ONTOLOGY-BASED CONSTRUCTION INSPECTION PLANNING: A CASE STUDY OF THERMAL BUILDING INSULATION

Sebastian Seiß, Markus Boden & Prof. Jürgen Melzner
Bauhaus-University Weimar, Germany

Yuan Zheng
Aalto University, Finland

Thibaut Delval & Rayan El Chamaa
Centre Scientifique et Technique du Bâtiment, France

ABSTRACT**:** *Poor construction quality is one of the most significant challenges for the construction industry. However, failures can be avoided or minimized by inspections based on detailed quality inspection plans as a part of quality assurance. Therefore, structured and project-specific planning of inspection plans is required to provide inspectors with the right information.*

Nevertheless, inspection planning is mainly manual, dependent on the individual's experience and high level of effort. As a result, inspection planning is often neglected and limited to providing general checklists that often lack semantically rich descriptions and are unspecific concerning individual project requirements. Furthermore, proper planning of inspections requires multiple information sources, such as building design, schedules, contractual and supplier guidelines, and standards, all of which must be provided or linked via an information model. Current research lacks an adequate formalized knowledge model to provide the knowledge-driven inspection planning process with the necessary domain knowledge to support inspection planning with heterogeneous information defined in isolated systems.

Therefore, this paper extends the Ontology for Construction Quality Assurance (OCQA) with the OCQA-Thermal Insulation (OCQA-TI) to formalize thermal insulation inspection planning knowledge. The OCQA offers a new linked data model that provides explicit knowledge of quality inspection planning. The development of the OCQA-TI follows the Linked Open Terms (LOT) methodology and is implemented using the Web Ontology Language (OWL).

The proposed ontology is evaluated using various approaches, including automatic consistency checking, answering competency questions, and criteria-based evaluation. The results indicate that the OCQA-TI can provide inspectors with relevant inspection planning knowledge and integrate various related information streams, thus providing a more comprehensive and efficient approach to insulation inspection planning. The functionality of OCQA-TI enables the fulfillment of increased sustainability and energy efficiency requirements by providing insulation inspection knowledge.

KEYWORDS: *semantic web, building insulation, ontology, quality assurance in construction, inspection planning*

1. INTRODUCTION

Construction faces a significant quality problem, evidenced by an analysis by the German insurance company VHV showing that the total cost of reported damage claims has risen for years (Böhmer et al., 2022). A study by BauInfoConsult (2022) concurred, assuming a defective cost share of 12.8% of the industry turnover. With a total construction industry turnover of 143 billion euros in 2020 issued by the German Construction Industry Federation, the study extrapolates error costs of approximately 18.3 billion euros (BauInfoConsult, 2022).

Research and practice approaches have primarily focused on defect management yet have often neglected proactive defect prevention through inspection planning (Seiß, 2022). However, proactive inspection planning could avoid many errors and save costs. The VHV Report shows that approximately 58% of the causes of damage can be traced to avoidable execution and assembly errors as well as interface and communication problems. In addition, inadequate construction supervision accounts for approximately 7% of the causes of damage (Böhmer et al., 2022). Thus, a proactive, construction-accompanying quality assurance approach can address approximately 65% of all causes of damage.

Currently, energy efficiency and building sustainability requirements are increasing significantly worldwide. The

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European Union has set targets for the construction and real estate industry's energy future. Climate neutrality in the building sector is to be achieved by 2050. Hence, new buildings must be constructed to the zero-emissions standard as early as 2028 (European Parliament, 2023). In the specific domain of insulation, quality assurance is particularly important. Insulation is crucial to buildings' energy efficiency, thermal resistance, and interior comfort since poor insulation installation and use can lead to heat loss, thermal bridges, moisture problems, and an overall decline in a building's energy performance (Sassine, 2013).

National policies were implemented after the oil shocks of the 1970s and the subsequent energy crisis to meet the requirements of stricter insulation and energy efficiency regulations. These policies led to adopting standards in France, such as the "*Documents Techniques Unifiés*" and the RT 2012 and RE2020 rules, regulating the materials used and their installation methods while quantifying buildings' losses, gains, and energy needs. However, the practical application of these rules has sometimes been questionable due to negligence or ignorance. Hence, it is difficult for a conventional inspection to identify potential defects since the insulation materials are always covered with various finishing elements (Antoine Szeflinski, 2007).

