sodia:applies ?MeasurementMethod .
}
```

Table 23: Results of Query 10.

InspectionMethodInstance	MeasurementMethodName
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"Transmission"
"inst:ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"Penetration"

5.3 Use of ICDD-Containers

5.3.1 Workflow

The system-integrated approach is using ICDD container for the validation (ISO, 2020a, 2020b). ICDD is a standard for a multi-model container approach that facilitates the use of LD and LBD (Senthilvel et al., 2020). The ICDD container enables the storage and interlinking of documents both internally, within the container itself, and externally, such as Web resources in heterogeneous file formats. Links can establish relationships between documents, or even between individual elements within documents via deep links. These relationships allow user-specific data queries (ISO, 2020a).To implement the container approach for the SODIA ontology, the RUB ICDD Platform is used (P. Hagedorn, 2024). This is a web-based platform that integrates the ICDD container and provides functionalities for uploading, editing and exporting ICDD containers (Hagedorn et al., 2023a).

The structure of the ICDD container is divided into the folders "Ontology Resources", "Payload Documents" and "Payload Triples". Figure 6 shows the folder structure of the RUB ICDD platform, enriched with documents.

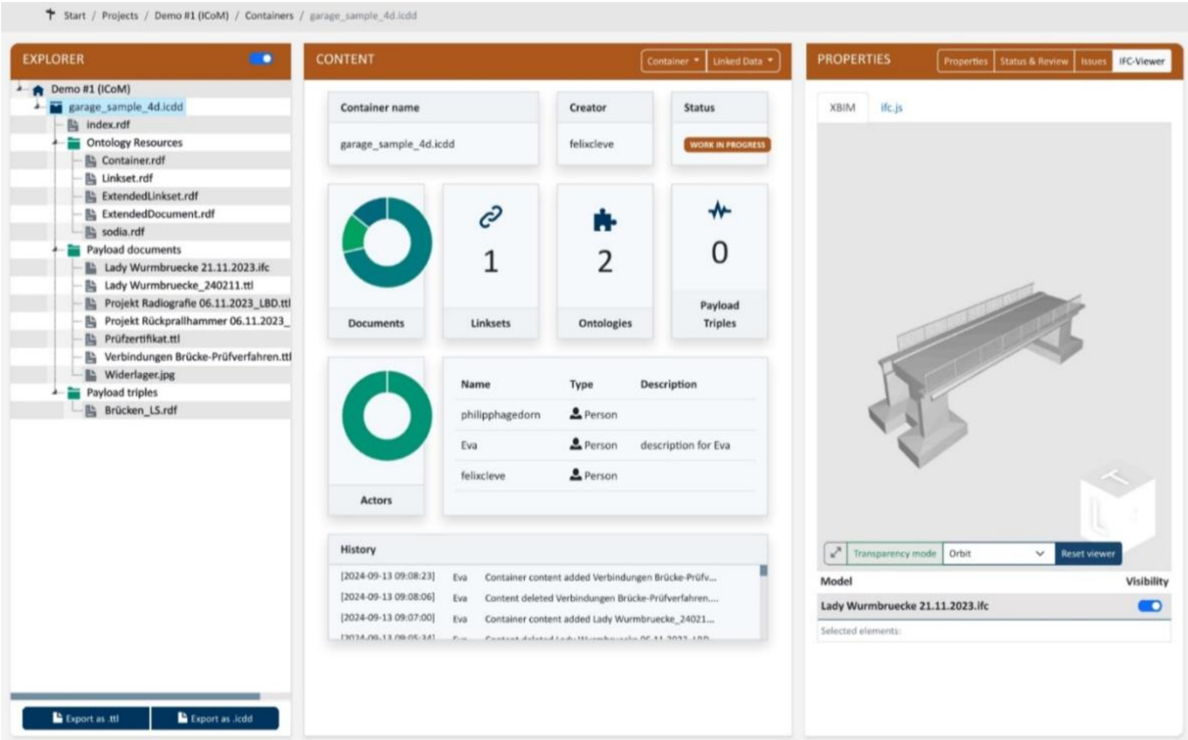

Figure 6: Overview of RUB ICDD platform (Hagedorn et al., 2023a).

