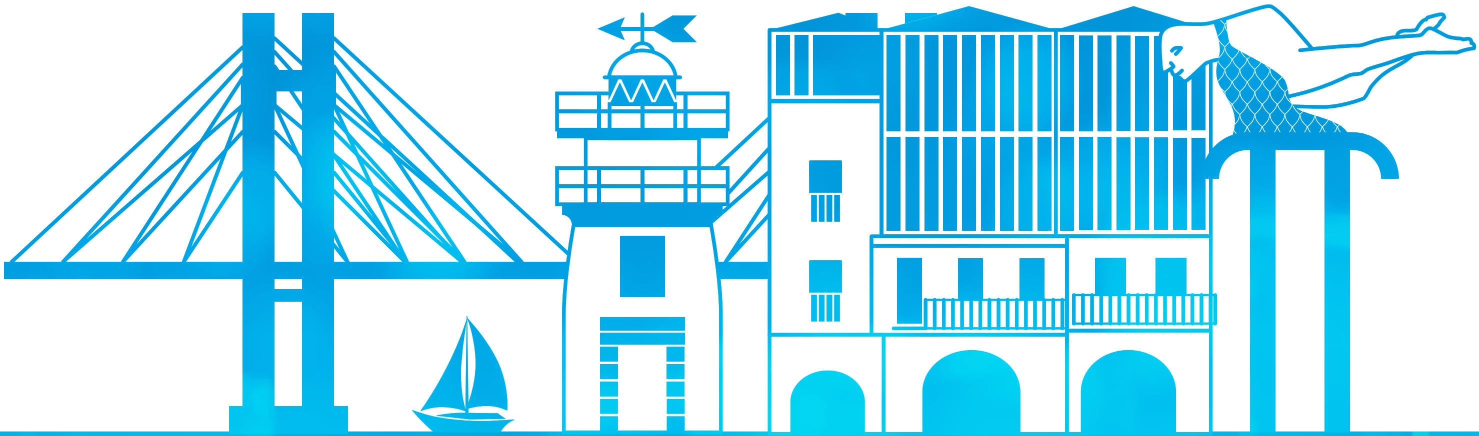

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Semantic Web-Based Risk Management System for Enhanced Construction Quality

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Abstract. Building construction constitutes a specialized and project-specific procedure, encompassing numerous risks. Specifically, the risks related to execution and the associated costs of defects are a constant challenge for the architectural engineering and construction (AEC) industry. To achieve a balance between the optimum level of quality and the associated costs, knowledge of the composition of quality-related costs is required. In this paper, the objective is to automatically determine expected appraisal and nonconformity costs from BIM objects by using semantic web tech-nologies. The ontology for construction quality assurance (OCQA), which is used for the automated planning of quality inspections serves as the initial ontology in this paper. Based on model data, historical quality data, and potential nonconformity costs, the expected quality defects will be deter-mined and automatically evaluated by using Shapes Constraint Language (SHACL) rules. The func-tionality of the ontology and its rules is demonstrated by defect type unevenness of screed.

1. Introduction

A defect represents a risk that can lead to construction delays and entail monetary consequences in the form of nonconformity costs (NCC). The cost of rectifying defective work amounted to 14.0 billion euros in Germany (BauInfoConsult, 2023). In relation to the construction industry's total turnover of 144.8 billion euros (ZDB, 2023), rectifying defects, therefore, accounted for around 9.7% of the industry's turnover. Modern quality management systems (QMS) must utilize all available quality data to detect potential defects early and initiate preventive measures. In the AEC industry, quality inspections serve as suitable means for reducing and preventing execution defects (Yuan et al., 2018). However, a quality inspection should only be carried out if the inspection is mandatory or if appraisal costs (AC) are proportional to the impending NCC (Shafiei et al., 2023). Therefore, estimating of both cost parameters is required to guarantee an objective comparison. The cost estimation requires knowledge of quality inspection planning and execution, as well as the composition of quality-related costs. With ontology for construction quality assurance (OCQA) (Seiß, 2022) and OCQA-AC (Seiß et al., 2023), a Linked Open Data (LOD) approach for automated quality inspection planning and cost estimation is already existing. This contribution presents the OCQA-Risk, an extension of OCQA designed to represent and estimate NCCs, as well as quality-related risks. The provided cost and risk parameters demonstrate the cost-effectiveness of quality inspections and can be used as a decision model for inspection planners.