Non-destructive testing plays a crucial role in addressing these issues, allowing for precise recognition of construction phases, authentic elements, original and restoration materials, construction techniques, deterioration, durability, and structural strength. These are essential for assessing the energy and environmental performance of the building envelope. Visual tests, thermographic tests, sonic and ultrasonic tests, thermal flux measurements, and microclimate analyses are used in energy audits to obtain accurate results (LUCCHI, 2011). Notably, thermal insulation implementation inspections often focus on performance after completing the construction work. Nonetheless, this approach has a major drawback: a delay in detecting implementation defects. While waiting for performance inspections, quality problems can develop and become more difficult and costly to correct.

Therefore, considering corresponding inspection plans to guarantee the quality of finishing trades such as thermal insulation and meet the expanding quality requirements is necessary. However, quality assurance in the building industry concentrates on shell construction trades (Berner et al., 2015), while finishing trades often cause increased costs due to defects. In analyzing the BSB's quality inspections during construction, damage to thermal insulation accounts for a comparatively high 10.7% of total damage (Böhmer et al., 2020). France's heat and climate protection ordinance has led to a steady increase in the proportion of thermal insulation measures (Böhmer et al., 2020). Sales of External Thermal Insulation Composite Systems (ETICSs) have also steadily risen in Germany since 2018 (Statista, 2023). In parallel, the number of defects caused by ETICS has also increased. For example, building projects with ETICS are often affected by defects such as cracking, moisture penetration, and delamination (Böhmer et al., 2020).

Hence, introducing inspections of thermal insulation implementation throughout the construction process would be beneficial in addressing this problem (Zhong, 2012). This approach would allow for early defect detection and correction, implementation quality improvement, and optimal energy performance assurance in buildings from completion. Thus, exploring automation solutions to evaluate inspections would be imperative to bridge the gap between regulatory standards and on-site inspections. However, to our knowledge, there is still a lack of a structured and computable representation for formalizing the thermal installation regulatory standards. Meanwhile, the interoperability between standards and the on-site inspection information also remains. Ontology is known as a formal specification of the domain knowledge, which has been widely explored in the construction domain to facilitate knowledge management and information integration issues (Pauwels et al. 2017). But an ontology that is adequate to represent specific domain knowledge of the thermal installation quality inspection is still missing. Therefore, in this research, we aim to extend the Ontology for Construction Quality Assurance (OCQA) for involving the specific domain knowledge for the thermal installation inspection process. The proposed ontology aims to formalize thermal insulation inspection planning knowledge and link the on-site inspection information to achieve an automated evaluation of the thermal insulation evaluation. Inspections related to thermal insulation require the integration of data from various and heterogeneous sources, and the choice of technologies associated with ontologies was made to provide a framework for aligning and connecting disparate knowledge.

This paper is structured as follows. Sections 1 and 2 provide a general review of quality assurance and thermal insulation. Section 3 reviews the work on ontologies related to general inspection planning, while Section 4 describes the methodology used to develop the proposed ontology. Next, Section 5 discusses the specifications of OCQA-Thermal Insulation (OCQA-TI) ontology, while Section 6 provides a methodological conceptualization and implementation, which is evaluated using an example in Section 7. Finally, Section 8 discusses the limitations and contributions of the research and provides conclusions.

2. BACKGROUND

2.1 Quality Assurance and Inspection in Construction

Presently, there is a greater focus on comprehensive quality inspections and defect management to satisfy contractors in their construction projects until the client's final acceptance. However, despite these efforts, many gaps and discrepancies are still identified near the project's end. The issues are related to a lack of on-site personnel for managing quality and defects, an overwhelming workload to meet deadlines, non-unified checklists with much manual paperwork, poor communication among different project stakeholders, and a complex and labor-intensive interior finishing process. These problems require additional work to rectify the defects, often leading to project delays (Young S. Kim, 2008). When defects are detected after acceptance, the contractor has claims, so for executing companies, the expense of eliminating defects is worth avoiding defective work at all costs. Moreover, the services of the subcontractors must be checked for defects. Indeed, when a subcontractor's defect is unrecognized before the execution and leads to a defective overall performance, it results in a renewed execution (Langen & Schiffers, 2005).

Currently, construction projects have become increasingly complex. Hence, the more complex the construction projects and processes, the greater the quality risks and the relevance of undistributed information and communication processes in the planning and construction process (Böhmer et al., 2022), often leading to avoidable errors. In addition, decisions regarding quality inspections, including construction activities not to overlook and tasks to inspect, the quality data to be collected and verified, and the acceptance criteria for quality, are evaluated on-site by inspectors based on their previous experiences, which can vary from one inspector to another (Tan, 2010). This variation may arise for several reasons, such as a lack or absence of knowledge concerning regulations or feeling overwhelmed by the amount of regulatory text referenced for applicable provisions during quality inspections. As a result, manual verification of construction quality compliance has been a time-consuming and error-prone task (C. Eastman, 2009).

