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DEVELOPING QUALITY LINKED-DATA AND PROCESS PATTERNS IN DIGITAL TWINS FOR ITERATIVE DEFECT TRIGGER IDENTIFICATION

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Abstract

Digital twins are increasingly applied in the construction industry. Utilizing real-time, structured data from digital twins for quality control remains a critical challenge. This paper defines the evolution mechanisms of defect triggers through a literature review. The quality linked-data is designed by using Resource Description Framework and related technical concepts to transform multi-source heterogeneous data into structured linked-data. A workflow with process patterns for defect trigger identification is developed to invoke the quality linked-data. The framework is validated with the reinforcement cage length deviation in cast-in-place piles. This work provides theoretical insights for automated defect trigger identification with digital twins.

Introduction

The construction industry is undergoing a rapid transformation toward digitalization and intelligence. China introduced the "14th Five-Year Plan for Intelligent Construction Development" [1], and Germany released "Construction 4.0 – The Digital Transformation of the Construction Industry" [2]. Both plans emphasize the promotion and application of intelligent construction technologies, such as Building Information Modeling (BIM) and Digital Twins. The digital twin is defined as a virtual model established using digital technologies to simulate, monitor, and analyze the real-time status of corresponding physical objects, systems, or processes in the physical world (Opoku et al., 2021). Digital twins provide robust digital support for construction, maintenance, and operational management in the construction industry (Liu et al., 2024; Ozturk, 2021).

Although quality management has been implemented as an essential component of construction project management, quality issues remain prevalent in the construction industry. The root causes lie in the multiple stages of construction projects, the involvement of numerous stakeholders, the complexity of processes, and the frequent occurrence of overlapping tasks (Wang et al., 2024). The construction industry currently emphasizes controlling the sources of major quality risks as the primary approach to addressing quality issues. However, quality problems, such as quality defects, are inherently linked to specific triggering factors (Forcada et al., 2014). The triggering factors of quality issues remain insufficiently defined, leading to a limited understanding of the processes underlying their formation and evolution. Therefore, the construction industry cannot implement targeted and effective quality control measures.

In construction industry, managing multi-source heterogeneous data sources is another critical challenge. Resource Description Framework (RDF) offers a solution by representing data as "subject, predicate, and object" triple structure. The RDF is a technical specification proposed by the World Wide Web Consortium (W3C) for data presentation on the semantic web. RDF has been widely applied and extensively studied in multiple domains, including the knowledge graphs, data integration, and spatiotemporal data management (Zhang et al., 2021). Combined with technologies like Semantic Web Rule Language (SWRL) and SPARQL Protocol and RDF Query Language (SPARQL), it enables inference of potential triples data and fast querying of RDF data (Pauwels & Zhang, 2015). Combined with Shapes Constraint Language (SHACL), RDF enables consistency validation of RDF data structures. The research by Pauwels et al. (2024) achieves the semantic interpretation of BIM data for automating regulatory compliance check and performance evaluation.

Based on the current background and challenges, this study defines the quality defect trigger leading to quality defects through a literature review and systematically analyzes the mechanisms driving the evolution of quality issues. By utilizing linked-data technology, a quality defect trigger identification framework is developed to integrate multi-source heterogeneous quality data.

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[1] https://www.gov.cn/zhengce/zhengceku/2022-01/27/5670687/files/12d50c613b344165afb21bc596a190fc.pdf

[2] https://baublatt.de/baubranche-4-0/

Furthermore, the validity of this study is demonstrated through the reinforcement cage length deviation in cast-in-place piles.

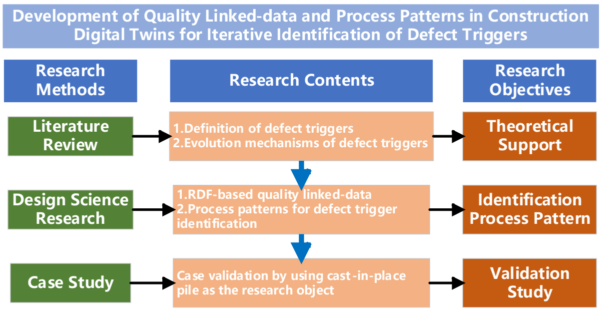


Figure 1: The research technical approaches

The evolution mechanisms of quality defect triggers

The frequent occurrence of quality issues is mainly due to the lack of a clear understanding of their formation mechanisms. Therefore, it is essential to define the relevant concepts of quality issues.