This paper aims to answer the following research questions: 1) How can semantic web technologies predict expected NCC? 2) Can the knowledge about the composition of NCC and AC be standardized by SHACL rules? 3) Can SHACL rules determine the component risk from the probability of occurrence and consequence? By answering these research questions, the long-term aim is to improve construction quality and reduce construction process disruptions. With the expansion of the OCQA, knowledge about the composition of inspection and NCC as well as the assessment of quality risks is to be made available online. The publication of the ontology on GitHub enables the user-specific reuse of the modelled knowledge.

The paper is structured as follows: Section 2 presents the basics of construction quality, construction defects, and risk management and draws on international literature as well as applicable standards such as DIN 55350, ISO 31000, and ISO 9000. Section 3 shows existing ontology applications on the topics of construction quality and risk management. Section 4 describes the methodology for extending the OCQA. Section 5 deals with the conceptual design and subsequent implementation of the ontology. To check the fulfillment of user requirements and the general applicability of the extension, Section 6 validates the extension by using the example defect type unevenness of screed. Finally, Section 7 concludes with a presentation of limitations and a summary of the results.

2. Fundamentals of Construction Quality Management

QMS should identify the processes and resources required to achieve the desired results and qualities (ISO 9000, 2015). Applied to the construction industry, QMS are intended to guarantee the contractually agreed quality of execution. Due to project-specific service descriptions and changing contract components, quality agreements vary from project to project. The quality requirements applicable to the construction project are defined as quality objectives as part of the quality planning process (ISO 9000, 2015). The generally accepted codes of practice provide a minimum standard for architects, civil engineers, surveyors, contractors, and tradesmen in planning and execution. A rule is considered accepted if it exists, is scientifically and theoretically correct, and has been proven in practice (Hankammer, 2007).

2.1 Construction Defects as Risks

The achievement of the set quality objectives is the result of internal and external factors. ISO 31000 describes the "*effect of uncertainty on objectives*" as a risk. Applied to quality management (QM), the "*non-fulfilment of a requirement*" (nonconformity, also known as a defect) represents a quality risk according to Qing et al., 2014. If the intended or specified use is not possible as a result of the quality deviation, it is a defect (ISO 9000, 2015). The risk consequences of defective work are NCC from rework, repair, scrapping, disposal, handling of rejects, unplanned sorting tests, repeat tests, downtime, warranties, and product liability (DIN 55350, 2021). In addition to economic damage, errors and defects in the AEC sector disrupt construction processes, waste environmental resources, and damage the company's image.

According to ISO 9000, inspections are used to determine conformity. Quality inspections according to DIN 55350 extend the understanding of inspections to include the verification of conformity with generally accepted or binding requirements and expectations. Depending on the result, quality inspections can therefore be used for verification purposes as well as to prove nonconformity. According to Qing et al., 2014, inspections are therefore a suitable measure to limit quality risks. To ensure completeness and cost-effectiveness, QM must create an inspection plan as part of the inspection planning process, which contains information about the inspection object and the definition of the inspection technology, -activities, and -processes (DIN 55350, 2021). The sequence of tests is defined in the associated inspection specifications, -instructions, and -schedules. The inspection plan aims to ensure compliance with the defined object and process qualities, considering economic aspects (DIN 55350, 2021). According to Eilers et al., 2020, a good third of construction companies rely solely on the experience of their employees rather than on detailed inspection planning. Since decision-makers never act in a risk-neutral manner, this behavior is inefficient in the long run.

2.2 Quality Risk Management Integration

According to ISO 9000, QMS must be able to identify risks and opportunities. Integrating risk management into QM aims to improve construction quality, minimize resource consumption, and reduce accidents and delays caused by construction quality. Instead of an uncoordinated approach to risks and uncertainties, the application of opportunity and risk management leads to coordinated risk control processes in an organization (ISO 31000, 2018).