The folder "Ontology Resources" contains ontologies that structure the contents and links between documents (ISO, 2020a). The SODIA ontology is stored here to structure the contents of the domain of non-destructive structural diagnostics. The "Payload Documents" folder is used to upload all project-relevant documents, including the IFC bridge model, which is also displayed in the IFC Viewer and an image of the abutment. In addition, the files converted to TTL format (see Workflow graph database) are uploaded as internal documents. This facilitates URI-based linking with other documents (Hagedorn et al., 2023c).

The document "Verbindungen Brücke-Prüfverfahren.ttl" must also be uploaded to establish the relationship between the inspection methods rebound hammer and radiography with the bridge, similar to the graph database approach. Linkset files are stored in the Payload Triples folder. A linkset is used to define relationships between two or more documents and between the elements within those documents (ISO, 2020a). An example of a linkset between two documents is shown in Figure 7.

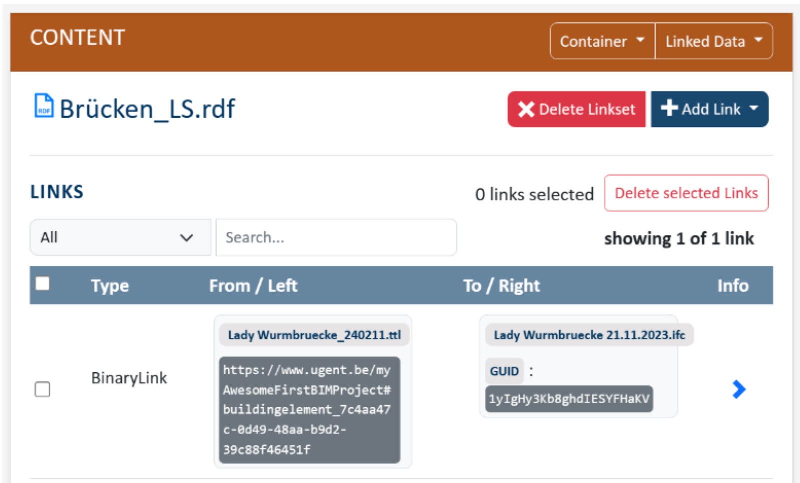

Figure 7: Example of a linkset.

The figure shows that an element, the object "abutment" of the bridge model's IFC file, is binary linked to the instance "abutment" of the bridge model's converted TTL file. For the TTL file an "ls:URIBasedIdentifier“ is selected as the LBD concept for the TTL file, while the object in the IFC file is identified via the "ls:StringBasedIdentifier" with the GUID (Hagedorn et al., 2023b).

5.3.2 Validation

To demonstrate the feasibility of linking heterogeneous data and the use of the SODIA ontology within the ICDD container, two SPARQL queries are executed on the RUB ICDD platform.

Query01 - Verification of the Linkage between IFC File and TTL File:

The objective of this query is to retrieve the previously described linkset between the IFC file and the TTL file. The query retrieves the link element, the container description, and the identifier. Figure 8 displays the results of this query.

The query confirms the functionality of the connection between two elements within an ICDD container. The instance and the object "abutment" of the bridge are displayed. Using the identifier, these elements can be uniquely identified. Thus, linksets enable the connection between two heterogeneous file formats, in this case, a TTL file and an IFC file.

