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Ontology-based BIM-AMS integration in European Highways

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ABSTRACT

BIM tools enable decision-making during the lifecycle of engineering structures, such as bridges, tunnels, and roads. National Road Authorities use Asset Management Systems (AMS) to manage and monitor operational information of assets from European Highways, including access to sensor and inspection data. Interoperability between BIM and AMS systems is vital for a timely and effective decision-making process during the operational phase of these assets. The European project Connected Data for Effective Collaboration (CoDEC) designed a framework to support the connections between AMS and BIM platforms, using linked data principles. The CoDEC Data Dictionary was developed to provide standard data formats for AMS used by European NRA. This paper presents the design and development of an Engineering Structures ontology used to encode the shared conceptualization provided by the CoDEC Data Dictionary. The ontology is evaluated, validated, and demonstrated as a base for data exchange between BIM and AMS.

1. Introduction

Building Information Modeling (BIM) is defined in ISO 19650-1:2018 (2018) as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions". Physical infrastructures, such as buildings, bridges and roads, can be modeled and managed across the whole asset lifecycle using BIM, together with necessary functional characteristics needed for decision making. The 3D visualization provided by BIM tools allows stakeholders to collaborate, share and exchange information, which is especially useful for decision support during the design, planning and construction phases. However, the use of BIM in transport infrastructures is still far from its wide application in the building industry, mainly due to the fact that vertical structures (buildings) have different operations, components and techniques in comparison to horizontal constructions (e.g., bridges, roads, tunnels) (Costin et al., 2018). Recent works show that the application of BIM in the transportation industry is slowly increasing and can be helpful along the lifecycle of the structures from the most common to the more complex activities (Biancardo et al., 2020, D'Amico et al., 2020, Koch et al., 2014). Furthermore, despite its potential application in all phases of the infrastructure life cycle, BIM use during the operational and management (O&M) phase is currently limited (Wijeratne et al., 2024).

National Road Authorities (NRA) in Europe have invested in Asset Management Systems (AMS) to ensure management, maintenance and structural safety during the operational phase of Engineering Structures in European Highways. These systems contain asset operational information such as sensor data and inspection results, usually stored in various formats. Ideally, information should be shared between BIM models and AMS so that more efficient and informed decisions can be taken during the operational phase of these engineering structures (in either system). While there are standards for BIM data, such as the Industry Foundation Classes – IFC (ISO 16739-1:2018 (2018)), these are not focused on operation phases or AMS integration. Due to the increasing number of solutions for asset monitoring (sensor technology and Internet-of-Things), the interoperability between these systems is vital for timely decision-making in an integrated environment. Linking 3D model data with asset management data allows access to an integrated view of information, reduces errors, and saves time and costs, while also enhancing compliance, customer satisfaction, safety, and risk mitigation during the operational phase (Wijeratne et al., 2024).

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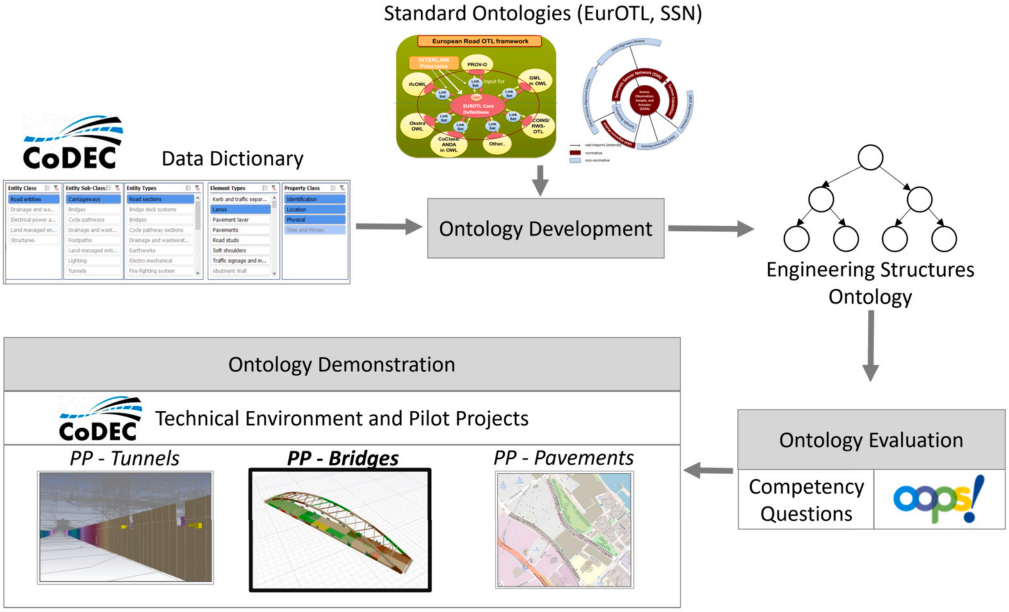

Fig. 1. Research methodology.

Highway infrastructures asset data stored in BIM models can provide AMS with a more accurate description of these structures and enable better decision-making in maintenance and repair activities. Interoperability between these systems can also improve stakeholder collaboration and coordination by ensuring that asset data remains available and consistent in both systems, regardless of the current stage of their lifecycle. Asset management can be improved by enriching BIM with semantic information through AMS, such as geographic information systems (GIS), or linked data integration. For example, Zhao et al. (2019) integrated BIM with GIS to improve the effectiveness of highway alignment and reduce planning risks, such as design errors and miscommunication, and avoid environmental hazards. Similarly, Meschini, Daniele, et al. (2022), Meschini et al. (2023), Meschini, Pellegrini, et al. (2022) integrated BIM information into GIS using a relational database to facilitate information management and improve the decision-making process through business intelligence reports in university buildings. Al-Kasasbeh et al. (2021) also proposed a relational approach to integrating asset management data with data extracted from BIM models, developing an integrated decision support system based on a work breakdown structure for all life cycle phases. Furthermore, Ait-Lamallam et al. (2021a, 2021b, 2021c) extended the IFC standard concepts and presented an ontological approach called IFCInfra4OM (Industry Foundation Classes for Operation and Maintenance of Infrastructures) to provide support to the O&M of transport infrastructures.

Semantically enriched solutions allow information to be presented to stakeholders more intuitively, enhancing the usability of BIM and improving the management of complex engineering structures (Jiang et al., 2023). A complete and detailed view of the structure, structural elements, and recent behavior-related dynamic data can enable structural engineers to plan, budget, and act more effectively, leading to cost savings, reduced downtime, and improved safety for road users. Nonetheless, different technologies, data formats, requirements, and standards used in AMS and BIM systems can hinder this interoperability (Kivits et al., 2013, Gao & Pishdad-Bozorgi, 2019, Garramone et al., 2020, Jiang et al., 2023).

In Europe, there have been efforts to standardize data formats for AMS, such as AM4INFRA (Marcovaldi & Biccellari, 2018, Kokot, 2019), but data management practices are largely tailored to the individual AMS within each NRA. Highways England (2020) and the Lithuanian NRA (Ratkevičiūtė, 2010) have made attempts to develop standardized “Data Dictionaries” for some asset types, but few other publicly-available data dictionaries were found in other countries. While some countries, like the Netherlands, Belgium, and Finland, have developed Object Type Libraries (OTL), there is a noticeable gap in the availability, extent and content of data dictionaries for highway assets, which hinders the effective use of data, especially within a BIM environment (Biswas et al., 2021a, 2021b)

The Connected Data for Effective Collaboration (CoDEC) project[1] aimed to implement BIM principles in the European Highways Industry, focusing on data exchange between BIM and AMS to manage asset data during the operational phase. The project was funded by the Conference of European Directors of Roads (CEDR). A “Master Data Dictionary” was developed during the project with legacy (AMS-based data) and sensor/scanner data concerning specific key infrastructures and assets, creating a base data structure for integrating different data management systems. This shared conceptualization was key to provide standard data formats that can be used between Europe’s NRA and their systems.

In the CoDEC project, a framework was designed to support the connections between AMS and BIM platforms, allowing information to flow and be enriched between these systems. CoDEC linked operational data to BIM environments using semantic web and linked data principles. Using an ontology to model and represent structures, structural elements, and operational data, such as sensor information or legacy data, allows for the development of a single format for information exchange (Hartmann & Trappey, 2020) and enhances decision-making during the operational phase of these assets.

This paper presents the design of engineering structures ontology used in CoDEC and the main challenges faced during its development, validation and evaluation. The objectives of this research are as follows: a) Develop an ontology to encode the shared conceptualization provided by the CoDEC Data Dictionary in a machine-readable way to allow for system interoperability; b) Formally evaluate and validate the ontology; and c) Demonstrate its use as a base for data exchange between BIM and AMS.

This research follows the methodology presented in Fig. 1. First, the Engineering Structures ontology is developed following a standard ontology development methodology (NeOn Methodology Suárez-Figueroa et al. (2015)), based on existing standard ontologies and the CoDEC

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[1] https://www.codec-project.eu/.

Data Dictionary. Afterwards ontology capabilities are evaluated using competency questions (defined by different stakeholders in the context of three pilot projects) and its formalization is validated using an online tool (OOPS! - Ontology Pitfall Scanner! Poveda-Villalón et al. (2014)). Finally, the ontology is demonstrated as a base for integration between BIM and AMS in three different pilot projects (tunnels, bridges and pavements).