Therefore, construction inspectors require assistance with planning inspections to effectively define inspection objectives, explore various options, and efficiently allocate inspection resources. Thus, the inspection planning process can be divided into four steps (Lin, 2018) used to specify inspections by answering key inspection planning questions (DIN9001, VDI2619). First, the necessity of inspecting a characteristic (what?) is determined, and the associated inspection objects are defined. Second, the inspection time (when?), frequency (how many?), and scope (how much?) are determined. The third step defines the inspection procedure (how should the inspection be conducted?) and equipment (what materials are required for the inspection?), which must be simultaneously conducted since they are interdependent. This step also includes the inspection location (where is the inspection?) and the inspector (who is inspecting?). Finally, the fourth step determines the recording, management, and evaluation of the collected inspection data (Lin, 2018).

Furthermore, the agreed quality must be clarified as a building requirement to assess the objective quality and secure the success of construction work. In Germany, this clarification results from the general contractual conditions, the performance specifications, and the technical contractual conditions, according to §1 Para. 2 VOB/B. The construction target and, thus, the quality requirements of each construction project vary according to the project-specific performance specifications and contract components. A minimum set of requirements is ensured in German construction law in §1 para. 1 VOB/B by the obligatory agreement on the provisions of VOB/C, the General Technical Terms of Contract for Construction Work (*VOB*, 2016).

Moreover, verification in the form of testing activities is necessary per DIN EN ISO 9000 to ensure the quality of construction projects. Therefore, meeting the specified requirements should be verified using objective proof (ISO 9000:2015). In the construction industry, these inspection activities are conducted with structural acceptances divided into the following types: internal acceptance (according to the quality management plan) and acceptance under public law. Hence, a defect exists if the executed construction work deviates negatively from the contractual construction target (Berner et al., 2015).

2.2 Semantic Web and Ontologies

Data in the construction industry is generated in isolated systems and exchanged using various file formats, often with an insufficiently described relationship. The semantic web and associated linked data concept offers technical standards for a comprehensive, machine-readable exchange of heterogeneous information (Beetz et al., 2021). In a semantic web context, ontologies describe a shared conceptualization of a specified knowledge domain in a community of users. Therefore, using semantic web technologies, an ontology represents a part of the real world in a semantic model (Synak et al. 2009).

The foundational semantic web language is the Resource Description Framework (RDF), and its data structure is organized in triplicate, consisting of a subject, predicate, and object. The subjects and objects are depicted as nodes, while predicates are represented as edges connecting these nodes. As such, these RDF structures are often referred to as triplestores or RDF stores (Hitzler et al., 2008). These RDF structures are characterized by directed and labeled graphs (Herman 2004).

The capabilities of the RDF are further enhanced by additional languages and schemas, such as the Resource Description Framework Schema (RDF-S) and the Ontology Web Language (OWL). For instance, RDF-S broadens the scope of the RDF schema by introducing classes and defining properties. In comparison, the OWL utilizes RDF-F to represent ontologies and extends the model by establishing constraints among classes, properties, and entities (Allemang et al., 2020).

Typically, ontology knowledge provided by semantic web technologies is divided into two main components: an assertion box (A-box) and a terminology box (T-box). In some semantic web applications leveraging a specific rule language, an additional component, a rule box (R-box), is included. The T-box holds intentional knowledge or the terminology outlining a specific domain using a database schema-like vocabulary that incorporates classes, properties, and relations. The T-box's concepts remain constant and do not vary over time. In contrast, the A-box manages the facts tied to the terminology terms introduced by the T-box. In this way, the A-box instantiates the predefined classes and conceptual model with real-world individuals. It encompasses extensional knowledge about specific situations likely to change over time (Baader et al. 2007; Baader et al. 2017; Pauwels et al. 2017).

3. ONTOLOGY WORKS RELATED TO INSPECTION PLANNING

As we step into a new era of digital transformation in various sectors, there has been a surge of research and development efforts in the field of ontologies. Some have been particularly related to construction and inspection planning. Thus, this section aims to provide a comprehensive literature review starting with general ontology work in the construction domain and ontologies used in inspection planning.