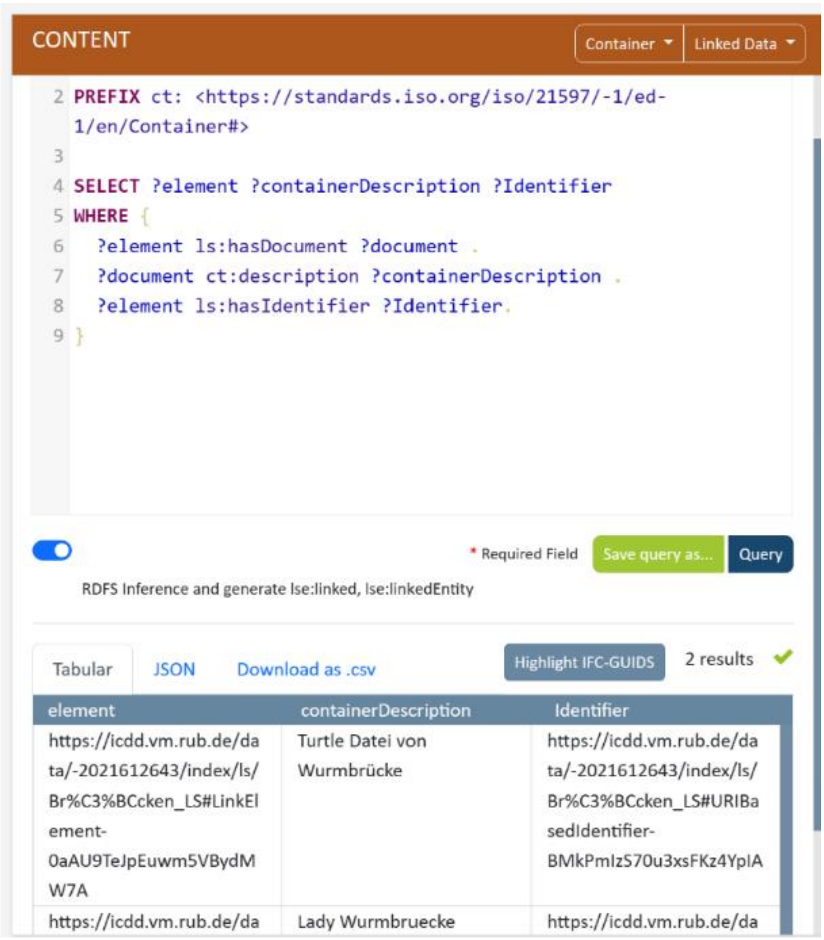

Figure 8: Result of Query 01.

Query02 - Utilization of the SODIA Ontology in the ICDD Container:

The second query demonstrates that the connections generated by the SODIA ontology can be queried. Additionally, the simultaneous connection to the linkset is demonstrated. This is shown in Figure 9.

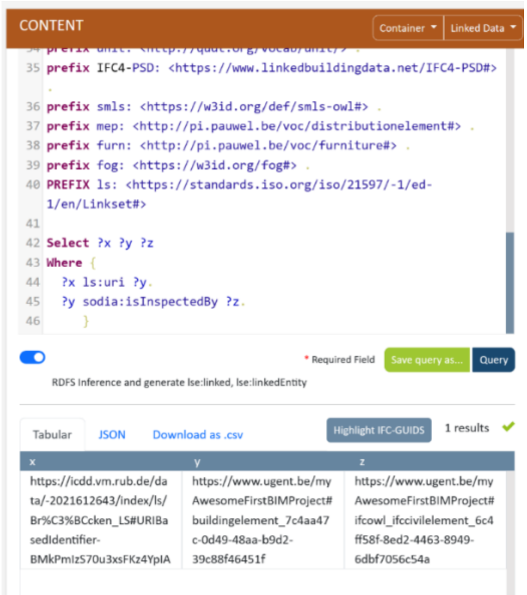

Figure 9: Result of Query 02.

It illustrates that the abutment is inspected with the rebound hammer. This connection to the inspection methods can be extracted from the file "Verbindungen Brücke-Prüfverfahren.ttl“ which was uploaded to the "Payload Documents" folder. Furthermore, the URI-based identifier of the abutment is queried, thus referring to the linkset. This linkset, in turn, references the linkage of the IFC file and the converted TTL file. In this manner, a semantic relationship can be established and queried through the SODIA ontology, while simultaneously referencing the original IFC files via linksets. Figure 10 presents the aforementioned relationships in a simplified form.

5.4 Consolidation of the Validation

Following the implementation of the data-integrated and system-integrated approach, the added value and challenges of the individual approaches are analysed and compared. The first added value of the data-integrated approach is the fast linking of the data with just one graph database as a central and consistent data store. It only requires a converter to automatically transform the digital 3D bridge models from IFC into the RDF data schema. In the context of diagnostic data, simple integration of all alphanumeric data is possible without any additional transformation. Another added value is the structured query option and obtaining linked findings between the building and diagnostic data by using the graph database and the structured query option via SPARQL.

