A standard-based ontology network for information requirements in digital construction projects

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Abstract
In digital construction projects, precise requirements are crucial for sharing relevant information and producing project deliverables that adhere to standards and regulations within the architecture, engineering, construction, and operation domain. These information requirements still often remain in semi-structured textual documents and are hardly machine-readable to support the process of information provision and validation. Therefore, in this paper, the relevant normative framework consisting of the Level Of Information Need (LOIN), Data Templates (DT), and properties from building codes is analyzed, and formal representations of corresponding ontologies are aligned to seamlessly use the standardized framework in digital construction projects. The alignment is done according to best practices and methodologies from the Semantic Web research domain. The resulting aligned ontology network is demonstrated in a use case for checking fire safety regulations.

Keywords
Digital Construction Projects, Information Requirements, Ontology Network, Alignment, ISO 23386, ISO 23387, ISO 7817

1. Introduction

The seamless and trustworthy information exchange is a fundamental part of the Building Information Modeling (BIM) method [1]. To achieve this information exchange, distinctly defined requirements are vital not only for the information exchange, but also for the generation of compliant project deliverables within the architecture, engineering, construction, and operation (AECO) industry [2]. An overview of techniques for defining information requirements in digital construction projects is done by Tomczak et al. [2]. According to their review, various approaches concur, such as the internationally standardized Information Delivery Manual (IDM) [3], the Information Delivery Specification (IDS) developed and promoted by the non-profit organization buildingSMART International (bSI) [4], and the internationally developing Level of Information Need (LOIN) [5]. The IDS and LOIN are currently under

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development regarding their XML-based machine-readable schemas [4, 6]. However, machine-readable information requirements are seldom defined in projects, which makes it hard to provide information according to these requirements and for the appointing parties to verify the delivered information according to these requirements.

Another obstacle within the AECO industry is the adoption of state-of-the-art approaches due to contractual agreements and expectations, which may result in additional costs. Therefore, standardized approaches are preferred. In this paper, the normative framework for information requirements management and their machine-readable schemas are analyzed. As a solution that is also provided by Tomczak et al. [2], Linked Data and ontologies are reviewed to achieve formal semantic descriptions of the normative framework and the information requirements. Parts of the standards are already available as either XML or ontological schemas that facilitate automated information processing. The respective ontologies and schemas are presented in the paper and are aligned to have a more seamless process of defining requirements, providing data according to these requirements, and validating delivered data. Particularly, an ontology to define and use LOINs is reviewed and integrated, a new ontology for representing data templates is developed, and an ontology for maintaining properties from building codes is integrated and altogether aligned to refer to the same terminology at the intersecting terms.

The result of this work is an aligned ontology network that is harmonized with current standardization and is demonstrated in a case of building design coordination considering fire safety. The aligned ontologies are provided as open-source deliverables.

2. Background

Given that standards are the foundation of the ontology alignment proposed in this paper, a short outline of key aspects of the three central standards (ISO 7817, ISO 23387, and ISO 23386) is provided. A general introduction to Linked Data and Semantic Web is given to align and develop a new ontology for representing the data templates from ISO 23387, and the preliminary works on ontological representations of the normative framework are discussed.

2.1. Normative Framework

As identified by Bolpagni et al. [7], standards related to BIM have two anchor standards: the ISO 19650 series [8] and the ISO 12006 series [9]. The information delivery process is thoroughly described in the ISO 19650 series, which lays the groundwork for the ISO 7817 series (currently under development) [10], thus addressing the specification of the information requirements using the LOIN approach.

The relations between the three main standards of this publication are depicted in Fig. 1. The construction domain information classification is addressed, among others, by ISO 23386 [11] and ISO 23387 [12]. ISO 23386 provides a methodology to describe, author, and maintain properties in interconnected data dictionaries. ISO 23387 builds upon the methodology proposed in ISO 23386 and describes an approach for data templates for construction objects, with emphasis on the reusability of templates. Both standards are harmonized with ISO 12006-3 [9]. ISO 7817 uses the principles from ISO 23387 to describe needed information for object types [10].