Recently, ontologies have become increasingly relevant in the AEC sector, addressing challenges like data integration and knowledge management (Pauwels et al. 2017). Various ontologies have been created in the construction field, including the generic e-COGNOS (El-Diraby et al. 2011) and IC-PRO-Onto (El-Gohary et al. 2010). These ontologies, while comprehensive, lack a detailed representation of construction inspection, necessitating further expansion for accurate inspection representation. Therefore, further development resulted in Digital Construction Ontologies (DiCon) by Zheng et al. (2021), defining broader construction workflow-related entities and successfully integrating data from diverse systems. Beyond construction, ontologies such as IFCOWL (Pauwels 2016) and the Building Topology Ontology (BOT) by Rasmussen et al. (2020) have offered valuable semantic structures for building information modeling and topological concepts, respectively.

In the realm of construction execution, ontologies have made significant strides in addressing issues such as construction data integration and knowledge management. Therefore, this section focuses on ontologies specifically tailored to construction quality inspection. Zhong et al. (2012a, 2012b) introduced the CQIEOntology for quality management. This ontology primarily focuses on quality compliance checking while supporting inspection planning in an ancillary manner. The ontology expresses complex constraints usually found in quality regulations using the Semantic Web Rule Language (SWRL). This ontology-based approach enhances the construction quality inspection process by integrating these regulations within the construction process.

Martinez (2019) proposed an alternative method involving SPARQL queries to retrieve quality regulations based on the construction object and materials used, as specified in the ontology. Although the study primarily focused on predefined checklists, it overlooked the planning and preparation of quality inspections. The research aimed to primarily explore offsite manufacturing processes related to drywall steel frames.

Lastly, Xu (2019, 2021) developed the Highway Construction Inspection Ontology (HCIOntology), formulating inspections based on pay items and specifications defined by the Indiana Department of Transportation. The user interface allows users to select predefined check items based on to-be-inspected pay items, supported by a risk matrix. These check items contain various fixed characteristics of inspections, such as frequencies, objectives, checking conditions, and training documents.

The review demonstrated that ontologies are viable for formalizing construction domain knowledge. However, it also indicated insufficient effort is spent integrating diverse information sources and making inspection planning knowledge of multiple domains (e.g., trades) available. Additionally, the inspections are inadequately described and undefined in light of the shared terminologies provided by ISO 9000, ISO 9001, and DIN 55350. Research has also neglected inspection planning for finishing trades, specifically the thermal insulation trade. Therefore, this research paper aims to 1) prove the reliability of OCQA for multiple trades, 2) provide knowledge for inspection planning of the thermal insulation trade, and 3) integrate heterogeneous information defined in isolated systems related to thermal insulation inspection planning.

4. METHODOLOGY

Concerning OCQA, a hybrid approach was adopted based on the Linked Open Terms (LOT) methodology developed by Poveda et al. (2022). LOT was designed as an industry-oriented ontology development methodology more related to practical engineering cases than others and has been well evaluated through practical use. Furthermore, the activities in applying LOT are described in detail and documented on GitHub (Poveda-Villalón et al., 2022). The detailed process of the ontology's development methodology is illustrated in Figure 1. The process is divided into four phases: 1) specification, 2) implementation, 3) publication, and 4) maintenance.

The specification phase defines the ontology's scope, purpose, use cases, users, and requirements (Fernández-López, M. et al., 1997). Throughout the entire ontology engineering process, knowledge acquisition remains an ongoing and iterative process. Thus, a conceptualization is created, incorporating existing ontologies and encoding by building upon the specification. Subsequently, the developed ontology is evaluated to ensure its effectiveness.

Various evaluation methods are employed to assess the developed ontology. Following the evaluation phase, the ontology is documented using a Hypertext Markup Language (HTML) sheet. For wider accessibility, the ontology is published on GitHub, enabling a broad range of users and developers to access and reuse it.

GitHub is a valuable platform for ontology maintenance, facilitating collaboration and version control based on a repository (GitHub, 2020). It ensures the ontology remains up-to-date and well-maintained for its users and stakeholders. Thus, the following sections present the process steps of specification, implementation, and publication.