The remainder of this paper is structured as follows: Section 2 introduces background concepts related to ontologies. Section 3 presents current literature related to BIM and ontology-based approaches. Section 4 presents the case study environment, detailing the CoDEC Data Dictionary and the real pilot projects. The Engineering Structures ontology specification and development is presented in Section 5, followed by the ontology evaluation and validation (in Section 6). Section 7 showcases the ontology demonstration, with a specific focus on the bridges' pilot project. Discussions and limitations are presented in Section 8. Finally, conclusions are found in Section 9.

2. Ontologies

Ontologies are used in Linked Data and Semantic Web to structure and share data between different users and systems. These "formal, explicit specifications of shared conceptualizations" Studer et al. (1998) allow sharing, reuse and analysis of knowledge concerning a domain of interest (Noy et al., 2001, Stephan et al., 2007). Ontologies encode domain concepts, properties, constraints, and relationships in a formal, explicit, and machine-readable way.

The World Wide Web Consortium (W3C)[2] defines the Resource Description Framework (RDF), RDF Schema (RDFS), SPARQL and the Ontology Web Language (OWL) as standards for the Semantic Web. RDF is the recommendation for the "creation, exchange and use of annotations on the Web" (Guarino et al., 2009, p.72). The resources are described in the form of triples (*subject property object*) (Pan, 2009), for example, "Professor" "rdfs:subClassOf" "Faculty Staff". The property used in the previous example (rdfs:subClassOf) is from the RDFS vocabulary, which added class and hierarchy concepts on top of RDF, together with the necessary inference rules. SPARQL is a W3C query language for accessing and manipulating data stored in RDF format, commonly used for querying semantic web data and knowledge graphs. Lastly, OWL provides additional vocabulary and expressiveness, such as disjointedness, symmetry, and cardinality. OWL also defines properties as either object (relationships between classes) or data (attributes) properties. The three OWL types, Lite, DL and Full, have different levels of expressiveness, with the choice of language coming down to a trade-off between expressiveness and inference capabilities, i.e., the more expressive a language is, the less inference it is capable of Su and Ilebrekke (2002).

2.1. Ontology engineering methodology

Mora et al. (2022) analyzed Ontology-Based Knowledge Management Systems (OKMS) implementation methodologies in real-world settings. 26 methodologies were identified in the literature review, from which the authors selected, through a set of criteria, analyzed and evaluated the following five methodologies: CommonKADS (Schreiber et al., 1994), Methontology (Fernández-López et al., 1997), On-to-Knowledge (Staab et al., 2001), NeOn (Suárez-Figueroa et al., 2015) and XDM, a agile methodology which was initially proposed as part of NeON (Blomqvist et al., 2016). CommonKADS and NeON were the most comprehensive and systematic for project management and technical systems development processes. The authors found that there are no standards or preferences for any of these methodologies in the literature and recommend using CommonKADS or NeON for medium or large OKMS projects, with agile methodologies, such as XDM, being preferred for smaller projects.

CommonKADS (Knowledge Acquisition and Documentation Structuring) (Schreiber et al., 1994) is a knowledge engineering methodology focused on knowledge management, analysis and knowledge system development. The construction of the system is based on a set of models: Organization, Task, Agent, Knowledge, Communication and Design. Templates are provided for these models, which can be completed or altered in parallel during the project (Schreiber et al., 2000).

Methontology was proposed in 1997 by Fernández-López et al. (1997) as an ontology engineering methodology. The authors present a set of activities and states, starting with planification. Specification, conceptualization, formalization, integration, implementation, and maintenance are the main activities identified by the authors for the development process. The evolving development lifecycle allows software or knowledge engineers to change between states during the development. Knowledge acquisition, evaluation and documentation are support activities that occur throughout the lifecycle.

Staab et al. (2001) proposed the On-To-Knowledge methodology for developing ontology-based Knowledge Management (KM) systems. The On-To-Knowledge methodology comprises six activities: feasibility study, kickoff, refinement, evolution and maintenance. It ranges from the early stage of starting a KM project to the final version of the ontology-based KM application.

The NeOn Methodology (Suárez-Figueroa et al., 2015) was developed during the Neon Project[3] to provide a framework for building ontology networks. It identifies and defines processes and activities for the construction process and introduces a set of nine scenarios that consider different Knowledge Resources inputs. According to Gómez-Pérez and Suárez-Figueroa (2009), the Ontology Requirement Specification Document (ORSD) is the main output of the ontology requirement specification activity. The authors propose that the conceptualization, formalization and implementation activities in NeOn should follow the Methontology or the On-To-Knowledge methodologies.

3. BIM and ontology-based approaches

The road infrastructure asset management field is rapidly becoming digital, leading to increasing data accessibility, integration, and collaboration challenges. Current processes lack full integration and face compatibility issues between systems, including BIM (Biswas et al., 2021a). To address this, ontology-based approaches have been proposed by several authors to integrate BIM data with other information (Farghaly et al., 2019, Zhong et al., 2019, Lei et al., 2021), such as sensor-based environmental information (Zhong et al., 2018) or regulatory data (Wang, 2021). Ontologies enable semantic representation for this information, trying to bridge the existing gaps in data management and automation. When compared to relational approaches, ontologies provide machine-readable and standardized models that allow accessibility and interoperability of knowledge related to an entity, which can be used to semantically enrich BIM data (Cursi et al., 2022). Jiang et al. (2023) state the integration of BIM with new technologies such as Linked Data as a future direction of BIM semantic enchantment to promote collaboration and improve efficiency of engineering projects.

Ontologies can be used in safety management, improving personal and structural safety during the construction stage (Chen & Bria, 2022, Li et al., 2022, Fang et al., 2020, Lee & Yu, 2023), but can also be used during the design and O&M stage (Jiang et al., 2023). By encoding product features information with an ontology, reasoning and validation rules can be used to ensure that manufacturing rules are followed during the design phase enabling real-time feedback to designers, regarding the product manufacturability (Cao et al., 2022). During the O&M stage, ontologies can be used together with BIM to improve

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[2] https://www.w3.org/.

[3] http://neon-project.org/.

several processes, such as energy performance assessment and management (Wu et al., 2023), monitor building environment variables (e.g., temperature, light, CO2) (Zhong et al., 2018), and provide a base for sharing construction defects information (Lee et al., 2016). Ontologies can also be used in project management during the infrastructure's lifecycle (Wu et al., 2021).

Wang (2021) presents a domain ontology to support O&M of underground utility called Utility Operation and Maintenance Ontology (UOMO) to integrate and encode standards, regulations, and expert knowledge, utility and environment data, and, inspection and maintenance reports. Based on this ontology, the author proposes a framework that supports O&M activities and decision-making, taking advantage of ontology querying, inference and rules. The integration with other systems (GIS) is presented as future work.

Ding et al. (2016) present an ontology-based methodology for risk knowledge management in construction, and integrate this knowledge within a BIM-environment for risk analysis. However, the authors present the lack of compatibility with IFC and other standards as one of their limitations. Furthermore, Zhou et al. (2023) introduce a dam safety monitoring systems domain ontology (OntoDSMS) to address the analysis of heterogeneous data and sources needed for evaluating dam safety. The authors reuse existing ontologies for sensor data and IFC and find that SPARQL is more efficient and allows for improved logical reasoning than traditional methods.

Hagedorn et al. (2023) present a solution for enhancing BIM-enabled infrastructure asset management for road owners using Information Containers for Linked Document Delivery (ICDDs) to meet the diverse requirements of stakeholders during the operational phase. The authors present the development of a web-based platform for asset management, utilizing the ICDDs, Semantic Web technologies (like RDF and SPARQL), and domain-related ontologies as schemas. Two use cases demonstrate the practical application, showing how ICDDs can be used in tasks such as visual inspection of bridges and decision-making for road pavement maintenance activities. Future research directions include aligning existing ontologies, automating geometric representation updates, and integrating sensor data for infrastructure digital twins.

In summary, three main limitations were found in this related work analysis. Firstly, most authors develop and use their domain- and task-specific ontologies. However, most works fail to use standard or higher-level ontologies, which undermines their interoperability efforts and hinder the use of the respective knowledge by other systems or potential users. Secondly, BIM data is usually imported to the ontologies, leading to ontology-based analyses most of the times, and creating an uni-directional flow of information. While not necessarily a problem *per se*, a bi-directional flow, where ontology knowledge can be integrated into the BIM model, can allow for BIM-based systems to display ontological information managed by external systems, such AMS (Ding et al., 2016). Lastly, the ontology-based analysis most of the times is presented using the development system (e.g., Protégé) or through SPARQL analyses. While effective, these solutions do not take into consideration user-friendliness, and better ontology visualizations should be provided (Lee et al., 2016, Lei et al., 2021).

4. Case study: the CoDEC project

This section introduces the research context for this manuscript, namely, the CoDEC Data Dictionary that details the main concepts and vocabulary for highway infrastructures, and three real-case pilot projects across European countries, focused on different types of assets.