However, the data-integrated approach also includes challenges. A central challenge is the limitation of integrable data in the context of the RDF data schema. While alphanumeric data can be easily integrated into the RDF data schema, non-alphanumeric data or data without the RDF data schema cannot be easily integrated. For alphanumeric data that is available in other data schemas, a transformation into the RDF schema is required. For other data types, e.g. images or entire documents, the graph database must be expanded into a hybrid database. Another limitation is the susceptibility to errors and the possibility of data loss during the transformation from IFC to RDF in the context of the bridge structure. In addition, there are limitations with the defined properties and classes of the ontology as well as the possibility of linking only at the data level and not with other systems.

Furthermore, there are also individual added values and challenges for the system-integrated approach. The first added value is the simple linking of heterogeneous databases in one platform using the ontology. At the same time, there is compatibility between alphanumeric and non-alphanumeric data by linking the databases in the multi-model. These links can be made in individual information containers on a case-by-case basis without having to access all data sets. Furthermore, the system-integrated approach does not require any transformation of proprietary data formats. This avoids possible data loss through the use of additional transformers. By linking different data, this also results in the possibility of linking different, specific domains. In the use case considered in the article, the bridge structure data can be easily linked with further damage data and diagnostic data. This makes it possible to obtain further, cross-domain findings.

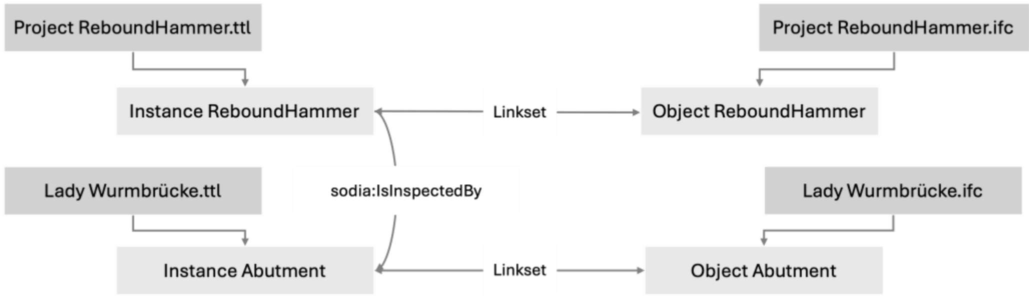

Figure 10: Illustrated example of the relationship between the SODIA Ontology and bridge model.

In contrast, the system-integrated approach also presents challenges that limit its efficient use. The first challenge is the manual and time-consuming creation of individual link sets to link the data sets under consideration in an information container. In addition, when integrating new data sets or creating new specific information containers, new linksets must always be created manually and integrated into the platform. This can lead to errors when defining the links. At the same time, the process is very time-consuming and resource-intensive.

Both approaches analyse the use of ontologies in connection with digital 3D bridge models using the BIM method. Both approaches can be used for the use case of building diagnostics. A general recommendation in a direct comparison cannot be made. Rather, when choosing an approach, it is important to consider which basic requirements and data sets are available. If only alphanumeric data is available and no integration of non-alphanumeric data is foreseeable, the data-integrated approach is suitable due to its consistent data storage, management and provision. If the use case under consideration involves working with many heterogeneous data types in different storage systems and many specific combinations of different data points are required, a system-integrated approach should be selected.

6. DISCUSSION & CONSLUSION

The article demonstrates the development and validation of an ontology for the field of non-destructive structural diagnostics on bridge structures using BIM models. Two different integration approaches of the ontology are analysed. On the one hand, this is done at the data level using a grap database and an RDF transformer (data-integrated approach) and, on the other hand, at the system level in connection with information containers according to ISO 21597-1:2020 (system-integrated approach). At the beginning of the article, the development and description of the SODIA ontology based on explicit and implicit knowledge is presented. This forms the ontological basis for the two integration approaches under consideration. This is followed by the implementation of the data-integrated approach by setting up a graph database, the transformation of the digital BIM model of a bridge structure from the IFC data schema into the RDF schema and the integration of all data into the graph database. Subsequently, 10 queries are carried out with SPARQL to validate the approach. The system-integrated approach is processed afterwards. This involves integrating the ontology, the inventory data records and further documents and data into an ICDD platform and linking them using a previously created link set. A total of two queries are carried out to test usability. The two approaches are then consolidated and the added value and challenges are presented, followed by a final comparison and validation.