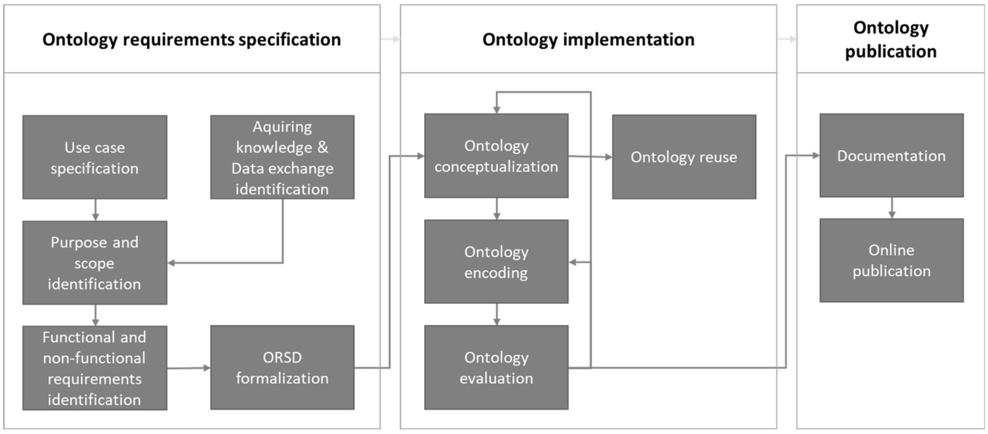

Fig. 1: Ontology development methodology according to Poveda-Villalón et al. (2022)

5. SPECIFICATION

This specification aims to create a formal document in natural language, utilizing competency questions (CQs) as the fundamental requirements (Fernández-López, M. et al., 1997). These CQs are derived from predefined use cases, aligning with the purpose and scope of the respective ontology. The resulting specification document is available on GitHub (Poveda-Villalón et al., 2022). The subsequent discussion formalizes the specification process steps.

Purpose: The ontology aims to formalize inspection plans for the domain of thermal insulation and related information of required domains, providing a shared representation of insulation inspection planning knowledge that specifies the terminology, semantics, and relations of inspection planning in the domain of thermal insulation. The terminology is defined according to DIN 55350:2021 and ISO 9000. Therefore, the purposes of the ontology can be summarized as follows:

1) providing a vocabulary for describing inspection plans and inspections for thermal insulation,
2) supporting manual inspection planning by providing detailed inspection planning knowledge,
3) supporting quality assurance decisions, and
4) strengthening the quality awareness of the staff.

Scope: OCQA-TI mainly focuses on representing the implementation of thermal insulation to ensure its proper installation and performance in new buildings and renovation. It provides structured knowledge on the optimal ways to install thermal insulation depending on the product and technique used while describing the necessary inspections, tests, equipment, and norms required to ensure its quality. Critically, our research focuses exclusively on process planning and the quality assurance of thermal insulation installation.

Use cases: The intended use cases of the ontology can be summarized as follows:

1) information retrieval by using queries,
2) heterogeneous data integration from isolated software solutions,
3) inspection planning support by querying inspection planning knowledge, and
4) inspection plan validation by reasoning.

End users: End users are project managers and management teams responsible for construction supervision, including inspectors, object planners, and building owners, depending on the project organization. In addition, the contractors can use the test plans provided for internal quality assurance. Notably, the users described do not use the ontology directly but interact with it via a software application. The ontology represents a substructure (backend) of software and is only used directly by developers (backend/substructure). Developers program software applications based on the ontology and store the data from heterogeneous sources in the ontology. End users use the ontology via an interface (superstructure or frontend) that ensures user-friendly operation (frontend/superstructure). For this purpose, users are provided with predefined queries for information or inspection planning knowledge retrieval.

Non-functional requirements (NFRs): NFRs pertain to how a system should perform, behave, and operate rather than focusing on what it should accomplish. In the field of construction ontologies, various studies have outlined NFRs, which can be summarized as follows: 1) coverage/sufficiency, 2) consistency, 3) usability, 4) extendibility/reusability, and 5) clarity and conciseness (Costin, A. and Eastman, C., 2017; Zhou et al., 2016; El-Gohary and El-Diraby, 2010; Zheng et al., 2021). These defined NFRs serve as evaluation criteria addressed through various evaluation methods.

Functional requirements (FRs): FRs are CQs aligned with the predefined use case of information retrieval. Table 1 provides a comprehensive list of the CQs that the proposed ontology aims to address based on questions for inspection planning from mechanical engineering that have been extended (Linß, 2018; Marxer et al., 2021).

Table 1: CQs related to the use case information retrieval.

Information retrieval
1. What are the characteristics being inspected?
2. What are the related entities of an inspection?
a. Where is the inspection location?
b. Who is responsible for the inspection?
c. What is the norm related to the inspection?
d. What equipment is required for the inspection?
3. What are the precedent and subsequent inspections?
4. What procedures are required for the inspection?
5. When is the start and end date of the inspection?

6. ONTOLOGY CONCEPTUALIZATION AND IMPLEMENTATION

6.1 Introducing the Ontology for Construction Quality Assurance (OCQA)

The basis for this work is the OCQA ontology (Seiß, 2022), designed to provide information about quality inspections in construction to support inspection planning. The main entities of the OCQA are the inspection, inspection plan, and regulations. The OCQA has a modular structure and can be supplemented as desired with inspection knowledge from different trades. Therefore, the OCQA-TI is designed as a trade-specific extension of the OCQA ontology. In addition, the Digital Construction Ontology (DiCon), with its previously described concepts for construction workflow, including agents, processes, and equipment, is integrated into the OCQA, extending the DiCon with detailed knowledge about inspection plans (Seiß, 2022).