4.1. Data dictionary

Although European NRA have started to use BIM during the design and building phase of projects and have well-defined processes and AMS, little has been done to use BIM for long-term asset maintenance management (Biswas et al., 2021b). An AMS holds information about a specific asset and allows users to analyze the data, but each NRA has their own AMS to suit their needs and often each asset type has its own AMS and there is no interaction of data across different AMS. On the other hand, BIM is a system to digitally model an asset, which makes it easier to create and share information during asset design, construction, and operating phases.

For the purpose of standardizing the data connectivity, the CoDEC Data Dictionary was developed to provide a shared vocabulary to enable the integration and sharing of data between different systems with a common data definition and an hierarchical system (Biswas et al., 2021a).

To obtain information for the data dictionary, engineering structures and highways' stakeholders were inquired, which include NRA from 14 different European countries (Austria, Belgium, Denmark, Finland, France, Germany, Lithuania, the Netherlands, Norway, Portugal, Slovenia, Spain, Sweden, and the United Kingdom), and implementations partners, such as BIM and AMS software companies. Also, several works such as AM4INFRA (Kokot, 2019), the Highways England UK-ADMM data dictionary (Highways England, 2020), the Data Standard for Road Management and Investment in Australia and New Zealand (Austroads, 2019) and ifcRoad (buildingSMART, 2020) were used to support the Data Dictionary development.

CoDEC had also a specific goal to handle sensors and their data, as these are increasingly used to support infrastructure asset management. Sensors were considered as separate objects, and not as an asset, and various property sets were created for both mobile and fixed-location sensors. This explains the variations in how fixed and mobile sensors are located and referenced covering different criteria (e.g. skid resistance, longitudinal evenness, rutting, cracking, raveling, potholes), different technical parameters for same criterion (e.g. IRI, WLP, NBO, EC for longitudinal evenness) and different combinations in indicators (e.g. safety indicator with different components).

The Data Dictionary was formalized in Excel and contains asset data, its metadata and attributes, the logical and hierarchical connections, and the list of data types for creating an Object Type Library (OTL). The last version of this resource is available on the project's website.[4]

4.2. CoDEC pilot projects

The Data Dictionary followed the requirements of the three pilot projects, with a focus on three key highway civil assets (tunnels, bridges and pavements), as well as preliminary concepts and relationships for supporting systems and assets (e.g., lighting, fire-fighting, and drainage).

Focused on tunnel structures, the first pilot project (*PP - Tunnels*) case study aims to demonstrate sensor data integration into the BIM exploitation environment. It was necessary to encode information about the sensors and their data to provide the BIM environment with the necessary operational data for decision support. This information is used to colorize the sensors in the 3D model, using a color pallet related to the air quality in the tunnel.

The bridges pilot project, *PP - Bridges*, aims to provide data about the risk and condition of bridge structural elements. The information from each assessment campaign about the structure's condition is loaded into the ontology and then used to apply a color encoding to the model elements according to a given scale, with respect to the risk level.

The last case study, *PP - Pavements*, focuses on road networks and highways. While the previous two pilot projects have the objective of delivering operational data into a BIM environment, this pilot project aims to enrich their GIS with information from BIM (requiring accurate spatial mapping between the two). GIS-based AMS are used for decision support in these types of structures.

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[4] https://www.codec-project.eu/Resources/projectreports.

5. Engineering structures ontology

This section presents the main contribution of this paper, namely the development of Engineering Structures ontology. The NeOn methodology (Suárez-Figueroa et al., 2015) was used to define the required activities for this development process due to its focus on knowledge resources inputs, in addition to being the most recent and complete methodology (see Section 2.1). Ontology requirements are presented in the Ontology Requirements Specification Document. Afterward, the development and conceptualization process is reported, discussing the main challenges and decisions.

5.1. Ontology requirements specification document

5.1.1. Domain and scope

The Engineering Structures ontology was developed to describe and store knowledge related to the European highways industry. Specifically, the ontology should represent concepts related to bridges, tunnels, and pavements, their structural elements, and the dynamic data associated with these assets.

5.1.2. Goals

The ontology should represent structures, such as bridges and tunnels, and their structural elements, such as pylons and cables, providing asset information in a formal, comprehensible, and explicit way. The concepts and relationships described in the ontology are based on the CoDEC's Data Dictionary. The ontology should also store information about sensor and inspection data (Risk and Condition Data) and ensure the connection between the BIM model and these entities. For interoperability purposes, the ontology should extend Interlink project's EurOTL.[5]

5.1.3. Users, use cases and applications

The Engineering Structures ontology should provide information about its domain to the users, i.e., structural owners, managers, and operators. The ontology should allow users to analyze structures and structural elements (information related to location, activities, size and other physical attributes) and how they are related, i.e., which elements are part of a particular structure. Furthermore, the ontology can provide sensor and sensor data information to the user, such as how many observations a sensor made and where they are located. The same should be valid for inspections and risk and condition analysis. Lastly, users can obtain information concerning pavement sections, layers and their geometric representation.

The ontology will be used as part of the CoDEC Technical Environment to provide the necessary information and knowledge for the execution of the three pilot projects and allow information exchange between AMS and BIM environments.

5.1.4. Knowledge sources and reusable ontologies (inputs)

The following Knowledge Resources were identified:

a) CoDEC Data Dictionary (see Section 4.1) is a Non-Ontological Resource that provides a shared vocabulary for knowledge acquisition and elicitation from the different stakeholders. This resource provides the main body of knowledge that will be formalized and encoded by the ontology;
b) EUROTL Framework Ontologies are ontological resources extended by the ontology. By extending these concepts, Engineering Structures ontology can be used by any EurOTL interface or application. The European Road OTL (EurOTL) was developed during the Interlink project and contains ontologies and Linking Rule Sets related to European roads. The core ontology is available at "http://www.roadotl.eu/def/". The linksets in Table 1 were also used, providing machine-readable mapping descriptions between the framework's domain ontologies and the EUROTL core ontology.
c) Sensor Network Ontology is a W3C recommendation for describing sensors, sensor networks and their observations. This ontology provides a starting for encoding the necessary dynamic data ad is available at "http://www.w3.org/ns/ssn/".

Table 1
EurOTL domain ontologies.

Domain Ontologies	Linkset Location
AM4INFRA	http://www.roadotl.eu/AM4Infra--eurotl/def/
IFC4x1_Final	http://www.roadotl.eu/IFC4x1_Final--eurotl/def/
GeoSPARQL	http://www.roadotl.eu/geosparql--eurotl/def/
INSPIRE transport networks	http://www.roadotl.eu/inspire--eurotl/def/
ISO19148 transport networks	http://www.roadotl.eu/iso19148--eurotl/def/

5.1.5. Competency questions

The definition of an ontology's scope is a crucial step in ontology development. The use of competency questions (CQ) to determine an ontology' scope is a standard practice in ontology development (Noy et al., 2001). CQs have been used in several works related to construction to evaluate an ontology's capability. (e.g., Cao et al. (2022), Zheng et al. (2021), Kukkonen et al. (2022)). This process helps to ensure that the ontology is designed to capture the relevant knowledge and information within its intended domain.

The CQ were formalized in the context of the three pilot projects (see Section 4.2) based on inputs from the different stakeholders. Table 2 presents a sub-set of the above-mentioned CQ for which the ontology is required to provide answers. The CQs are divided into General Questions and PP-specific questions related to the pilot project requirements and corresponding use cases. Specifically, *PP - Tunnels* focuses on sensor data, *PP - Bridges* is related to risk and condition data of bridge structural elements, and *PP - Pavements* focuses on road network pavements.

5.2. Ontology development

The Engineering Structures ontology development followed an incremental lifecycle. The first conceptualization was based on the Data Dictionary, while the remaining lifecycles focused on each pilot project requirements. The Engineering Structures ontology was developed in OWL using Stanford's Protégé.[6]

5.2.1. Initial development

The Engineering Structures ontology initial development was done by mapping or aligning Data Dictionary concepts (classes or properties) to EurOTL concepts. If a given concept is already available in EurOTL, there is no need to create and extend the same concept in CoDEC. However, if this is not the case, the new CoDEC concept is created as a sub-class of an existing EurOTL entity, ensuring interoperability between the two ontologies. For example, the "Bridge" concept already exists in the EurOTL framework, specifically in the AM4Infra vocabulary, so it is not necessary to extend concepts. However, "Structural Elements", or equivalent, are not found in any of the vocabularies or ontologies from the EurOTL framework. In this case, the "PhysicalObject" class from EurOTL was extended in the Engineering Structures ontology with a new class used to represent structural elements. Fig. 2 shows an example of the mapping between the Data Dictionary and the Engineering Structures ontology.