Formula 1: Estimation of Monetary Risk Value in Accordance with ISO 31000, 2018

$$risk = probability\ of\ occurrence * consequence$$

In the AEC industry, the application of Formula 1 represents a possibility for quantitative risk assessment. Applied to QM in the AEC industry, Hankammer, 2007 explains the formula using the example of the production of an exposed concrete wall. In the production of 10 concrete walls, the probability of damage occurring is 10% according to historical values. The cost of repairing the damage (consequence) is estimated at €10,000. Based on the equation, the risk of producing 10 exposed concrete walls is €1,000 (= €10.000 * 0.1). According to Formula 1, the probability of occurrence and consequence are mutually dependent for determining a risk. The equation shows that a scenario with a low probability of occurrence and high damage has an identical risk value as a scenario with a high probability of occurrence and low damage.

2.3 Estimation of Expected Nonconformity Costs

In this paper, the consequence of a risk is derived from the expected NCC of a component. According to Linß and Linß, 2023, NCC occur when products or services do not meet the defined quality specifications. According to Bruhn, 2013, the resulting costs can be divided into costs for the legal correction of defects (direct costs) and costs resulting from the defect (indirect costs). An overview of these costs is given in Table 1.

Table 1: Selected Cost Components of Direct and Indirect Nonconformity Costs

Direct Nonconformity Costs (Hankammer, 2007)	**Indirect Nonconformity Costs (Hankammer, 2007 / Linß and Linß, 2023)**
Cost of subsequent	Legal costs
Damage compensation costs	Contractual penalties
Cost of self-redemption	Costs from repeat inspection
Reduction costs	Disposal costs
	Costs from additional planning

According to Shafiei et al., 2023, quality-related costs are difficult to estimate in terms of their magnitude and interdependence, as they occur across all areas and activities. Accordingly, DIN 55350 recommends structuring the recording of these costs in an organization according to specific criteria. Linß and Linß, 2023 point out that precise cost estimation is not absolutely necessary, as general methods are sufficient to identify trends. To simplify the cost estimation, the approach of Rauh et al., 2014 is used, which estimates the average direct nonconformity cost (NCC) of building construction projects at 10 to 15% of the original production cost. Indirect costs and other consequences of construction defects are not considered in this paper due to difficulties in quantification.

3. Related Works

Ontologies can formalize and link knowledge from different domains and reuse it in domain-specific ontologies. Through a semantic representation, ontologies are an efficient tool for networking heterogeneous knowledge by defining concepts, relationships, and axioms that allow queries and inferences under different conditions. Existing interoperability problems between AEC stakeholders can thus be reduced (Lee et al., 2016). This section presents previous research in Table 2 that focuses on quality assurance in the field of Building Information Modelling (BIM), construction quality ontologies, and QM risk ontologies.

Table 2: Overview of Previous Work for Quality Risk Management

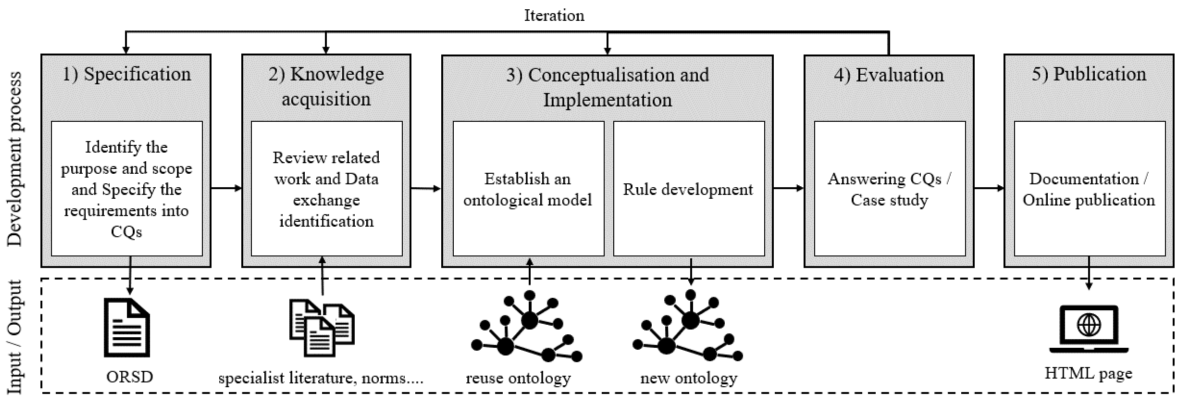
Ontologies	**Application**	**Information sources**	**Limitation**
C3R²-Ontology (Yurchyshyna et al., 2008)	none	Design information based on BIM	Use case-specific on compliance checking; missing construction process, regulation, and organizational information; missing risk management;
CQIE Ontology (Zhong et al., 2012)	Inspection-Item-Checking-Action, Inspection-Task, Inspection-Object,	Design, construction process, regulation, and organizational information	Use case-specific on regulatory compliance checking; custom terminology; monolithic ontology; BIM-based design information;
Lee et al., 2016	Defect classification, Component-related assignment	Design information based on BIM, manual Input of defect data	Use case-specific on defect ontology for systematic and standardized recording of construction defects; missing probability of occurrence
Ding et al., 2016	Reuse of construction risk knowledge	Design information based on BIM	Use case-specific on dynamic linking of BIM objects with common construction risks; missing probability of occurrence, NCC and inspection assignment
Martinez et al., 2019	Material Testing, Element Inspection, Finishing (aesthetic inspection)	Design information based on BIM and manufacturing process information	Specialized for manufacturing inspections of steel frames used in drywalls; focused and purpose-specific inspection planning; tailored terminology
Damage Topology Ontology (DOT) (Hamdan et al., 2021)	Classification of structural damage	Damage-related documentation	Use case-specific on generic damage modelling approach for topological damage classification; missing probability of occurrence, NCC and inspection assignment