The article proves that both approaches of a possible use of ontologies in the context of NDE and bridge structures are usable and performant. At the same time, it is shown that a domain-specific ontology can be used both at the data level and at the system level. Two alternatives for the integration of all complex data from the field of building diagnostics into an IFC model are shown. The resulting interoperability between different data sets avoids data loss in connection with necessary data transformations. The data-integrated approach focusses on the interoperable use of alphanumeric BIM data and NDE data in the spectrum of a graph database. In contrast, the system-integrated approach specifies the use of the ontology to link heterogeneous data sets, consisting of alphanumeric and non-alphanumeric data, as well as their embedding in information containers. Furthermore, both approaches show that formalised knowledge in an ontology can be made usable in various ways and that complex facts in the NDE domain can be made machine-interpretable with the help of the ontology.

Both validated approaches address the stakeholders involved in operation and maintenance management, such as plant operators, structural inspectors and diagnosticians. Both approaches discussed in the article show possibilities for data linking and interoperable data use to further optimise data management in the operation of bridge structures using BIM models.

In addition to the added value of the new ontological approach, there are also limitations. The ontology is currently only focussed on the area of non-destructive structural diagnostics and therefore only covers a partial area. The areas of semi-destructive and destructive diagnostic methods are still missing. Another aspect is that the ontology is designed on a very generic level, so that the ontology must be specifically expanded for each diagnostic test method. The ICDD approach only contains a small number of parameters that can be referenced in the linkset. Furthermore, the article only shows the feasibility of the two approaches and does not provide any further quantitative parameters for measuring quality and efficiency.

Regarding the two approaches analysed, it should be emphasised that the implementation and processing in both cases are associated with a high expenditure of time and resources. In addition, specific knowledge is required in the specific areas of ontology development, data transformations, the RDF data schema and the SPARQL data query language. There is also a limited number of established software applications for both approaches. This limits a transfer and simple application in practice. In addition, individual limitations in the individual approaches can be identified. The data-integrated approach is always dependent on a transformation of all data types used into the RDF data schema with converters. This implies the risk of data loss before a qualitative utilization using the graph database can be established. In the context of the article, an established converter was used that first transforms the IFC model into a structure for buildings. The further conversion into the structure of a bridge was carried out manually. Moreover, the graph database is focussed on alphanumeric data. Integration of other data types is excluded. Again, the system-integrated approach is limited in its scope of utilization unless new link sets are developed for the intended information container for each integration cycle.

For future research activities, both approaches should be iteratively tested and validated with a larger data set. At the same time, both approaches should be used for different bridge types, construction conditions and diagnostic scenarios to demonstrate future generalisability. Building on this, metrics should be developed to measure efficiency, accuracy and the quality of decision-making. This creates further foundations for the medium-term practical integration of the two still theoretical approaches. At the same time, it should be investigated which tools can be used to establish friendly and simple interaction between the systems of the two approaches. Furthermore, an extension of the ontologies including the two approaches focussing on further life cycle phases should be investigated. This means that the approaches can be used not only in isolation in the operational phase, but in all life cycle phases.

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APPENDIX

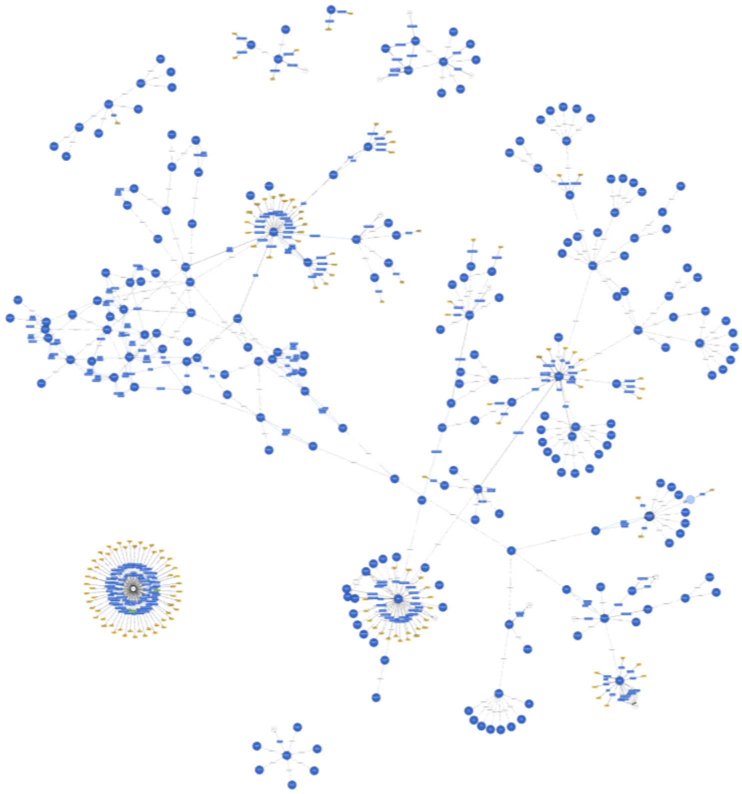

Figure 11: Visualization of the SODIA Ontology using WebVOWL (based on Lohmann et al. (2015)).