5.2.2. Semantic sensor network

The main requirement from *PP - Tunnels* was the integration of sensor metadata and data in the ontology for operational safety man-

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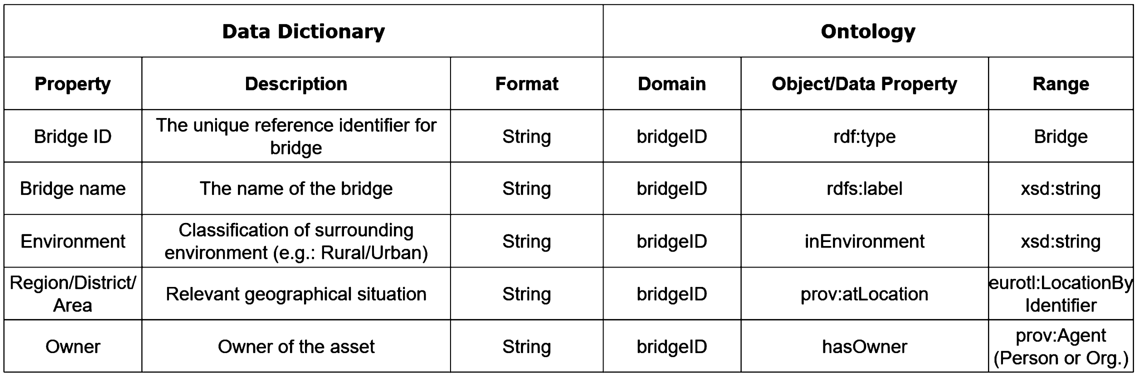
[5] https://www.roadotl.eu/.

[6] https://protege.stanford.edu/.

Table 2
Competency questions.

General Questions	
CQ1	When did a certain structure ended its construction phase?
CQ2	Where is a certain structure located?
CQ3	What are the measurements of a certain structure?
CQ4	Who is the owner of a certain structure?
CQ5	Which and how many elements are part of a structure?
***PP - Tunnels* Specific Questions**	
CQ6	Which sensors are hosted by a structure and how many observations did they make?
CQ7	What is the location of the sensor data related to an observation?
***PP - Bridges* Specific Questions**	
CQ8	What are the results of a certain inspection by element?
CQ9	What is the risk of a given structure according to an inspection?
CQ10	What is the last risk analysis result of a certain element?
***PP - Pavements* Specific Questions**	
CQ11	What is the total thickness of a given section and how many layers does it contain?
CQ12	How is a given section subdivided?
CQ13	What is the geometric representation of a given pavement subsection?



Data Dictionary			Ontology		
Property	**Description**	**Format**	**Domain**	**Object/Data Property**	**Range**
Bridge ID	The unique reference identifier for bridge	String	bridgeID	rdf:type	Bridge
Bridge name	The name of the bridge	String	bridgeID	rdfs:label	xsd:string
Environment	Classification of surrounding environment (e.g.: Rural/Urban)	String	bridgeID	inEnvironment	xsd:string
Region/District/ Area	Relevant geographical situation	String	bridgeID	prov:atLocation	eurotl:LocationBy Identifier
Owner	Owner of the asset	String	bridgeID	hasOwner	prov:Agent (Person or Org.)

Fig. 2. Data dictionary to engineering structures ontology. Mapping example for “bridge” entity. Adapted from CoDEC Project Report (2021).

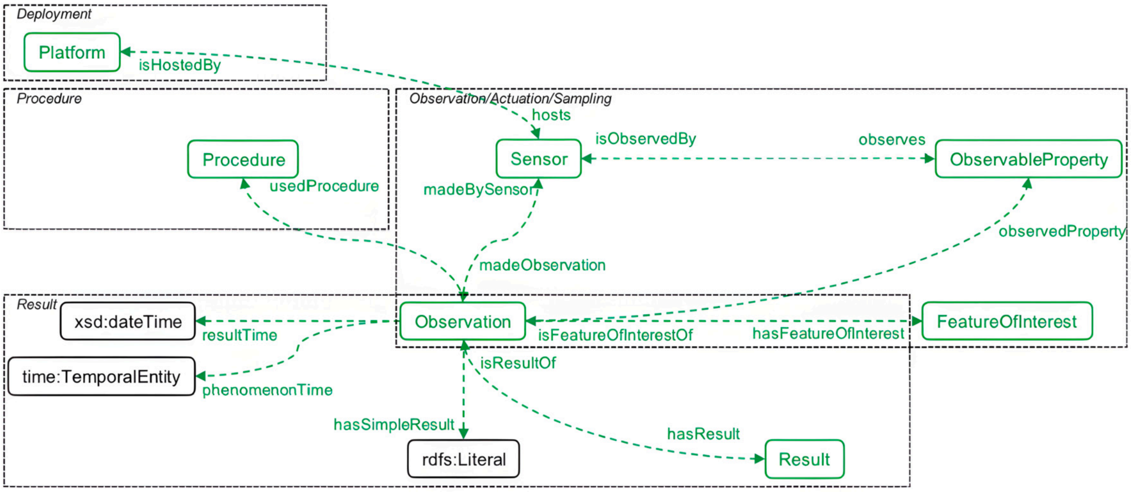


Fig. 3. Semantic sensor network ontology. Retrieved from Open geospatial consortium (2017).

agement and monitoring, specifically air quality analysis in tunnels. The EurOTL framework does not provide vocabulary or domain ontologies concerning dynamic data. The Semantic Sensor Network (SSN) Ontology,[7] a W3C standard, was used to encode this information (Fig. 3).

In the Engineering Structures ontology, structures are seen as platforms that host a set of Sensors. Each time-series concerning an “ObservableProperty” is encoded as an Observation. However, the sensor data itself is not stored within the ontology. Instead, each time-series is stored in a JSON file. The location of this file is obtained from any Observation using the data property “hasDocument”, from eurOTL.

5.2.3. *Risk and condition data*

As stated before, *PP - Bridges* aims at analyzing Risk and Condition data. Contrary to the dynamic data automatically collected by sensors, Risk and Condition data is generated during assessment campaigns, rep-

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[7] https://www.w3.org/TR/vocab-ssn/.

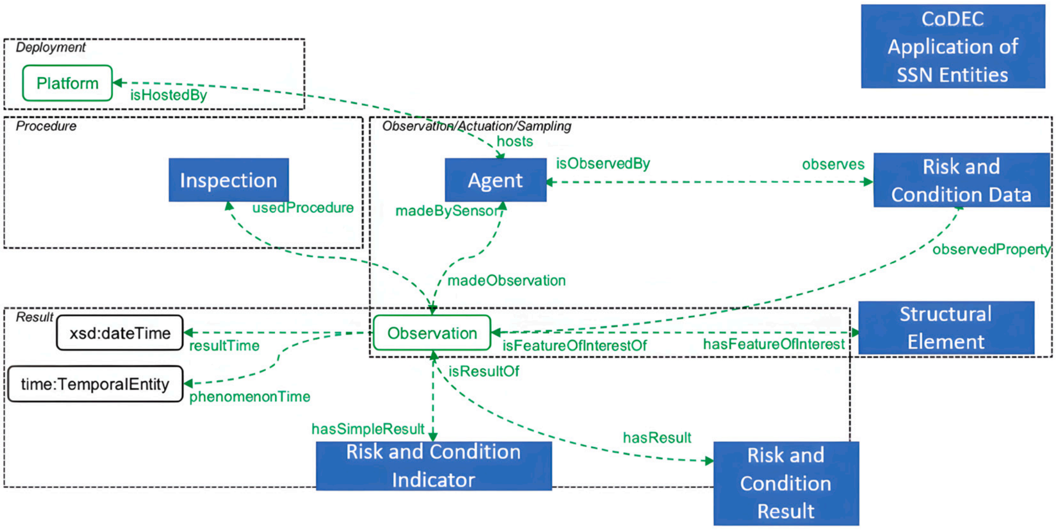

Fig. 4. CoDEC risk and condition data over SSN.

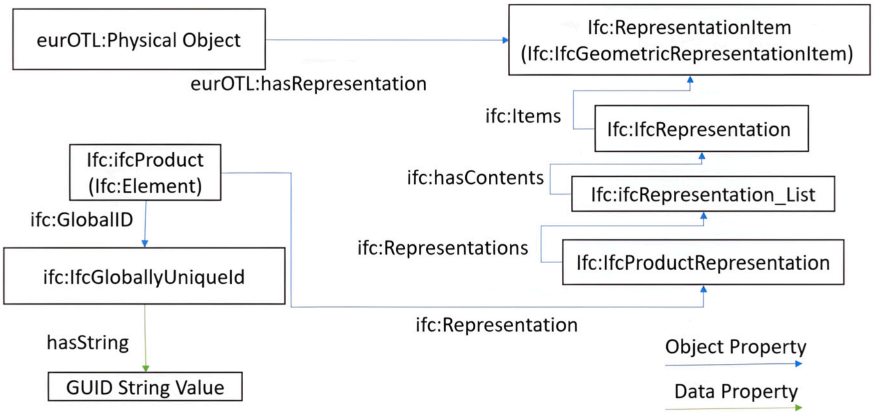

Fig. 5. Connection between PhysicalObject to a ifcElement GUID.

resented as Inspections in CoDEC. The SSN concepts were then extended to encode the necessary information about Observations obtained by a particular Procedure (in this case, the Inspection itself, as seen in Fig. 4). The Observation is done by an Agent, taking the Sensor role, and concerns a given Structural Element ("hasFeatureOfInterest").