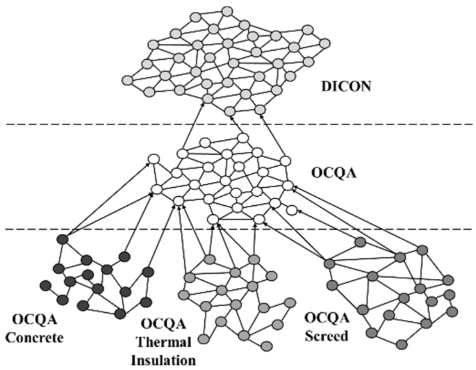

Fig.2: OCQA-TI as an extension of the OCQA

The integration among the various ontologies is depicted in Figure 2 and is achieved through hard reuse via owl:imports. This approach allows the complete and unaltered reuse of the imported ontology (Poveda-Villalón et al., 2022). The OCQA ontology also includes trade-specific modules catering to task-specific inspection planning. For instance, the OCQA-screed extension encompasses all inspections related to the screed trade. The OCQA-TI will be developed as a trade-specific extension of the OCQA.

6.2 OCQA – Thermal Insulation (OCQA-TI)

This section overviews the OCQA-TI and the associated ontologies in detail. Therefore, the classes, relations, and properties needed to describe inspections related to the domain of thermal insulation appear in Figure 3. The top of Figure 3 illustrates the DiCon ontology and the main classes used as a basis to define the OCQA. The OCQA provides the general terminology to describe inspections, which the OCQA-TI will use to specify inspections for the trade of thermal insulation.

Representing all aspects of the thermal insulation inspection was essential to conduct it, including the actual inspections, the corresponding inspection plan, inspection equipment, personnel involved, inspection procedures, and inspection regulations through specific classes within the DiCon and OCQA ontologies, defined as subclasses of the DiCon ontology. The *ocqa:Inspection* class is a specialized subclass of *dicp:Activity* class, highlighting its unique role in the context of activities defined by DiCon.

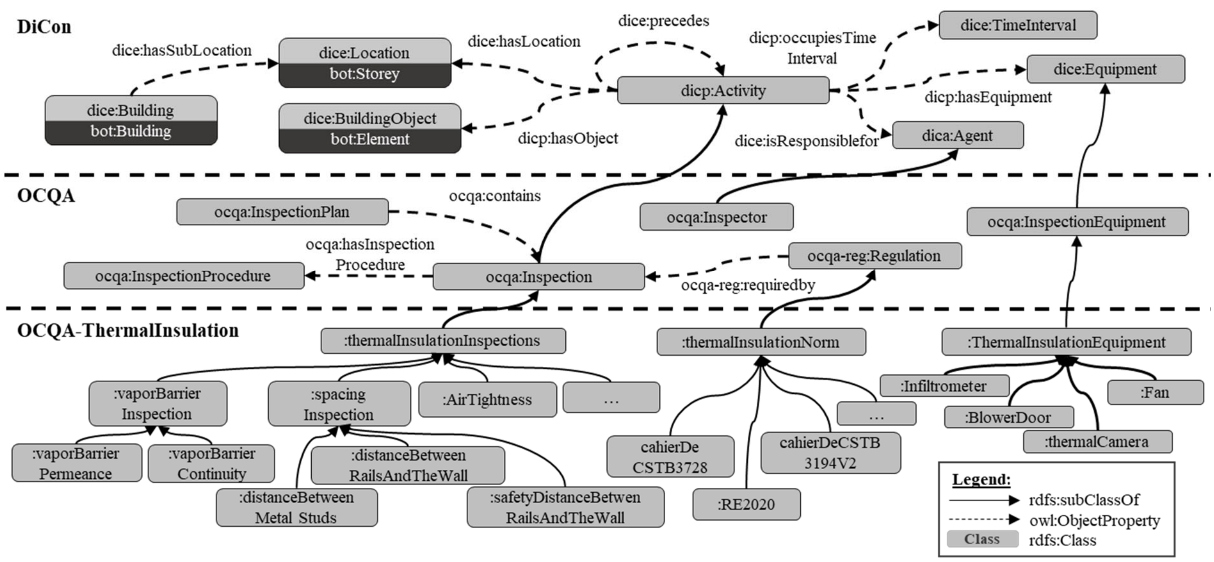

Fig. 3: Overview of classes, relations, and data properties of OCQA-TI and aligned ontologies.