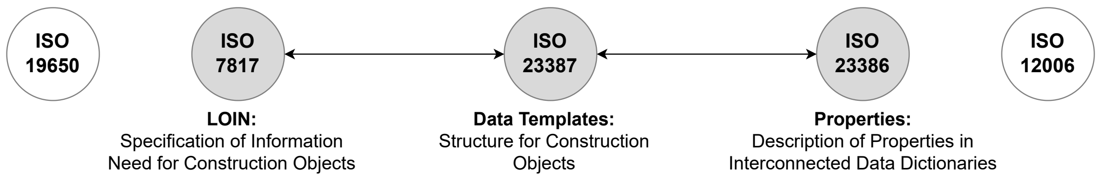

Figure 1: Direct relations between relevant standards implemented in this research

2.1.1. Level of Information Need (LOIN)

The LOIN approach was first presented in ISO 19650-1, conceptualized in the European standard EN 17412-1, and recently established as an international standard in ISO 7817 Part 1 [10]. An XML-based schema is expected to be published in Part 3 of this standard series [10]. Within the approach proposed by the ISO 7817 standard series, required information can be specified for objects on all levels of a project, thus allowing a wide range of granularity and dissolving the previous static levels approach (except for the *Detail* attribute within the *Geometrical Information*, which will still allow defined levels). The approach followed by the current schema development suggests that the LOIN specification schema will be agnostic, meaning that various classifications and data models will be supported, e.g., IFC, but also others, such as LandXML. The specified information needed for a required object within the LOIN approach is structured in *Geometrical Information*, *Alphanumerical Information*, and *Documentation.* Lastly, a LOIN has four *Prerequisites* (sending and receiving actors, milestones, and purpose). The ISO 7817-1 standard (and later, Parts 2 and 3 of this series) is interconnected with other standards within the information delivery process as well as information classification standards. Especially ISO 7817-3 establishes a schema specification for the LOIN, as shown in the current schema version [6], referencing ISO 23387.

2.1.2. Data Templates (DT)

The standard ISO 23387, which is currently being updated, will establish an XML-based schema for data templates to be used in the life cycle of built assets. In this context, a data template is a subset of the model described in ISO 12006-3:2007 [9] that provides the concepts and relationships required to describe information about building objects. The XML schema proposed in the updated standard establishes relationships between properties and specializations of properties to describe characteristics of construction objects. It establishes a base element called *Library Component* that can associate this element with a *Reference Document* and an *External Dictionary*. The *Library Component* serves as a base for the *Data Template* element, which in turn links a *Construction Object* to a *Set Of Properties* or to a single *Property* [6, 12]. These data templates intend to provide a standardized and reusable data structure for the description of construction objects, enabling the free exchange of information within the construction industry regardless of the life cycle of assets. Emphasis must be given to the fact that the barrier-free information exchange must be supported by machine-interpretable information. Given the inherent property of reusability that templates display, ground principles used by the DT schema, such as data catalogs, originate in ISO 23386.

2.1.3. Property Management in Data Dictionaries

In the AECO industry, data catalogs form a structure for the clear classification and differentiation of objects and serve as a basis for the standardized exchange of information. The structuring and linking of properties from these classifications can be carried out based on ISO 23386. The ISO 23386 standard includes general instructions for describing, creating, and maintaining features in interconnected data catalogs to ensure a quality-assured, seamless exchange of information between the parties involved in BIM processes based on ISO 12006-3 [11, 9].

The aim of establishing this standard and the corresponding definitions and management rules is to facilitate interoperability between data catalogs and BIM or other digital tools. The focus is linking similar *Properties* in independent data catalogs to avoid ambiguities and duplicates. In addition, the standard offers a further structuring level for *Properties* with the introduction of *Groups of Properties*. *Groups of Properties* are organized in a tree structure (cf. Figure 2) in which the *Properties* are passed on to the subordinate *Groups of Properties* [11].