Two properties can be used to obtain the results from an Observation: (1) "hasSimpleResult", returning a Risk and Condition Indicator with a numeric scale from 1 to 5; and (2) "hasResult", which points to a Risk and Condition Result, containing a descriptive state, the inspection due date and a URL for photos.

5.2.4. *ifcOWL*

A link needs to be established to be able to transfer any exchange any information between Engineering Structures ontology and the BIM model. The ifcOWL ontology, which is part of the eurOTL framework, provides a way to represent IFC models (a BIM data format) in OWL. Through a series of complex relationships (see Fig. 5), the ontology can relate any eurOTL Physical Object (from which structures and structural elements are extended in the Engineering Structures ontology) to an ifcElement global unique identifier. In *PP - Bridges*, this link is needed to relate Risk and Condition indicators to the element's BIM representation and colorize each Structural Element.

5.2.5. *Pavement sections and layers extensions*

The EurOTL's linear referencing method was used in *PP - Pavements* to identify and locate pavement sections in a given road network. Pavement sections, subsections and layers were added to the Engineering Structures ontology to ensure the needed representation detail, together with data properties such as layer thickness or vertical position.

5.3. *Ontology population*

Ontology population is the process of adding instances in the ontology (called A-Box statements). To validate and evaluate the Engineering Structures ontology, data related to each pilot project was added using a Protege plugin called Cellfie.[8] Cellfie was used to define a set of import rules and mappings (based on Manchester OWL Syntax[9]) from Excel spreadsheets into OWL axioms (see Fig. 6). This solution was used for *PP - Tunnels* and *PP - Bridges*, while *PP - Pavements* used a different method, based on Python scripts, to directly import and export data from the ontology.

6. Ontology evaluation

This section presents the ontology evaluation process. Following the NeON methodology, the ontology is evaluated regarding competency question answering and common pitfall detection. The evaluation should be done independently from the application scenario or technical environment that will take advantage of this ontology.

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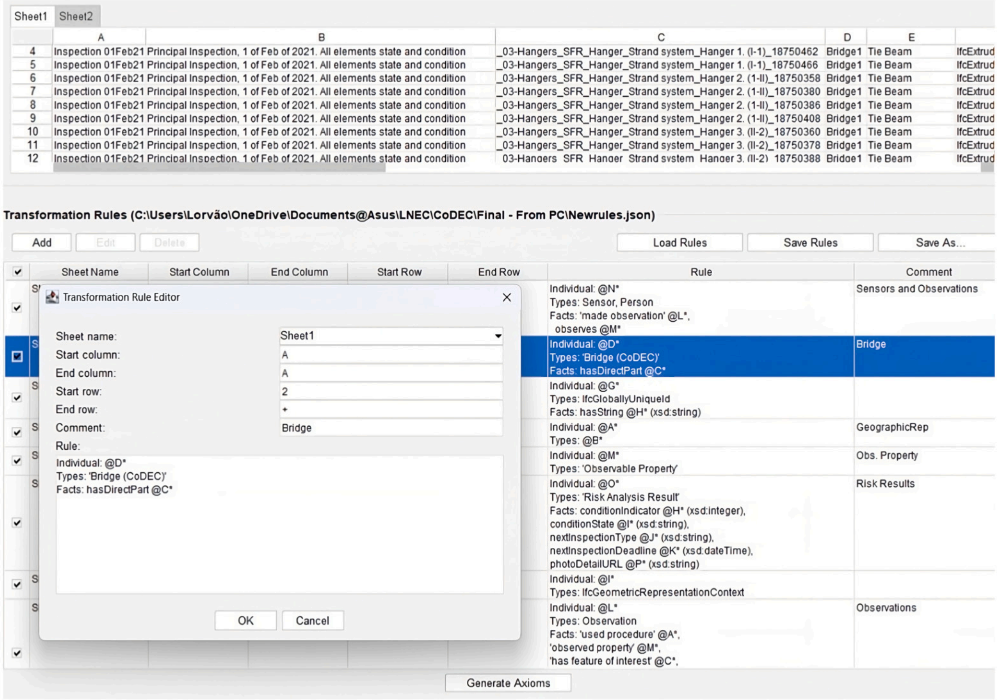
[8] https://github.com/protegeproject/cellfie-plugin.

[9] https://www.w3.org/TR/owl2-manchester-syntax/.



	A	B	C	D	E	
4	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 1. (I-1)_18750462	Bridge1	Tie Beam	IfcExtrud
5	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 1. (I-1)_18750466	Bridge1	Tie Beam	IfcExtrud
6	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 2. (1-II)_18750358	Bridge1	Tie Beam	IfcExtrud
7	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 2. (1-II)_18750380	Bridge1	Tie Beam	IfcExtrud
8	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 2. (1-II)_18750386	Bridge1	Tie Beam	IfcExtrud
9	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 2. (1-II)_18750408	Bridge1	Tie Beam	IfcExtrud
10	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 3. (II-2)_18750360	Bridge1	Tie Beam	IfcExtrud
11	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 3. (II-2)_18750378	Bridge1	Tie Beam	IfcExtrud
12	Inspection 01Feb21	Principal Inspection, 1 of Feb of 2021. All elements state and condition	_03-Hangers_SFR_Hanger_Strand system_Hanger 3. (II-2)_18750388	Bridge1	Tie Beam	IfcExtrud

Transformation Rules (C:\Users\Lorvão\OneDrive\Documents@Asus\LNEC\CoDEC\Final - From PC\Newrules.json)

☑	Sheet Name	Start Column	End Column	Start Row	End Row	Rule	Comment
☑	S					Individual: @N* Types: Sensor, Person Facts: 'made observation' @L*, observes @M*	Sensors and Observations
☑	S					Individual: @D* Types: 'Bridge (CoDEC)' Facts: hasDirectPart @C*	Bridge
☑	S					Individual: @G* Types: IfcGloballyUniqueId Facts: hasString @H* (xsd:string)	
☑	S					Individual: @A* Types: @B*	GeographicRep
☑	S					Individual: @M* Types: 'Observable Property'	Obs. Property
☑	S					Individual: @O* Types: 'Risk Analysis Result' Facts: conditionIndicator @H* (xsd:integer), conditionState @I* (xsd:string), nextInspectionType @J* (xsd:string), nextInspectionDeadline @K* (xsd:dateTime), photoDetailURL @P* (xsd:string)	Risk Results
☑	S					Individual: @I* Types: IfcGeometricRepresentationContext	
☑	S					Individual: @L* Types: Observation Facts: 'used procedure' @A*, 'observed property' @M*, 'has feature of interest' @C*,	Observations

Transformation Rule Editor

Sheet name: Sheet1
Start column: A
End column: A
Start row: 2
End row: +
Comment: Bridge
Rule:
Individual: @D*
Types: 'Bridge (CoDEC)'
Facts: hasDirectPart @C*

Fig. 6. Cellfie import rules and mappings.

6.1. Competency questions

In this section, the Engineering Structures ontology will be used to answer the Competency Questions defined in the Ontology Requirements Specifications Document.

The set of attributes from the Data Dictionary, now formalized by the Engineering Structures ontology, allows for a more detailed definition of structures and structural elements. Information related to time, location, physical properties, such as measurements and materials, and relationship with agents, such as the owner or commissioner, can now be asserted in the ontology. Competency questions were defined to illustrate how the ontology can currently answer these questions (CQ1 to CQ4). The SPARQL query for CQ1 is shown in Listing 1, which returns the end date (xsd:date) of a given structure's construction phase.

Listing 1. CQ1 - when did a certain structure ended its construction phase?

```
SELECT ?date
WHERE {
    <Structure> codec:hasConstructionDate ?date
}
```

Another competency question concerns structural elements and their relation to a structure (CQ5). The "cmo-simple-cdt:hasDirectPart" object property from eurOTL was used to encode this relationship. Although the relationship itself is not transitive, SPARQL can be used to make inferences as if this were the case. This inference allows information to be obtained about elements that are directly part of a structure or all elements related to a structure, as shown in Listing 2.

The query in Listing 3 can be used to obtain the risk associated with a structure according to a given inspection. All elements related to the structure are obtained, as well as the observations of these elements in a given inspection. The Structure risk (on a scale from 1 to 5) is obtained by calculating the minimum Risk and Condition Indicator from all observations.