The studies conducted have highlighted the potential benefits of an ontology-based approach for decision models in inspection planning. However, there are some limitations that make it difficult to use ontologies to predict risk impacts in terms of expected damage costs. Nowadays, neither research nor industry has widely adapted or implemented the ontologies presented. Furthermore, most of these ontologies do not comply with the standards of DIN 55350, ISO 9000, and ISO 31000, and an extension of the existing ontologies is not feasible because most ontologies are not available online. The current study aims to develop a set of higher-level ontologies. These ontologies should (1) map CW data in detail and link activities and flow entities, (2) integrate heterogeneous, flow-related information sources from ICT-based systems, and (3) represent cross-context data.

4. Methodology

The methodology of the underlying ontology is employed to ensure the consistency of the ontology extension. The OCQA utilizes a hybrid model that combines the Linked Open Terms (LOT) method (Poveda-Villalón et al., 2022), the METHONTOLOGY approach (Fernández-López et al., 1997), and the TOVE methodology (Grüninger, M. and Fox, M., 1995). The individual steps of the methodology are presented in Figure 1.

Figure 1: Ontology Development/Engineering Methodology



<u>1) Specification:</u> At the beginning of ontology development, the intended use and the end user must be defined. According to Figure 1, the result of the specification is an Ontology Requirements Specification Document (ORSD), which answers the requirements for the ontology in a natural language in the form of competency questions (CQ) (Fernández-López et al., 1997). In this context, CQs are used to define use cases based on the previously defined purpose and scope (Grüninger, M. and Fox, M., 1995).

<u>2) Knowledge acquisition:</u> Knowledge acquisition is an independent, continuous, and iterative process throughout the ontology development process. Expert interviews, books, figures, tables, previous ontologies, and other sources of knowledge are used to acquire the necessary foundations (Fernández-López et al., 1997). The process starts at the beginning of the specification and reduces in scope as the development phase progresses.

<u>3) Conceptualization and implementation:</u> The previously derived domain knowledge is processed in a structured way within the conceptualization process. The result is a conceptual model that theoretically describes the concepts, instances, verbs, and properties (Fernández-López et al., 1997). During conceptualization, available ontological resources must be reused for problem-solving (Suárez-Figueroa et al., 2015). In addition to the formalization of knowledge, the development of SHACL rules is required to define the permissible relationships between properties (Knublauch, H. and Kontokostas, D., 2017).

<u>4) Evaluation:</u> According to Suárez-Figueroa et al., 2013, validations are necessary to verify the fulfillment of user requirements and to assess effectiveness and completeness. El-Gohary and El-Diraby, 2010, distinguish between technical validation by the developer and user validation. The technical validation checks the correct implementation, while the user evaluation checks compliance with the requirements of the ORSD (Poveda-Villalón et al., 2022).