```
# Query01 Inspection
SELECT
    (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionInstance)
    (STRAFTER(STR(?inspectionType), "#") AS ?InspectionMethodName)
    (STRAFTER(STR(?abutment), "#") AS ?BridgeInstance)
    (STRAFTER(STR(?abutmentType), "#") AS ?BridgeComponent)
WHERE {
    ?InspectionMethod sodia:inspects ?abutment.
    ?InspectionMethod rdf:type ?inspectionType.
    ?abutment rdf:type ?abutmentType.

    FILTER(?inspectionType IN (sodia:ReboundHammer, sodia:Radiography))
    FILTER(?abutmentType IN (brcomp:Abutment))
}
```

Run to File | Text | Charts | Visualize | 2 Results, 449 ms

InspectionInstance	InspectionMethodName	BridgeInstance	BridgeComponent
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"Radiography"	"buildingelement_593659d2-1e06-415e-8603-93c28d83a203"	"Abutment"
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"ReboundHammer"	"buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10"	"Abutment"

Figure 12: Query01 – Inspection.

```sparql
# Query02 Access
SELECT
    (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionInstance)
    (STRAFTER(STR(?TypeName), "#") AS ?InspectionMethodName)
    ?AccessCount
    ?errorMessage
WHERE {
    {
        ?InspectionMethod sodia:inspects ?Abutment.
        ?InspectionMethod sodia:hasAccess ?AccessCount.
        ?InspectionMethod rdf:type sodia:Radiography.

        FILTER(?AccessCount = 1)
        BIND("Error: Radiography requires 2 accesses" AS ?errorMessage)
        BIND(sodia:Radiography AS ?TypeName)
    }
    UNION
    {
        ?InspectionMethod sodia:inspects ?Abutment.
        ?InspectionMethod sodia:hasAccess ?AccessCount.
        ?InspectionMethod rdf:type sodia:ReboundHammer.

        BIND("" AS ?errorMessage)
        BIND(sodia:ReboundHammer AS ?TypeName)
    }
}
```

Run to File | Text | Charts | Visualize | 2 Results, 460 ms

InspectionInstance	InspectionMethodName	AccessCount	errorMessage
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"ReboundHammer"	1	""
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"Radiography"	1	"Error: Radiography requires 2 accesses"

Figure 13: Query 02 – Access.

```sparql
# Query03 InspectionParticipant
SELECT ?ParticipantName ?QualificationTitle ?IssueDate ?TaskDescription
WHERE {

    ?participant a sodia:InspectionParticipant ;
                 foaf:name ?ParticipantName ;
                 sodia:hasQualification ?certificate .

    ?certificate a sodia:Qualification ;
                 dcterms:title ?QualificationTitle ;
                 dcterms:issued ?IssueDate .

    ?task a foaf:Project ;
          dcterms:description ?TaskDescription ;
          sodia:needsQualification ?certificate .
}
```

Run to File | Text | Charts | Visualize | 1 Results, 1233 ms

ParticipantName	QualificationTitle	IssueDate	TaskDescription
"Eva Heinlein"	"Training Certificate"	2023-11-13	"Training on non-destructive testing of structures"

Figure 14: Query 03 – InspectionParticipant.