The OCQA-TI is an ontology extension that enhances and refines the OCQA ontology, building on the DiCon ontology's foundational concepts. Within the OCQA-TI, the *:ThermalInsulationInspection* class represents various types of thermal insulation inspections like *:SpacingInspection*, *:AirTightnessInspection*, and *:VapourBarrierInspection* and is connected to the *ocqa:Inspection* class in the OCQA, signifying their specific role within the scope of quality inspections. Moreover, the *Inspection* class links to the *ocqa:InspectionPlan* class through the object property *ocqa:contains*, establishing a relationship between inspections and their inclusion in inspection plans. Additionally, *the ocqa:hasInspectionProcedure* object property connects the *ocqa:Inspection* class to the ocqa:InspectionProcedure class, specifying the procedures associated with each inspection. The *:ThermalInsulationNorm* class in the OCQA-TI, encompassing norms relevant to each thermal insulation inspection like RE2020, cahierDeCSTB3728, and cahierDeCSTB3194_V2 is introduced by the object property *ocqa-reg:requiredby,* which link this class to the *ocqa-regulation:Regulation* class.

Furthermore, the *:ThermalInspectionEquipement* class is introduced to describe the equipment required for thermal insulation inspections like *:ThermalCamera*, Infiltrometer, and *:BlowerDoor* and is directly linked to the *ocqa:InspectionEquipement* class in OCQA, which, in turn, is connected to the *dice:Equipment* class in the DiCon ontology, establishing a hierarchy of equipment concepts. Through these interconnected classes and object properties, the ontologies provide a comprehensive framework for managing and understanding thermal insulation inspections in the construction industry, utilizing construction quality assurance and workflows.

7. ONTOLOGY EVALUATION

The ontology evaluation is essential to check whether the developed ontology meets all the predefined requirements in the specification process (Fernández-López, M. et al., 1997). Different evaluation methods can be used to check compliance with different criteria (Zheng et al., 2021; El-Gohary and El-Diraby, 2010). This research evaluates the proposed OCQA-TI by automated consistency checking, CQs, and a task-based evaluation.

7.1 Automated Consistency Checking

Automated consistency checking aims to assess the developed ontology's consistency, guaranteeing no logical conflicts or inconsistencies. This process is achieved with description logic (DL) reasoners to assess the logical coherence of the ontology and maintain its integrity by ensuring there are no contradictions. Regarding the OCQA-TI, the automated consistency checking was conducted within the Protégé environment using the built-in Pellet reasoner. The automated consistency checking results showed that the OCQA-TI is consistent and coherent.

7.2 Answering the CQs and Task-Based Evaluation

We obtained practical inspection data from a residential building project about air tightness inspections, which are essential to ensure the condition of the air permeability before proceeding with the installation of thermal insulation. The assessment involved of implementing blower door tests while utilizing an infiltrometer as the specialized equipment to measure the value of the air permeability. The blower door tests were aligned with the stipulated guidelines of the RE2020 regulations, in which an air permeability constraint requires the measured value should be less than 0.6m3/(h.m3) for individual building types and 1m3/(h.m3) for residential building types.

The above example data was mapped and instantiated to OCQA-TI for two evaluation tasks. First, we used the instance data for answering the specified CQs. For the OCQA-TI, a SPARQL query was conducted to retrieve the target information of the thermal insulation inspection task to answer the example-specified CQs adapted from ontology CQs defined previously to check the coverage of the ontology. The CQs and results appear in Table 2. The results show that the OCQA-TI can retrieve accurate inspection information to answer the CQs, proving that OCQA-TI satisfies the ontology coverage criteria.

Second, based on the obtained data, we conducted a task-based evaluation to assess the usability of the proposed OCQA-TI ontology to solve a particular task. In this case, we conducted a use case to check if the measured air permeability values satisfied the RE2020 constraint. A SPARQL was conducted to identify the location where the air permeability value did not fit the constraint to provide the site manager with useful information to support awareness of the site condition and take actions to solve issues that occurred to ensure the upcoming tasks. The SPARQL query and result appear in Table 3. The result shows that the air permeability value in Zone B was 1.2, exceeding the maximum value in RE2020. Thus, the site manager should consider reducing the air permeability in Zone B to ensure the following insulation installation work. In summary of the task-based evaluation, the OCQA-TI can be used to check the inspection with the compliance of constraints from the norms.

Table 2: Specified CQs and answers based on the task of the blower door test.