<u>5) Publication:</u> To facilitate reuse, the ontology will be made available as a machine-readable file via its URI on GitHub. In addition to the code, the ORSD document and a textual description of the ontology are included to make it available for reuse in line with the open-source approach (Poveda-Villalón et al., 2022).

5. OCQA Risk

According to Lee et al., 2016, errors and defects have a repetitive nature. Consequently, insights for construction QM can be derived from historical quality data. Processing and analyzing large amounts of data requires a logic that 1) identifies potential errors and construction defects, 2) assesses the resulting risk, and 3) creates an inspection plan considering project-specific risks. To achieve this goal, this article introduces OCQA-Risk, a decision model discussed in detail in the following sections.

5.1 Specification

Purpose: The ontology aims to digital plan project and company-related quality inspections, considering historical construction defects. Instead of using standardized checklists, the ontology identifies potential construction defects and plans the appropriate quality inspection to prevent them. The ontology thus provides a decision model for inspection engineers by comparing the expected NCCs with ACs. In addition to demonstrating the cost-effectiveness of an inspection, the ontology is intended to increase the quality awareness of employees by revealing the impending NCCs.

Users: The users of the ontology are derived from the purpose of the ontology. Those are involved in construction management, and in particular, site managers and quality assessors, have been identified as the target group. Performers who are not part of site management are not part of the OCQA-Risk target group.

Functional Requirements: The functional requirements are described as CQs according to the previously defined use cases. The following CQs are to be answered with the proposed ontology:

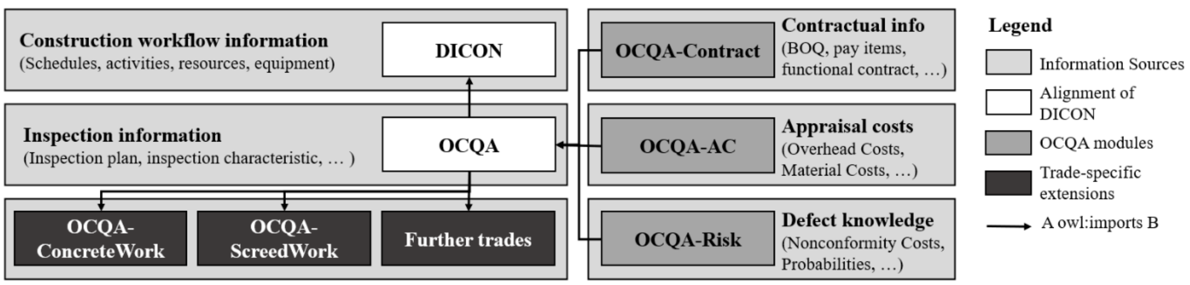
1.) What potential nonconformity can be associated with a component and what is the probability of its occurrence?

2.) Are ACs used to identify the deficiency appropriately in relation to the potential NCCs?

5.2 Conceptualization and Implementation

According to Figure 2, the developed OCQA-Risk ontology extends the OCQA ontology to provide information about quality inspections in construction and supports the planning of inspections. OCQA already defines entities and properties for construction QM. SHACL rules are used to automatically derive and plan the necessary inspections from standards, legal requirements, and project-specific requirements. The OCQA is an extension of the DiCon ontology and provides fundamental concepts for construction workflows, including agents, processes, and equipment (Zheng et al., 2021).