```sparql
# Query04 Information about ReboundHammer Inspection
SELECT
    (STRAFTER(STR(?ReboundHammer), "#") AS ?ReboundHammerInstance)
    ?InspectionDate
    (STRAFTER(STR(?AccessPoint), "#") AS ?AccessPointInstance)
    (COUNT(?InspectionArea) AS ?InspectionAreaCount)
WHERE {
    ?ReboundHammer a sodia:ReboundHammer ;
                   sodia:inspects ?AccessPoint ;
                   sodia:inspectionDate ?InspectionDate ;
                   sodia:hasInspectionArea ?InspectionArea .
}
GROUP BY ?ReboundHammer ?InspectionDate ?AccessPoint
```

Run to File | Text | Charts | Visualize | 1 Results, 439 ms

ReboundHammerInstance	InspectionD...	AccessPointInstance	InspectionAreaCount
"ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"2023-11-21"	"buildingelement_e6904e30-a4f3-4171-b98b-4c9130275d10"	15

Figure 15: Query 04 - Information about ReboundHammer Inspection.

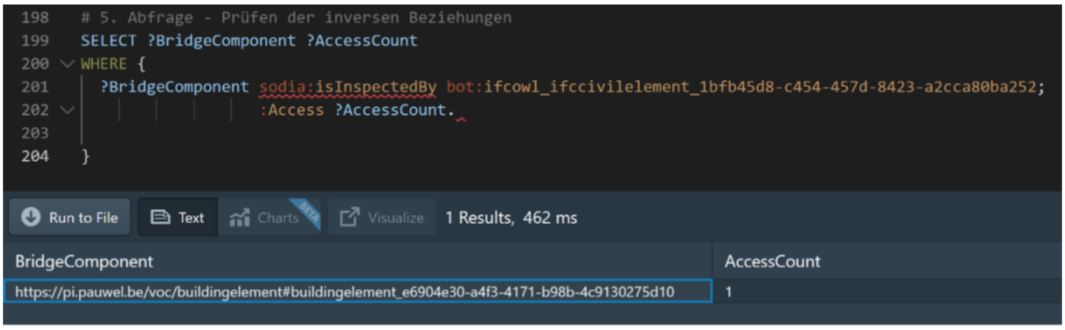

Figure 16: Query 05 - Inverse Relationship.

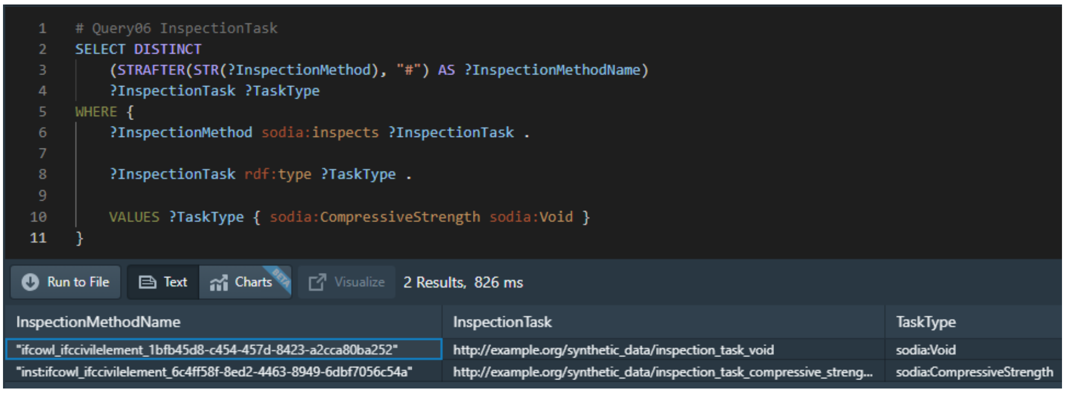

Figure 17: Query 06 – InspectionTask.