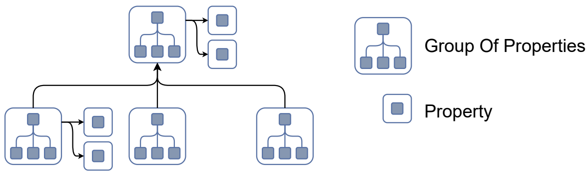

Figure 2: Example of Groups of Properties arranged in tree structure with attached properties

2.2. Technology

The Semantic Web extends the World Wide Web by incorporating standardized technologies for structured, machine-readable data [13]. It uses ontologies to interpret resource metadata, allowing both computers and humans to access resources in a contextual framework [13]. Linked Data (LD) within the Semantic Web emphasizes globally interconnected, openly accessible data using URI and HTTP protocols. LD involves using IRIs, the Resource Description Framework (RDF), as well as the SPARQL Protocol and RDF Query Language (SPARQL) to work with instance data and query structured semantic data [13]. The combination of ontologies and instance data in RDF graphs is known as knowledge graphs. In addition to XML-based specifications, as often proposed in the current standardization contexts, ontologies are a valid approach for defining the logic of information requirements within a construction project [2, 14, 15]. Ontologies are structured machine-readable specifications that provide formal semantics for establishing a shared understanding of a particular domain [13]. As part of the Semantic Web, they serve as frameworks for organizing and representing knowledge about a subject or domain [16]. Ontologies define terms, meanings, and relationships, forming a standardized vocabulary for enhanced comprehension and interoperability [16]. The Web Ontology Language (OWL) is a standardized language for representing and reasoning about knowledge in the Semantic Web [13]. It enables the formal specification of relationships in an ontology and provides a framework for expressing complex information in a machine-readable format [13].

2.3. Preliminary works

This section conveys the foundational concepts and existing methodologies relevant to this study. First, an examination of the ontological representations of the LOIN standard is given. Followed by an overview of the latest advancements in Data Templates. The chapter concludes with a discussion on an ontology for Property Management in Data Dictionaries and other relevant concepts facilitating the ISO 23386 standard.

2.3.1. Ontological representations of the LOIN standard

To enhance compatibility with the BIM method, requirement specifications must also be machine-interpretable [17]. The LOIN approach, as described in ISO 7817-1, formerly published as EN 17412-1, defines required information that should be delivered in the information exchange processes. The LOIN development is ongoing in both industry standardization and academia. Various approaches have been investigated for encoding the LOIN concept [5, 2]. Part 3 of ISO 7817, currently under development, introduces an XML-based schema (XSD) for the LOIN specification, which is harmonized with ISO 23387 and, therefore, uses data templates to specify the alphanumerical information [6]. Based on ISO 7817-1, a LOIN ontology was developed for defining a machine-readable Information Delivery Manual [18]. In this ontology, not only the IDM and LOIN paradigms but also the IDS and Information Container for Linked Document Delivery (ICDD) were considered. Given the introduction of the alignment with the ISO 23387 (data templates) in ISO 7817-3, this study addresses aligning the LOIN ontology with data templates and property management in interconnected data dictionaries.

2.3.2. Machine-readable Data Templates (DT)

Given the novelty of the DT standard and the ongoing update and development of an XML-based schema, few approaches regard it. Mellenthin Filardo et al. [17] successfully used the DT mechanism proposed in ISO 23387 by partly implementing an automated import for the current XML-based LOIN schema from ISO 7817-3 for integrated information requirement within an established modeling environment. The DT mechanism was used to describe alphanumerical information, e.g., specific properties and their values assigned to specific construction objects.

While different platforms and models exist to describe and share product data, current systems must address vendor-specific constraints, as identified by Kebede et al. [19]. The authors proposed an OWL-based ontology for handling lighting product data according to CEN/TS 17623 [20]. This technical specification specializes in lighting and luminaires but still regards the basis for the property definition set by ISO 23386. ISO 23387 was not used, given that no actual Product Data Templates for luminaries were found, which can also be explained by the novelty of the standard. Wagner et al. [21] developed an ontology for Linked Building Product Data. The proposed ontology is defined as a generic ontology for (building) products, including their interconnections, properties as well as assembly (geometry).