Listing 2. CQ5 - which and how many elements are part of a structure?

```
SELECT (?type as ?ELEMENTTYPE) (COUNT(?element) AS ?
    ELEMENTCOUNT)
WHERE {
    <Structure> cmo-simple-cdt:hasDirectPart+ ?element.
    ?element rdf:type ?type.
    ?type rdfs:subClassOf codec:Structural_Element.
} GROUP BY ?type
```

Listing 3. CQ9. What is the risk of a given structure according to an inspection?

```
SELECT (MIN(?result) as ?minResult)
WHERE {
    <Structure> cmo-simple-cdt:hasDirectPart+ ?element.
    ?o sosa:usedProcedure <Inspection>;
        sosa:hasFeatureOfInterest ?element;
        sosa:hasSimpleResult ?result.
}
```

Listing 4. CQ10. What is the last risk analysis result of a certain element?

```
SELECT ?predicate ?object
WHERE{
        ?inspectionID rdf:type sosa:Procedure;
                rdf:type eurotl:InspectionActivity.
    {SELECT (MAX(?time) as ?mostRecent) WHERE{ ?
        inspectionID prov:atTime ?time}}
    ?inspectionID prov:atTime ?mostRecent.
    ?o sosa:usedProcedure ?inspectionID;
        sosa:hasFeatureOfInterest <ELEMENT>;
        sosa:hasResult ?result.
    ?result ?predicate ?object.
```

However, the ontology can also be used without specifying an inspection. The query for CQ10, presented in Listing 4, collects all inspection activities that are also procedures and selects the most recent. Then, given a structural element, the query returns all the information related to the Risk and Condition Results, including the condition indi-

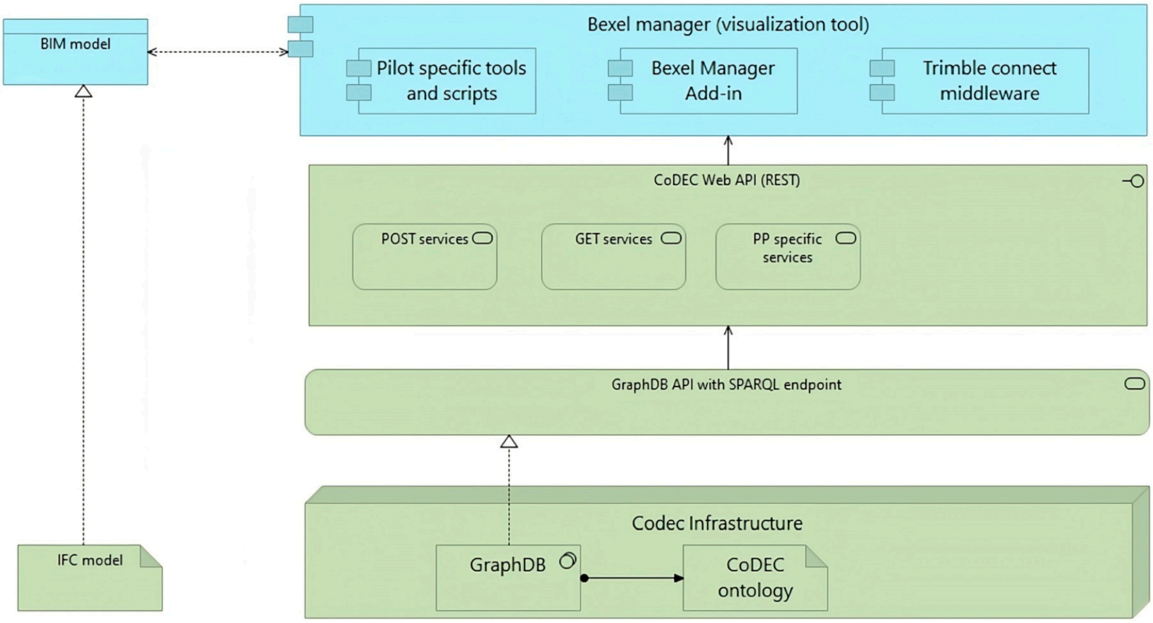


Fig. 7. CoDEC technical architecture. Retrieved from CoDEC Project Report (2021).

cator and state, the next inspection deadline and type, and a URL of the photo detail.

Listing 5. CQ8 - what are the results of a certain inspection by element?

```
SELECT ?element ?connectedTo ?result ?GUID where {
    ?o sosa:usedProcedure <Inspection>;
       sosa:hasFeatureOfInterest ?element;
       sosa:hasSimpleResult ?result.
    ?connectedTo cmo–simple–cdt:hasDirectPart ?element.
    ?element eurotl:hasRepresentation ?representation.
    ?shape ifc:items_IfcRepresentation ?representation.
    ?repList <https://w3id.org/list#hasContents> ?shape.
    ?prodDef ifc:
        representations_IfcProductRepresentation ?
        repList.
    ?ifcElement ifc:representation_IfcProduct ?prodDef;
                ifc:globalId_IfcRoot ?GUIDObj.
    ?GUIDObj <https://w3id.org/express#hasString> ?GUID.
}
```

Lastly, Listing 5 presents the SPARQL query that answers CQ8 and showcases the intricate connection between elements and their BIM representation. This complex set of relationships utilizes ifcOWL to connect elements' risk and condition indicators collected during a particular inspection to their IFC's global unique identifier.

6.2. OOPS!

The ontology was validated using OOPS! (Poveda-Villalón et al., 2014). OOPS! (OntOlogy Pitfall Scanner!) detects common mistakes and pitfalls made during ontology development. When analyzing the Engineering Structures ontology, the tool did not detect any critical pitfalls, which "could affect the ontology consistency, reasoning, applicability, among others" (Poveda-Villalón et al., 2014, p.15). However, 55 important pitfalls are reported, although only one is directly related to the ontology, with the remainder being related to the imported ontologies (i.e., EurOTL, SSN). The tool also detected nine minor pitfalls, with three being related to the Engineering Structures ontology.

However, some of the detected pitfalls do not represent a problem or error. For example, the important pitfall identified related to the Engineering Structures ontology relates to equivalent classes not being explicitly declared. The tool warns that "Span" and "Bridge" classes might be equivalent (Span is a synonym for bridge outside the civil engineering context), which is not the case. The remainder pitfalls are minor and related to different concepts in the same class and the different naming conventions in the ontology. For example, the "Drainage and wastewater collection" class was identified as the terminology for a type of "Structural Element" in the data dictionary, which the tool identifies as a possible pitfall.

7. Ontology demonstration

The CoDEC pilot projects were used to demonstrate the use and usefulness of Engineering Structures ontology. *PP - Tunnels* takes advantage of the integration of the SNN ontology with the eurOTL concepts and Engineering Structures ontology to present air quality analysis in a BIM environment. The Engineering Structures ontology's extension of the SNN ontology, which allows risk and condition analysis of structural elements, is demonstrated in *PP - Bridges*, together with the connection of these elements with their BIM representation (IFC model). Lastly, *PP - Pavements* utilizes Linear Referencing concepts (provided by eurOTL) and Engineering Structures ontology's section and layers pavement extensions to correctly map GIS and BIM elements. Due to the focus on the integration and extension of SNN ontology for Risk and Condition data and the use of ifcOWL to connect structural and operational data with BIM elements, this section is focused on *PP - Bridges*, showcasing the use of the Engineering Structures ontology as an enabler for data exchange between BIM and AMS systems.

7.1. Technical architecture

Fig. 7 presents the Technical Architecture used for the pilot projects. The figure uses ArchiMate 3.0 notation[10] to define the components and layers.

The CoDEC infrastructure (bottom layer) stores ontology instances according to pilot project requirements, allowing knowledge to be accessible and manipulated. The Engineering Structures ontology (presented as CoDEC ontology in Fig. 7) and its details are present in Sec-

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[10] https://pubs.opengroup.org/architecture/archimate3-doc/.

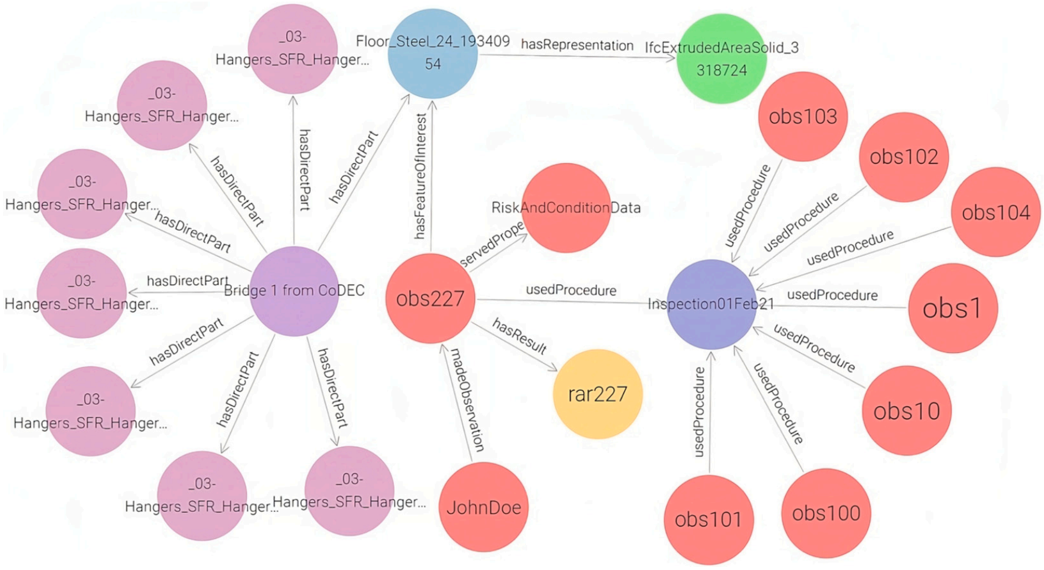


Fig. 8. Populated ontology in GraphDB.

tion 5. To access this environment, the CoDEC Web API was developed. The Application Programming Interface (API) services are critical for this solution because they create an abstraction layer between the ontology (data) and its users or applications (logical levels). This abstraction layer allows any solution to access the linked data environment without any technical dependencies and without needing to know and follow the ontology's structure or its evolution (i.e., there is no need to develop standalone queries for each application or scenario).