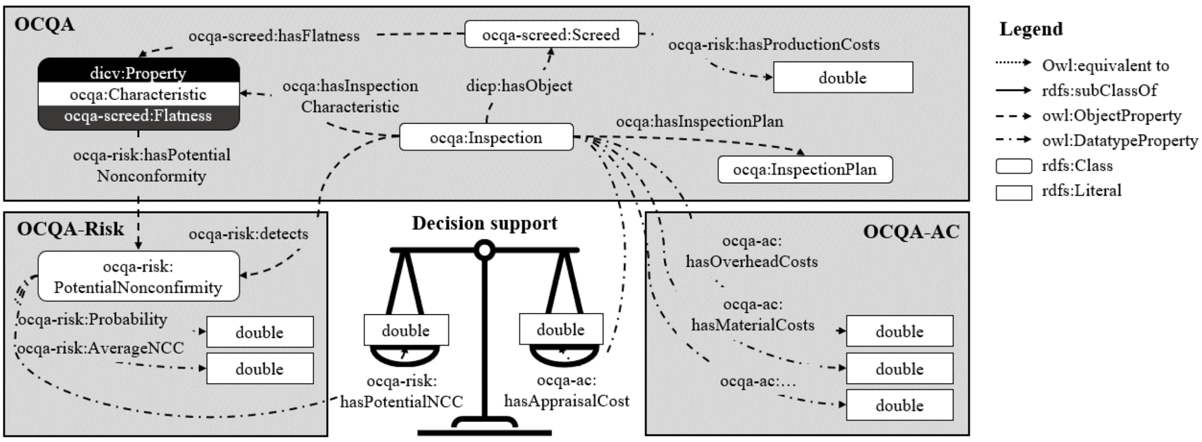
Figure 2: OCQA-Risk as an extension/alignment/reuse of the OCQA and DiCon ontology



The classes, relations, and properties shown in Figure 3 are essential for the estimation of NCC. Within the OCQA risk ontology, causality relationships between construction activities and defect types were represented by the class *ocqa-risk:PotentialNonConfirmity*. According to Lee et al., 2016, knowledge about potential component-related defects can be derived from historically recorded construction defects. Formula 1, which considers both the probability and consequence of a defect, is used to estimate the potential damage value. In accordance with section 2.3, the calculation approach of Rauh et al., 2014 is applied, which estimates the average NCC at 10-15% of the construction costs. The imminent NCC is described with *ocqa-risk:AverageNCC* and the probability of occurrence with *ocqa-risk:Probability*. Based on the production costs, which are recorded by *ocqa-risk:hasProductionCosts*, the anticipated costs to rectify the defect can be calculated.

To facilitate the identification of construction defects at an early stage, a relationship between the *ocqa-risk:detects* and *ocqa-risk:PotentialNonconfirmity* ontological classes was added. The *ocqa:Inspection* class is a subclass of the *dicp:Activity* class. The cost types associated with the inspection are stored in the OCQA-AC data catalog. This enables a comparison of the expected ACs with the potential NCCs.

Figure 3: Overview of Classes, Relations, and Data Properties of OCQA-Risk and Aligned Ontologies



6. Evaluation

This section assesses the OCQA risk and details the methods and results used to verify compliance with the functional requirements. The use of CQs allows for the assessment of the coverage of the ontology, while tasks are used to assess the usability of the ontology in specific use cases based on the intended purpose. The combination of both approaches enables a more comprehensive assessment of the strengths and weaknesses of the OCQA, which can in turn lead to a more effective and robust ontology.

To ensure a comprehensive and meaningful evaluation, screed was chosen as the case study. The choice of screed as a case study is based on its crucial importance in the construction process. The case study is based on real project data provided by DERICHS and KONERTZ (DEKO). In the initial phase, the project data provided is transferred and integrated into the instance data of the OCQA for the task-oriented evaluation, including the CQs. Stardog Designer is used to import, transform and map the instance data to OCQA. This evaluation is divided into two use cases. Firstly, the derivation of potential nonconformities and the resulting NCC is demonstrated using the instance data provided from the case study. Then, the query of the derived error, evaluation, and error cost information for a specific inspection is shown.

In Listing 1, the potential risk of nonconformity is determined for screed. First, the rule selects all instances of the class *ocqa:Characteristic* (line 4). Secondly, it checks whether the selected instances have the characteristic *ocqa-screed:hasFlatness* and whether this is linked to the class *ocqa-screed:Screed* (lines 6 to 11). If this condition is met, a new instance of class *ocqa-risk:hasPotentialNonConfirmity* is created using a SPARQL construct statement and is then linked to the characteristic. In a next step, this newly created *ocqa-risk:PotentialNonConfirmity* is assigned to the *ocqa-risk:Uneveness* class and associated with the corresponding inspection *ocqa:hasInspectionCharacteristic* (lines 15 to 17). Finally, the average NCC is estimated by multiplying *ocqa-risk:hasProductionCost* of the screed by the expected *ocqa-risk:hasAverageNCC* in amount of 10% according to Rauh et al., 2014 (lines 19 and 24).