2.3.3. An ontology for Property Management in Data Dictionaries

Following the proposed data schema and management rules from the ISO standard 23386 (cf. Section 2.1.3) the Interconnected data dictionary ontology (IDDO) was initially conducted to transfer knowledge from text-based construction-related standards into a hierarchically structured tree of groups of properties and properties (cf. 2). The *Groups of Properties* and *Properties* are linked with metadata and management information, ensuring a structured and organized framework. Each property is defined by attributes and restrictions that can take various forms, such as minimum and maximum values accompanied by their respective units, specific options selected from predefined lists or arrays, and links to other properties. [15] In a follow-up step, the structure of IDDO has been expanded to include terminology from the Data Catalog Vocabulary (DCAT), which is a recommendation from the World Wide Web Consortium (W3C), to enhance its compatibility with standard ontologies on the Semantic Web [22]. This extension enriches the IDDO by integrating a structured methodology for dictionary creation and organization, streamlining data management and retrieval [15]. The assignment of properties to a desired Feature of Interest (FOI) like a `bot:Building` or a `dice:Equipment` can be realized using the OPM property state pattern introduced by Rasmussen et al. [23].

Despite the usage within the IDDO, the data schema proposed in the ISO 23386 standard is used in other research works. Alani et al. [24] leveraged the data schema to transform product data templates into an ontological format, with the results being utilized in asset management software. The buildingSmart Data Dictionary (bSDD) also provides functions for managing properties from classifications and offers since 2021 the possibility to provide the recorded data in a format compliant with ISO 23386 [25].

3. Methodology

The methodology followed in this paper consists of two steps: first, harmonizing the ontologies with the international standards framework, and second, aligning the ontologies according to ontology engineering principles [26] to make them a usable aligned network for managing the information requirements in digital construction projects. To that end, the necessary harmonization of the existing ontologies with the standards is addressed, followed by the design and implementation of a new ontology and necessary modifications in the existing ontologies to achieve the desired alignment between the ontologies. Finally, a demonstration is provided to establish the validity of the proposed standard-compatible and aligned ontology network.

Considering that the current version of the XML schema developed for ISO 7817-3 uses mechanisms from the schema for ISO 23387, which in turn relies heavily on ISO 23386, it becomes clear that harmonization is necessary. Given the availability of previously developed ontologies for ISO 7817-1 by Liu et al. [18] and ISO 23386 by Zentgraf et al. [15], a third ontology for DT is developed and presented in this article. This new ontology builds a link between all three ontology domains, thus enabling compatibility between the normative information specification and delivery processes and the linked data approach [14]. To achieve an aligned ontology network, the standards and current versions of XML schemas [6] were analyzed for overlaps, discrepancies, naming issues, and references. Regarding ISO 7817, it was mainly identified that an extension to address the *Construction Object* element was necessary since it is a central element within the design of the 7817-3 schema and, therefore, part of the link between ISO 7817-3 and ISO 23387. Further, the content of the *Alphanumerical Information* element needed to be adjusted to accommodate the link to the new data template ontology explained in Section 4.

In the domain of ISO 23386, it was crucial to identify the interconnected elements within the developed ISO 23386 ontology and the ISO 23387 schema. Special care must be taken to identify the corresponding elements and put them in the correct relation. These regarded mainly the elements (1) *Property* and (2) *External Dictionary Reference*, which are central elements in both domains. The complete alignment is described in Section 4. Subsequently, the classes, subclasses, and relationships were implemented to mirror the aligned ontology network, thereby creating an updated, standard-compliant LOIN ontology and an updated ISOProps ontology, formerly IDDO, compatible with the new DT ontology.

The ontology alignment is supported by visualizing ontology vocabulary in standardized notations as provided in the ontology design template defined by Donkers [27] and the best practices for ontology visualization provided by Poveda-Villalón et al. [16].

The development of the DT ontology is based on concepts and principles for creating templates from ISO 23387 and the associated XML data schema, which is currently under development [6, 12]. Similar to the creation of software products, requirements are also defined when creating ontologies, which ensure that the developed ontologies meet the set requirements and can be used in the intended use case. To formalize these requirements, requirements specifications are often created during the development of ontologies [28, 26]. In this case, the requirements for the ontology development are directly derived from the XML schema of the standard and are considered with high accuracy to create a compliant ontology.

In addition to technical accuracy, an ontology's applicability is also crucial. Ensuring usability can be achieved by adhering to the FAIR principles for data sharing, which refer to Findability, Accessibility, Interoperability, and Reusability [16]. These principles are designed to ensure that data and metadata are managed to facilitate their easy discovery, access, integration, and reuse by both humans and machines. By aligning the development and structuring of ontologies with the FAIR principles, it is possible to enhance their practical utility and ensure that they serve their intended purposes effectively in various contexts [16]. An evaluation of the FAIR requirements for the ontology network is provided in the GitHub appendix of this paper. The requirements analysis needed for the DT ontology was carried out following the LOT methodology [26].