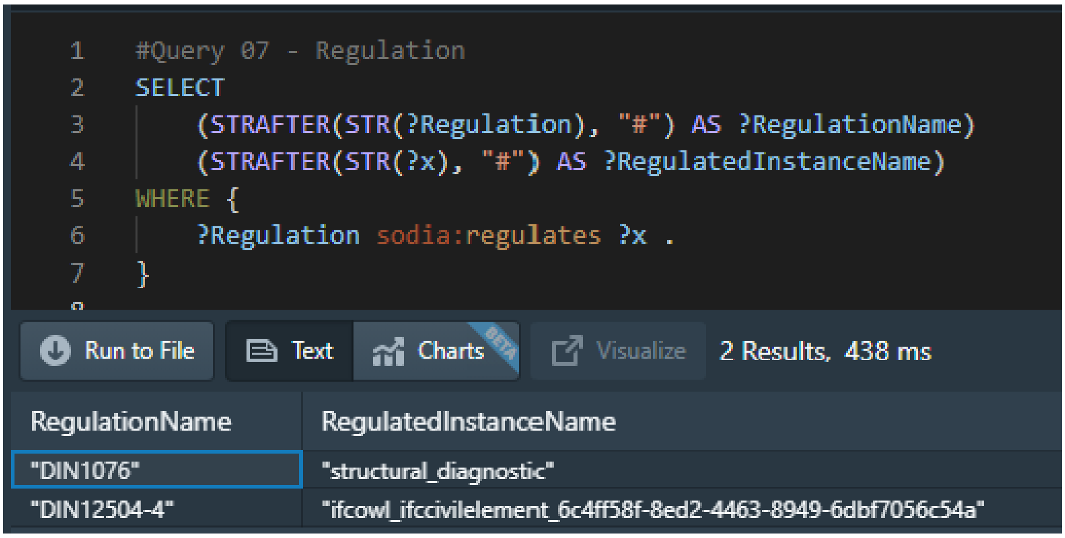

Figure 18: Query 07 – Regulation.

```
# Query08 InspectionTool
SELECT DISTINCT
    (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionMethodName)
    ?ToolName ?ToolProducer ?ToolID
WHERE {
    ?InspectionMethod sodia:uses ?InspectionTool .
    ?InspectionTool sodia:inspectionTool_Name ?ToolName ;
                    sodia:inspectionTool_ID ?ToolID;
                    sodia:inspectionTool_Producer ?ToolProducer .
}
```

Run to File | Text | Charts | Visualize | 2 Results, 906 ms

InspectionMethodName	ToolName	ToolProducer	ToolID
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"X-Ray Inspection System 2000"	"YXLON International"	"RT-200"
"inst:ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"Schmidt Rebound Hammer Type N"	"Proceq"	"RH-001"

Figure 19: Query 08 – InspectionTool.

```
# Query09 Evaluation
SELECT DISTINCT
    (STRAFTER(STR(?InspectionResult), "#") AS ?InspectionResultName)
    (STRAFTER(STR(?Evaluation), "#") AS ?EvaluationName)
    ?Durability ?Stability ?TrafficSafety ?EvaluationComment
WHERE {
    ?InspectionResult sodia:enables ?Evaluation .
    ?Evaluation sodia:hasEvaluation_Comment ?EvaluationComment ;
                sodia:hasEvaluation_Durability ?Durability ;
                sodia:hasEvaluation_Stability ?Stability ;
                sodia:hasEvaluation_TrafficSafety ?TrafficSafety .
}
```

Run to File | Text | Charts | Visualize | 1 Results, 874 ms

InspectionResultName	EvaluationName	Durability	Stability	TrafficSafety	EvaluationComment
"inspection_result"	"evaluation_instance"	2	1	0	"Abutment West, concrete, localized spalling with exposed reinforcement at the side surfaces and undersides"@en

Figure 20: Query 09 – Evaluation.

```
# Query10 Measurement Method
SELECT DISTINCT
    (STRAFTER(STR(?InspectionMethod), "#") AS ?InspectionMethodInstance)
    (STRAFTER(STR(?MeasurementMethod), "#") AS ?MeasurementMethodName)
WHERE {
    ?InspectionMethod sodia:applies ?MeasurementMethod .
}
```

Run to File | Text | Charts | Visualize | 2 Results, 856 ms

InspectionMethodInstance	MeasurementMethodName
"inst:ifcowl_ifccivilelement_6c4ff58f-8ed2-4463-8949-6dbf7056c54a"	"Penetration"
"ifcowl_ifccivilelement_1bfb45d8-c454-457d-8423-a2cca80ba252"	"Transmission"

Figure 21: Query 10 - Measurement Method.