Listing 1: SHACL Statements to Infer Potential Nonconformity and NCC (CQ1)

```
1.     [Prefixes]
2.     ocqa-screed:NonConfirmityShapeScreed
3.      a sh:NodeShape ;
4.      sh:targetClass ocqa:Characteristic;
5.      sh:rule [
6.          a sh:SPARQLRule ;
7.             sh:condition[
8.              sh:property [
9.                  sh:path (sh:inversePath ocqa-screed:hasFlatness);
10.                 sh:class ocqa-screed:Screed
11.                         ];];
12.                 sh:construct """
13.             [Prefixes]
14.             CONSTRUCT{
15.             $this ocqa-risk:hasPotentialNonConfirmity ?PotentialNonConfirmity.
16.             ?PotentialNonConfirmity a ocqa-risk:Uneveness;
17.             a ocqa-risk:PotentialNonConfirmity.
18.             ?Inspection ocqa-risk:detects ?PotentialNonConfirmity.
19.             ?PotentialNonConfirmity ocqa-risk:AverageNCC ?averageNCC.
20.             }
21.             WHERE{
22.             $this   ^ocqa:hasInspectionCharacteristic ?Inspection;
23.             ^ocqa-screed:hasFlatness/ocqa-risk:hasProductionCost ?ProductionCostScreed.
24.             BIND ((?ProductionCostScreed * 0.1) AS ?averageNCC).
25.             }""";
26.      ].
```

The SPARQL query presented in Listing 2 illustrates a decision support model that compares the *ocqa-ac:hasAppraisalCost* with the monetary risk value *ocqa-risk:hasPotentialNCC*. The risk value is comprised of the *ocqa-risk:hasAverageNCC* of a nonconformity and its probability of occurrence, represented by *ocqa-risk:hasProbability*. In the event that the assessment costs exceed the calculated risk value, it is recommended to refrain from an inspection ("INSPECTION IS NOT RECOMMENDED"). If the assessment costs are lower, an inspection is deemed appropriate.

Listing 2: SPARQL Statement to Retrieve the Potential Failure as well as Appraisal - and NCC for Evaluating the Economic Viability (CQ2)

```
[Prefixes]
SELECT ?PotentialNonConfirmity IF(?AppraisalCost > (?AverageNCC * ? Probability * ?Produc-
tionCost AS ?MonetaryRiskValue),"INSPECTION IS NOT RECOMMMENDED","INSPECTION
RECOMMMENDED") AS ?DecisionSupport
   WHERE {ocqa-screed:42015 ocqa-risk:detects ?PotentialNonConfirmity;
          ocqa-ac:hasAppraisalCost ?AppraisalCost.
          ?PotentialNonConfirmity  ocqa-risk:hasAverageNCC ?AverageNCC;
          ocqa-risk:hasProbability ?Probability;
          ^ocqa-risk:hasPotentialNonConfirmity/^ocqa-screed:hasFlatness/ocqa-risk:hasPro-
ductionCosts ?ProductionCost
}
```

7. Conclusion

The method describes the monetary valuation of risk costs represents as a novel approach to risk assessment within the construction industry. By analyzing historical construction failures, valuable lessons can be learned for new construction projects. The work presented demonstrates an innovative technological implementation of this evaluation method, thereby facilitating its application within the construction industry.

The estimation of potential NCC in this paper follows a simplified procedure. A comprehensive assessment of construction defects should also consider indirect consequences such as disruption to the construction process, waste of resources, and damage to reputation. A rough cost estimate is sufficient, comparing of NCCs with ACs illustrates the cost-effectiveness of inspections. This comparison allows unprofitable inspections to be avoided and components with an unfavorable NCC/AC ratio to be excluded. However, an evaluation based on a comprehensive prototype and analysis of its application in a real project is still lacking. In addition, the evaluation is currently limited to the screed trade and should be extended to other areas of the construction industry in further studies.

By using OCQA-AC, a cost balance between accepted and NCC is achieved. In addition, OCQA facilitates the integration of different types of data and emphasizes the importance of reusing ontology models at a higher level to effectively represent and link information. Finally, OCQA-Risk promotes collaboration between project stakeholders, supports the development of new web applications for inspection planning, and provides comprehensive documentation capabilities for future research and applications.

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