4. Results

Following the methodology as described in Section 3, the new Data Template (DT) ontology was created, which refers to both the LOIN and the ISOProps ontologies.

4.1. Data Templates Ontology

Given that the ontology is based on an XML schema, the nature of a root element was emulated, even though it is not a necessity for ontologies, as shown in Figure 3.

This pseudo-root element, `dt:LibraryComponent`, has relations to a `dt:Reference-Document` and to a `dt:ExternalDictionaryReference`. The latter is equivalent to

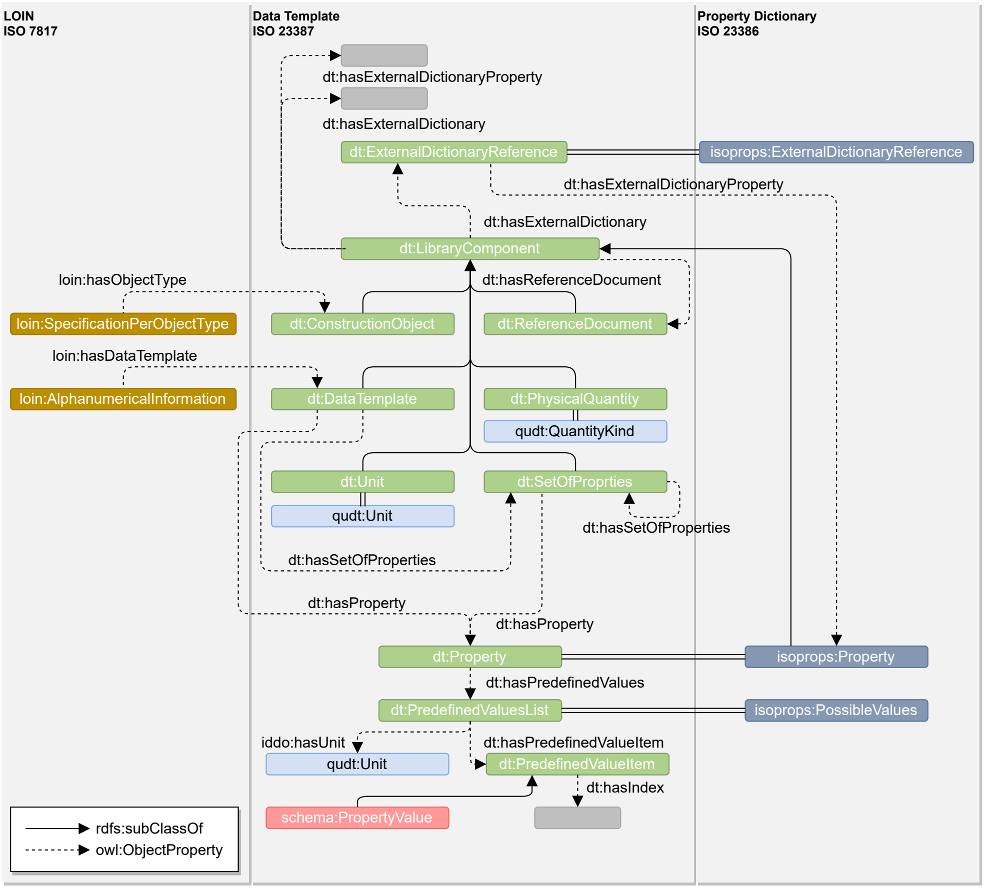

Figure 3: DT ontology schema and the alignment with LOIN and Property Dictionary

the `isoprops:ExternalDictionaryReference` element. By defining the `dt:LibraryComponent` with these two core components, it is achieved that all subclasses inherit these references as well. Through this mechanism, set by the original XML-based schema, various references to simple documents, e.g., descriptions for construction objects, or norms for sets of properties or templates, can be made. In addition, more detailed references to entries in data dictionaries can be made for all elements. Subclasses of `dt:LibraryComponent`, that profit from these references, are `dt:ReferenceDocument`, which allows the incorporation of miscellaneous documents, and `dt: ConstructionObject`. The LOIN ontology references the latter through the `loin: SpecificationPerObjectType` element to describe the objects for which the information is needed. Another subclass is `dt: DataTemplate`, which is called upon by the LOIN ontology `loin: AlphanumericalInformation` element to provide a structure for the defined alphanumerical information. Further, `dt:PhysicalQuantity` is also a subclass of `dt:LibraryComponent`, and was put in equivalence to the `qudt:QuantityKind` element from the QUDT (Quantities, Units, Dimensions, and Data Types) ontology [29]. The QUDT ontology is a framework designed to facilitate the understanding and use of data by precisely defining the quantities involved and how they are measured, including the units of measure and data types [29]. Similarly, the `dt:Unit` was set in equivalence to `qudt:Unit` as well. Finally, the subclass `dt:SetOfProperties` can describe properties using the `dt:Property` element. Both elements to describe a property within DT and ISOProps ontologies were set in equivalence to each other. Furthermore, the `dt:Property` and therefore indirectly also the `isoprops:Property` can also be used by the `dt:DataTemplate` directly. The set of properties mechanism from DT and the group of properties mechanism from ISOProps differ in the sense that properties within a set (DT) can come from different groups of properties (ISOProps). Both structures, sets, and groups, are needed to enable modular reusability. The `dt:Property` element has predefined values inside the `dt:PredefinedValuesList`, which is equivalent to the `isoprops:PossibleValues` element. It has a `dt:PredefinedValueItem` and a `qudt:Unit`.

4.2. Ontology Alignment