Finally, applications or tools for data management and visualizations are created, such as Bexel Manager Add-In. These tools allow access to the API to retrieve and present the information, hiding environment and ontology complexity from the end user.

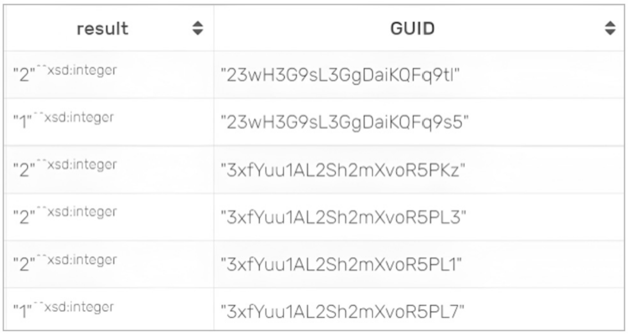
7.2. *Accessing the ontology*

CoDEC uses GraphDB[11] as a linked data environment to store the populated ontology (see Fig. 8). GraphDB is a graph database compliant with W3C standards (i.e., RDF, OWL, SPARQL). Once stored, the ontology can be queried or updated using SPARQL endpoints. Inside the CoDEC environment (see Section 7.1), an API was developed to create an abstraction layer between application and (ontological) data layers. A set of REST services are exposed by CoDEC's API, which allows users and applications to easily communicate with complex linked data environments stored in GraphDB.

One of the services provided by CoDEC's API, "GetInspectionResult", uses a simplification of the query presented for CQ8 (see Listing 5) to return, given an inspection, pairs of risk and condition indicators and element's IFC global unique identifier. Using the inspection "codec:Inspection01Feb21" as the request parameter, the API returns a response as demonstrated in Fig. 9, encoded in JSON.

7.3. *PP - Bridges demonstration*

For *PP - Bridges*, an existing bridge IFC model was imported using Bexel Manager,[12] and an add-in was created from the application side. This add-in communicates with the CoDEC API to retrieve existing inspections related to the bridge. Afterwards, the user can select an inspection and risk indicators related to each element are retrieved ("GetInspectionResult" service) from the ontology and used to colorize the bridge (see Fig. 10). Furthermore, the completed risk and condition assessment of a single or a set of elements can also be obtained, with additional detail such as photo URLs and information related to the following inspection schedule for each element.



result	GUID
"2"^^xsd:integer	"23wH3G9sL3GgDaiKQFq9tl"
"1"^^xsd:integer	"23wH3G9sL3GgDaiKQFq9s5"
"2"^^xsd:integer	"3xfYuu1AL2Sh2mXvoR5PKz"
"2"^^xsd:integer	"3xfYuu1AL2Sh2mXvoR5PL3"
"2"^^xsd:integer	"3xfYuu1AL2Sh2mXvoR5PL1"
"1"^^xsd:integer	"3xfYuu1AL2Sh2mXvoR5PL7"

Fig. 9. Response example.

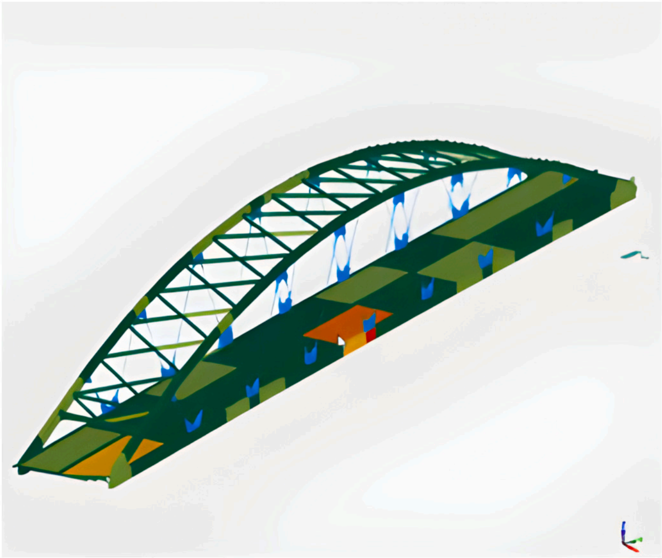


Fig. 10. Bridge elements colored according to risk indicator from an inspection. Retrieved from CoDEC Project Report (2021).

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[11] https://graphdb.ontotext.com/.

[12] https://bexelmanager.com/.

8. Discussion

This article presents the design and development of the Engineering Structures ontology. The Engineering Structures ontology was developed to address: a) the interoperability challenge within NRA systems, e.g., the integration of operational and sensor data with BIM models; and b) the sharing of relevant information between NRA, based on a shared and formal conceptualization.

The shared conceptualization provided by the CoDEC Data Dictionary was validated by experts from several European NRA in the CEDR project's scope. The proposed ontology, based on the Data Dictionary, allows NRA to encode their data in a homogeneous way, enabling semantic and data interoperability between them. The use of the ontology for representing operational asset information was validated by experts and is now formally evaluated using competency questions and validated with OOPS! (see Section 6). The ontological approach offers a flexible, scalable, and interoperable integration framework for integrating AMS data into the BIM environment, ensuring semantic clarity and facilitating efficient data management and analysis.

8.1. Contributions to the theory

This research makes several contributions to the theory regarding the integration of BIM with AMS, particularly focusing on European highways. Physical infrastructure elements like buildings, bridges, and roads can be modeled and managed with BIM, enabling stakeholders to collaborate, share, and exchange information needed for decision support throughout their entire lifecycle, namely during the design, planning, and construction phases. However, the application of BIM in transport infrastructures is not yet widespread (Costin et al., 2018), particularly in the O&M phase (Talebi, 2014, Wijeratne et al., 2024). NRAs use AMS to manage, maintain, and ensure structural safety during their O&M phase.

The seamless integration of BIM with AMS presents an opportunity to optimize decision-making processes in the O&M phase of engineering structures. As asset monitoring solutions continue to evolve, managing critical information, interoperability between these systems becomes increasingly vital for timely decision-making in an integrated environment. By linking 3D model data with asset management information, stakeholders can access crucial insights more readily, leading to reduced errors, improved cost-effectiveness, and heightened safety and compliance measures (Wijeratne et al., 2024). However, achieving seamless interoperability is a complex challenge due to the different technologies, data formats, and standards utilized across AMS and BIM platforms (Kivits et al., 2013, Gao & Pishdad-Bozorgi, 2019, Garramone et al., 2020). The adoption of semantically enriched approaches offers a way of improving the usability of BIM environments, contributing to the management of complex engineering structures. By presenting information in a more intuitive way, these solutions promote better decision-making, which can ultimately lead to the optimization of the performance and longevity of infrastructure assets (Jiang et al., 2023).

This work addresses the gaps identified in the literature review regarding the use of semantic techniques with BIM (see Section 3). Firstly, this study addresses the identified limitations in existing literature regarding the development and use of domain-specific ontologies. While previous works often develop and utilize their own task-specific ontologies (e.g., Wang (2021), Ding et al. (2016), Zhou et al. (2023)), authors frequently neglect to incorporate standard or higher-level ontologies. By taking advantage of standard ontological frameworks, such as the EurOTL framework and the Sensor Network Ontology, the Engineering Structures ontology proposed in this study contributes to ameliorate interoperability challenges. The proposed ontology serves as a formal representation of the shared conceptualization provided by the CoDEC Data Dictionary, ensuring that NRAs can encode their data in a homogeneous way, addressing the identified need for standardized data formats and facilitating semantic and data interoperability between European NRA and their systems.

Secondly, this research contributes to the literature by acknowledging and addressing the uni-directional flow of information often observed in ontology-based analyses. In current literature, BIM data is typically imported into ontologies (e.g., Zhao et al. (2019), Al-Kasasbeh et al. (2021), Meschini, Pellegrini, et al. (2022), Zhou et al. (2023)), creating an uni-directional flow of information. Although existing solutions, such as the use of Protege or SPARQL analyses, are effective, they often lack an intuitive and familiar interface (i.e. similar to the interfaces of BIM environments for managing the assets of road structures). This study contributes to the literature by highlighting the importance of user-friendliness in ontology-based analyses. By integrating operational asset information managed by AMS with BIM models, as shown in Section 7, the ontology-based approach enables BIM-based systems to display relevant ontological knowledge, thereby enhancing interoperability and decision-making processes during the O&M phase (Lee et al., 2016, Lei et al., 2021).

8.2. Contributions to the practice

Being machine-readable, the ontology can be used as a base for data exchange between BIM and AMS, or other systems. As demonstrated in Section 7, when used within the CoDEC framework, the ontology enables BIM-based analysis of operational data, such as risk and condition data, from AMS. While the Engineering Structures ontology can be used in isolation to provide a similar analysis, users (i.e., structural owners, managers, and operators) can now access data in a familiar decision environment by integrating operation information in a BIM environment. Furthermore, ontology-based analysis can be enabled in the decision-support environment, allowing users to take advantage of the knowledge representation and inference provided by this encoded shared conceptualization and other semantic web technologies, such as SPARQL, Shapes Constraint Language (SHACL)[13] or SWRL: A Semantic Web Rule Language.[14] These technologies can be used to validate information stored in the ontology (e.g., ensure that each structural element is represented by a BIM model entity), or automatically infer new knowledge, allowing, for example, risk evaluation to be performed based on previous inspections or sensor data analysis.