Information retrieval	**Answer**
1. What are the characteristics being inspected by inspection :*Test001*?	*:AirPermeability _7832-3783-173*
2. What are related entities of an inspection?	
a. Where is the location of an inspection?	*:ZoneA*
b. Who is responsible for the inspection?	*:Inspector_XYZ*
c. What is the norm related to the inspection?	*:RE2020*
d. What equipment is required for an inspection?	*:NQ80YU64K*
3. What are following/precedence inspections of an inspection?	:*Test002*
4. Which procedure is required for an inspection?	*:BlowerDoorTest*
5. When is the start and end date of the inspection?	Start: *:04072023-1* End: *:04072023-2*

Table 3: SPARQL query and the result of air permeability constraint checking.

SPARQL query

```
SELECT ?test ?location ?value ?characteristic
WHERE {
  ?inspection a ocqa:Inspection .
  ?inspection ocqa:hasSubInspection ?test .
  ?test dicp:hasLocation ?location .
  ?location :hasAirPermeability ?characteristic .
  ?characteristic ocqa:hasAssignedCharacteristicValue ?AssignedCV .
  ?AssignedCV :maxvalue ?maxvalue .
  ?characteristic ocqa:hasActualCharacteristicValue ?ActualCV .
  ?ActualCV :value ?value .
  FILTER (?value > ?maxvalue)
}
```

Result illustrated in GraphDB

	test	location	value	characteristic
1	:Test002	:ZoneB	"1.2"^^xsd:double	:AirPermeability_7832-3783-174

8. CONCLUSION

In conclusion, poor construction quality remains a significant challenge in the construction industry, leading to increased costs and avoidable damage. Therefore, this paper proposed an innovative solution by developing the OCQA-TI. This ontology extension was designed to tackle the complexities of inspection planning and evaluation in thermal insulation and enhance the overall quality assurance process.

The research successfully extended the OCQA to incorporate thermal insulation, allowing for the description of insulation inspections and finishing trades. By bridging the gap between required and actual inspections on construction sites, the ontology provided proper knowledge, semantics, and terminology specific to thermal insulation, supporting inspectors and project teams in making informed decisions during an inspection. Additionally, the ontology facilitated gathering and integrating heterogeneous data from various software applications, promoting the traceability of information between systems. It also offered a practical solution for handling conflicting product guidelines, allowing references to guidelines instead of norms, thereby ensuring dual compliance with specific product requirements and regulatory norms.

This ontology development is expected to significantly improve construction site quality by enabling proactive defect prevention and enhancing the efficiency of inspection planning. With comprehensive and project-specific inspection plans readily available, construction teams can reduce the impact of work by better adhering to the inspection plans and rectifying any issues promptly. However, while the OCQA-TI ontology presents a valuable contribution, no ontology can be considered the definitive or best solution. As construction practices, regulations, and technologies evolve, continual improvement and updating of the ontology will be necessary to maintain its effectiveness.

Admittedly, there are several limitations of this study which are summarized as follows. First, the proposed ontology-based approach of thermal insulation inspection planning relies on the construction domain knowledge such as norms, standards, and production codes, which may be different in different regions or countries. For example, in this research, we adopt RE2020 to model the constraints, which is the French regulation that may not be applied to other countries. Therefore, to improve the usage of OCQA-TI globally, further efforts are needed to collect more international domain knowledge into the ontology. However, it is difficult to achieve by a single research team. Thus, in the future, we are aiming to provide a shared knowledge platform based on the OCQA-TI to collect more comprehensive knowledge for inspection by interaction and collaboration of users in different countries. Second, ontology needs to be continuously updated and maintained corresponding to changes of the domain knowledge and accommodating new inspection procedures, equipment, and reference values. Third, the ontology has not been fully applied or utilized on construction sites. Therefore, future research may expand the ontology to cover additional construction trades, enabling a comprehensive and interconnected quality assurance framework for various construction activities. Moreover, investigating automated inspection planning for the OCQA-TI using rule languages or other advanced technologies could further enhance the ontology's usability and efficiency. Additionally, there is the challenge of testing these technologies on a construction site in a real-world context, while also considering the socio-economic implications for construction workers and inspectors.

Overall, the OCQA-TI ontology offers a knowledge-driven approach to thermal insulation inspection planning, promoting enhanced information retrieval and data integration while supporting quality assurance decisions. By enabling early defect detection and addressing implementation issues, the ontology contributes to improved energy efficiency, interior comfort, and reduced building maintenance costs. As the construction industry continues to evolve, adopting such knowledge-driven approaches is crucial for ensuring safer, more durable, and energy-efficient buildings in the future.

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