During the alignment of the three ontologies considered in this work, terminological and structural changes were also made to the LOIN and the ISOProps ontologies, formerly known as the IDDO, which are presented below. To ensure consistency with the LOIN-XML-Schema [6], the core classes about contextual information and the specification of information needs (e.g., the LOIN classes in Fig. 4) of the LOIN ontology classes are renamed. In addition, classes related to the extension of information delivery specifications from previous work [18] are separated into a dedicated namespace, which aims to improve the clarity of the ontology. LOIN and DT ontology are aligned to facilitate standardized definitions using data templates. Using the object property `loin:hasObjectType`, an instance of `loin:SpecificationPerObjectType` can be declared with an instance of dt:ConstructionObject. Using `loin:hasDataTemplate`, an instance of `loin:AlphanumericalInformation` can be specified with an instance of `dt:DataTemplate`, which can then be detailed with instances of the class `dt:Property` or of the class `dt:SetOfProperties`.

Before implementing structural changes within the ontology that formalize the ISO 23386 standard, the namespace of the ontology was adjusted. As already mentioned, IDDO was renamed to ISOProps Ontology. This renaming was done to emphasize that the central elements of the ontology are properties. In addition to the adjustment of the namespace, further editorial changes were made to the ontology, which can be found in the documentation of the ontology.

Following the terminological adjustments, the DT and ISOProps were aligned. For this purpose, the class `isoprops:Property` was first assigned to the `dt:LibraryComponent` as a subclass, which enables class equivalence and thus an alignment between the classes (cf. Figure 3 bottom right). Furthermore, both ontologies have adapted the mechanisms for referencing external data catalogs. All classes that are a subclass of `dt:LibraryComponent` after the alignment can now reference an object of the class `dt:ExternalDictionaryReference` or `isoprops:ExternalDictionaryReference` via the predicate reference `dt:hasExternalDictionary`. From such an `:ExternalDictionaryReference` object, a reference to an external data catalog (`:hasExternalDictionary`) and, if desired, a reference to a specific property (`:hasExternalDictionaryProperty`) in this data catalog is possible.

In addition to the alignment carried out, structural adjustments were made within the ISO-

Props ontology. The processing of boundary values that can be specified in a property was adapted based on the principle proposed in ISO 23387. Through this adjustment, it is now possible to store a unit and the information on whether the boundary value is considered inclusive or not in each `isoprops:BoundaryLimitMin` or `isoprops:BoundaryLimitMax`. Furthermore, the handling of dimensions, physical quantities, and the associated units has been simplified. This was achieved by a class equivalence between the classes `isoprops:PhysicalQuantity` and `qudt:QuantitiyKind`. This link bundles all relevant information about the physical quantity of the properties in one place.