Semantic and data interoperability is key for enabling data and information exchange between NRAs and their systems, namely in the European highway industry. CEDR has helped European NRAs to obtain and manage asset information, ensuring timely and informed decision-making and reducing risks. In this industry, asset data can change ownership or be exchanged throughout its lifecycle, often being shared between different entities within and outside NRAs (which are often interdependent) (Biswas et al., 2021a, 2021b). Consequently, the integrated management of asset data from various NRAs necessarily has to solve typical integration and data quality challenges, such as lack of interconnectivity (silo view), inaccuracies, incompleteness and semantic inconsistencies. These challenges significantly increase the risk of making wrong decisions and the costs associated with information management. This is why European CEDR projects, such as Interlink and CoDEC, have sought to find open and scalable information management standards that European NRAs can use to find, manage, use, analyze and share AMS data, while allowing them to connect to other industry standards, such as IFC.

The presented approach or any future applications designed with this ontology can be used by any NRA, provided their data is mapped to the ontology. Furthermore, the use of standards and higher-level ontologies, such as eurOTL and SSN, also ensures the interoperability of the Engineering Structures ontology with these ontologies or applica-

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[13] https://www.w3.org/TR/shacl/.

[14] https://www.w3.org/submissions/SWRL/.

Table 3
Cost-benefit dimensions.

Benefits	Costs
B1. Ontology-driven analysis (including knowledge validation and inference) in a familiar decision-support environment (BIM)	C1. Multidisciplinary Team Required
B2. Industry standards adoption (use of eurOTL and SSN ensures interoperability)	C2. Data Integration (including ontology mapping)
B3. Semantic and Data interoperability improve communication, data exchange, and decision-making across European NRAs	C3. Software Development
B4. Provide a base for several asset management processes across the whole asset lifecycle	C4. User Training and Adoption
	C5. Infrastructure and upkeep

tions based on them. The integration and reuse of industrial standards in a flexible way minimizes the risk of obsolescence of such solutions, extending their adoption lifetime and, consequentially, reducing operational costs in the future.

In addition, semantic web technologies can play a crucial role in facilitating compliance and governance efforts by improving external communication and alignment. Semantic web technologies streamline documentation and reporting, enabling users to verify adherence to regulatory requirements and compliance with relevant standards, such as those set by industry policymakers. Thus, the European Commission, as a policymaker, can establish a set of formalized rules, which can be translated into SWRL and SHACL, and automatically validated against the ontological representation of each asset. For example, this can be used to validate whether or not a certain type of structural element is being monitored according to a set of observable variables.

AMS support industrial practitioners in key areas, including condition assessment, forecasting future deterioration, and identifying maintenance and repair needs and strategies. Structural operators typically use visual inspections and sensor networks to monitor structural response and environmental variables (such as displacements, temperatures or energy consumption) and collect essential data, enabling effective and efficient management during the O&M phase. The Engineering Structures ontology allows users to access dynamic data, normally stored in AMS, providing a basis for the analysis of European road sector assets, namely highway structures and their structural elements. By providing reliable historical information about the assets, the ontology can be used for various asset management processes, including maintenance, condition assessment and performance prediction.

CoDEC's three pilot projects demonstrated the applicability of this ontological artifact: *PP - Tunnels* showcased the integration of sensor data in a BIM environment, *PP - Bridges* presented a risk analysis based on structural inspections, and, finally, *PP - Pavements* demonstrated the possibility of exchange data between BIM and GIS. There are no discernible barriers preventing the application of this semantic-based approach throughout the entire lifecycle of infrastructure assets. By facilitating data exchange between systems and NRAs, this approach enables data-driven decision-making across the various lifecycle processes of each structure, simplifying workflows and reducing data duplication and errors. This semantic interoperability also improves collaboration and communication among stakeholders involved in facility management, maintenance planning, and asset lifecycle management. Moreover, it reduces discrepancies and improves data reliability, leading to a more efficient and reliable decision-making, optimizing asset performance throughout the lifecycle.

However, integrating AMS data into the BIM environment through an ontology-based approach entails several important cost considerations. Firstly, the application of essential components such as the Engineering Structures ontology and the CoDEC framework requires a multidisciplinary team including domain/industry experts, stakeholders, knowledge engineers and software developers to ensure alignment with user needs.

Secondly, the costs associated with conceptual integration and data migration include efforts to map concepts between AMS and BIM (which usually requires human intervention), to transform and populate data into the ontology. In addition, although there are tools to automatically obtain an ifcOWL representation from a BIM model, it is still necessary to manually map the relationships between the entities in the Engineering Structures ontology and their BIM representation.

Thirdly, additional costs may arise from the need to develop or customize software for seamless integration between AMS and BIM systems, such as creating additional API services or customizing existing software to visualize ontological knowledge within the BIM environment. Training and adoption costs should also be considered, as users must learn to access, interpret, and use AMS data in this decision-support environment. Infrastructure and upkeep costs, as well as those related to the maintenance and evolution of the ontology (including version control), are also critical considerations.

It is worth noting that estimating project costs depends on variables such as the size of the project, the tools/software used, data requirements and forward planning. For example, recognizing the need to use BIM throughout the asset lifecycle (including O&M) can lead to the design of AMS with BIM identifiers for each asset, simplifying future ontology mappings. Although the assessment of costs and benefits will inevitably vary depending on the specific case, Table 3 provides an overview of the main dimensions for benefits and costs of using the Engineering Structures Ontology as the basis for data exchange between BIM and AMS. This table provides future stakeholders with a starting point to derive cost-benefit factors for their project-specific analysis.

8.3. Limitations and future work

The Engineering Structures ontology and its use still have limitations that require further research and development. Currently, knowledge of the ontology is limited to the primary structures associated with the CoDEC pilot projects (i.e. tunnels, bridges and pavements). Likewise, the use cases presented in this research focus on these pilot projects. Although formalized in a W3C standard, the full potential of the ontology remains to be explored. Standards such as SHACL or SWRL, capable of validating and inferring knowledge, offering new analytical possibilities, have not been addressed in this research. Furthermore, the process of populating the ontology still depends on manual intervention, including the export of operational data and the mapping between the Engineering Structures ontology and the ifcOWL instances

Future research should focus on resolving these limitations and expanding the usefulness of the Engineering Structures ontology. In particular, future research should broaden the scope of the ontology to cover a wider range of structures and elements beyond those addressed in the CoDEC pilot projects. The independent use of the Engineering Structures ontology to validate, analyze and infer knowledge in its domain is another avenue of research that could be explored. The use of W3C standards and other reasoning tools can fully exploit the ontological representation of this knowledge. In addition, it is imperative to develop automated tools or algorithms to simplify the process of populating operational data into the ontology. These tools should also facilitate the seamless mapping between the entities of engineering structures and the instances of ifcOWL, enabling real-time decision making in BIM environments.

9. Conclusion

BIM environments are used for decision support during the design, planning and construction phases. However, decision support in the operational phase is usually ensured by each NRA's AMS, supported by information related to monitoring, maintenance, and sensor data. Integrating operation data from AMS with BIM models is key to providing a real-time and continuous decision-making process throughout the complete structure lifecycle in the same (integrated) environment. The CoDEC research project proposed using semantic web and linked data principles to link operational data with the BIM environment, increasing system interoperability. A Data Dictionary was developed to provide a shared conceptualization that can be used as a base for a standard data format to enable interoperability between Europe's NRA and their systems.

This paper presents the development and evaluation of an Engineering Structures ontology used in the CoDEC project to encode this shared conceptualization. The Engineering Structures ontology represents structures, their structural elements and relationships in a formal, comprehensible and explicit way. Furthermore, the ontology can also describe sensor, and risk and condition data. The Ontology Requirements Specification Document (ORSD, see Section 5.1) is presented, following the NeON methodology, with information regarding the ontology a) goals, domain and scope, b) users, use cases and applications, c) knowledge inputs and d) competency questions.

The ontology design and development process is described, focusing on the requirements of each pilot project. The ontology was validated and evaluated by answering the competency questions defined in the ORSD and using the OOPS! tool. Lastly, the integration of this knowledge in a decision-support environment was demonstrated using a pilot-project related to risk and condition data in bridge elements, showcasing the ontology as a base for data exchange between BIM and AMS systems.

Theoretical and practical implications are presented, including an analysis on cost and benefit dimensions and applicability of this approach. Limitations are also presented in the discussion section. By addressing these limitations in future research, the Engineering Structures ontology can evolve into a more comprehensive and versatile tool for facilitating data exchange and decision-making in the context of BIM and AMS integration.

CRediT authorship contribution statement

António Lorvão Antunes: Conceptualization, Methodology, Software, Validation, Writing – original draft. **José Barateiro:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Vânia Marecos:** Investigation, Writing – original draft. **Jelena Petrović:** Resources, Software, Visualization. **Elsa Cardoso:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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