In addition to the alignment steps already listed, further changes were made to the ontologies. However, since comprehensive documentation of all adjustments made during the harmonization and alignment process would exceed the scope of this paper, the authors refer to the documentation of the ontologies, which can be found in the section *Data Availabilty* of this work.

5. Demonstration

To demonstrate the definition of the information requirement using the aligned ontology network proposed in this article, a simple use case is presented for requiring partition wall properties during structure design in a public building. Given the high importance of fire safety in public buildings, the non-load-bearing but space-enclosing partition walls should be designed to fulfill fire resistance requirements. In this use case, the building structure needs to substantiate a fire resistance of 120 min. The building structure design is based on the European standard DIN EN 1992-1-2 [30]. Therefore, the thickness and the related fire resistance class of partition walls are the relevant properties according to Table 5.3 of DIN EN 1992-1-2 that need to be delivered considering the building-specific fire resistance requirement.

The specified requirements can be defined using LOIN, DT, and ISOProps ontologies, as illustrated in Figure 4. In the first step, the information delivery milestone, the purpose, and related sending and receiving actors can be instantiated using classes of the LOIN ontology. The partition wall as an object type and the required alphanumerical information are instantiated on the project-milestone-specific level. Independent of whether an object type template is already available for the partition wall, using the DT ontology, a data template of the construction object `:Wall_Partition_NonLoadBearing_SpaceEnclosing` as an instance of `dt:ConstructionObject` can be defined and aligned with the project-milestone-specific instance `Partition_Wall` in the second step. This alphanumerical information can be specified with the data template `:Wall_Fire_Resistance_Template` as an instance of class `dt:DataTemplate`. For detailing the template with information content, instances of `dt:SetOfProperties` can be assigned to the template. In this case, `:Wall_Fire_Resistance_PSet` is created as a property set. Furthermore, relevant documents can be linked to the defined object as defined in the use case. For instance, `:DIN_EN_1992_1_2_2008` is created using class `dt:ReferenceDocument`.

In the third step, a property or a group of properties that are assumed to be predefined and maintained in a digital form based on ISO 23386 should be used to facilitate the setup of a data template. The instance `:Wall_Partition_PGrp` of `isoprops:GroupOfProperties` refer-

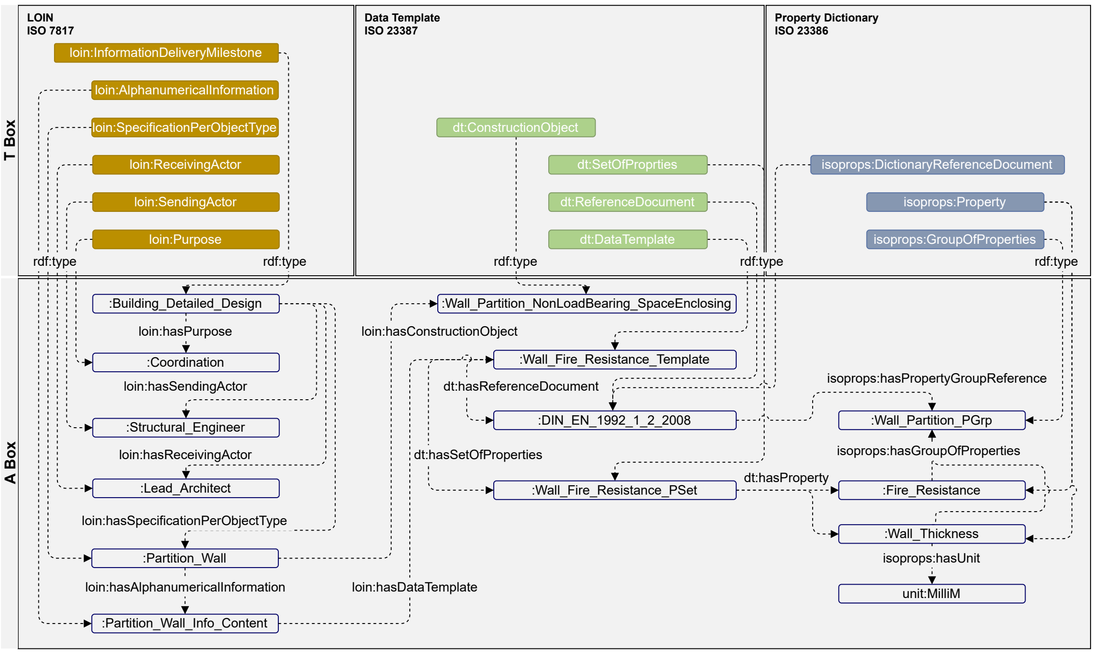

Figure 4: Exemplary definition of information requirements using the standard-based ontologies

ences the requirement defined in `:DIN_EN_1992_1_2_2008`. Within this group of properties, two relevant properties are instantiated as `:Wall_Thickness` and `:Fire_Resistance` via the class `isoprops:Property`. Using `dt:hasProperty`, the two property instances can be assigned to the `:Wall_Fire_Resistance_PSet`.

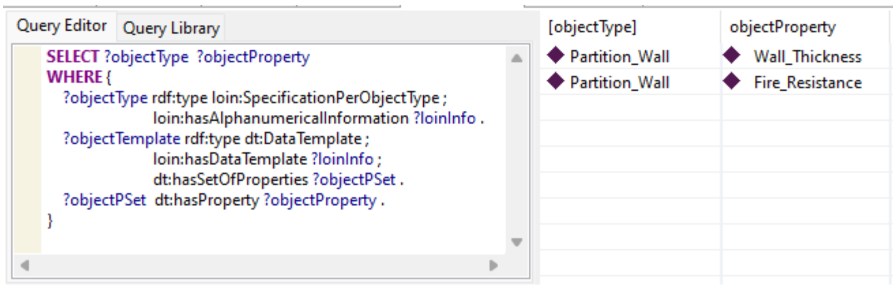

Figure 5: SPARQL query and the query results of predefined use case

After the ontological definition, the required information of a certain construction object can be retrieved using a SPARQL query. As illustrated in Figure 5, the SPARQL query selects the requirement of alphanumerical information of the declared object types in the use case. As the query result, the two required properties are listed for the object type `loin-dt-isoprops:Partition_Wall`. By explicitly defining the information requirements in this way, the structural engineer, as the sending actor, has a better understanding of the information to be delivered. Furthermore, associated checking rules can be delivered after the definition of information requirements by the receiving actor, which facilitates quality control considering predefined requirements. For instance, previous work by Zentgraf et al. [15] using ISOProps showed how a Shapes Constraint Language (SHACL) shape is used to check the cardinality, unit, and value of the required property. However, the data validation with SHACL is not in this paper's scope and can be found in [15].

6. Conclusion and Outlook

This study showed the integration potentials of the standards for LOIN, Data Templates (DT), and properties in interconnected data dictionaries (ISOProps) using an alignment of modular ontologies. By cross-referencing and class and property equivalency mechanisms, three ontologies were successfully integrated into an aligned ontology network for exhaustively describing and defining properties as well as construction objects harmonized with the analyzed standards ISO 7817, ISO 23386, ISO 23387, as well as indirectly regarding ISO 12006 and ISO 19650 standard series. Furthermore, the proposed ontology network presents modular and reusable descriptions for properties and construction objects. Aligning these standard-conforming ontologies prevents taxonomy problems, facilitating uniform query searches. The use case demonstration for building design coordination considering fire safety highlighted the application of the proposed ontologies for a recurrent problem within the industry. Given that neither the LOIN nor the DT approaches proposed in standardization and implemented in this study propose static structures, this ontology network can be modeled from a generic perspective, reducing overhead and implementation efforts imposed by rigid schemas. By implementing these entangled standards as ontologies, this study emphasized the degree of harmonization between existing and ongoing state-of-the-art standards and state-of-research Linked Data approaches.

Future work addresses applying all three ontology domains to a broad range of example products and construction objects to identify limitations. In addition, the development of databases and data dictionaries should be observed and regarded, given their closeness to the presented study. Finally, interfaces between modeling environments, DTs, and property databases should be developed or extended to make the state-of-research knowledge accessible to end users in the industry.

Data Availability

The aligned and harmonized ontologies, the DT ontology, and demo data are available via GitHub: https://rub-informatik-im-bauwesen.github.io/ir-ontologies/.

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