Definitions of quality issues

- Quality accidents

Quality accident refers to an unexpected event in which a product fails to meet the required standards of functionality and usage, resulting in economic loss, personal injury, or other forms of financial damage. Quality accidents may be precipitated by superficial causes such as the low quality of construction materials or the instability of construction machinery (Carrillo-Castrillo et al., 2017). Additionally, they can also be triggered by deeper systemic issues, including excessive project schedule pressures or an irrational organizational structure of the project (Cui, 2011).

- Quality defects

According to the Chinese construction industry specification “Code for Construction Quality Acceptance of Concrete Structures"(GB50204-2015), the quality defect refers to a situation where the construction quality of a building project does not meet the mandatory standards for construction and the inspection items specified in the contract. Quality defects can be categorized into severe defects and general defects based on their severity. The severity is assessed by determining whether the defect has a decisive impact on the building's structural performance, durability, and functional usability. Quality defects differ from quality accidents in that minor defects may still pass acceptance, while quality accidents are intolerable in any construction project. Severe defects can lead to quality accidents under certain circumstances.

- Quality defect triggers

The formation of quality defects is complex, with studies often classifying causes into direct causes and root causes (Josephson & Hammarlund, 1999) or endogenous factors and exogenous factors (Lambers et al., 2023). A useful framework is the Swiss Cheese Model, which identifies four dimensions of defect formation: organizational influence, defective supervision, preconditions for defective acts, and the defective acts themselves (Aljassmi et al., 2013). Research posits that quality defects are triggered by objective events, which this study defines as "quality defect triggers". These defect triggers are potential events during the project process that may result in building products failing to meet quality standards. These defect triggers manifest in various forms, including non-compliant material conditions, non-compliant human behavior, unfavorable construction environments, defective production processes, management deficiencies and force majeure factors.

Efficient identification and timely rectification of quality defect triggers on construction sites can effectively prevent the occurrence of quality defects and accidents. However, research on the identification of defect triggers remains a significant gap in the current literature.

- Quality deviations

Quality deviation refers to the deviation value of product construction quality from the criteria value specified in the design blueprints. The magnitude of construction quality deviations plays a decisive role in the overall project quality. Therefore, many industry standards in the construction field define allowable deviation ranges. For example, the design length of the longitudinal reinforcement of the concrete beam is 3200mm, and the processing length is 3205mm, so the quality deviation is considered as 5mm. According to GB50204-2015, the allowable deviation ranges of longitudinal reinforcement is 10mm, so the longitudinal reinforcement of the concrete beam is eligible.

Evolution mechanisms of defect triggers

The evolution mechanisms of defect triggers primarily refer to the process through which defect triggers form and evolve into quality defects and quality accidents. Defect triggers can be classified into six categories across three dimensions. Based on the quantifiability of the defect trigger, they can be divided into deviation-type defect triggers and non-deviation-type defect triggers. Based on the objective formation process, they can be classified into defect triggers based on physical evolution mechanisms and defect triggers based on management evolution mechanisms. Based on the relationship of their evolution, they can be categorized into defect triggers based on causal relationships and defect triggers based on correlational relationships.

This study organized the physical formation process and management formation process of construction quality by examining eight quality formation element sources: manpower, machinery, materials, methods, environment, measurements, modifications, and management. The study suggested that the formation of quality defect triggers is latent in quality deviations and non-compliant behaviors (Lambers et al., 2023; Lee, 2019). Therefore, an analysis was conducted on the evolution mechanism from construction quality deviations and non-compliant behaviors to quality defect triggers, quality defects, and even quality accidents. This study focuses on the identification of deviation-type defect triggers. The evolution mechanism hypothesis is presented in Figure 2.

The deviation-type defect trigger evolution mechanism can be illustrated by the precast concrete laminated slab DHB-01 as an example. According to the "Technical Standard for Prefabricated Concrete Buildings" (GBT51231-2016), the permissible length deviation range for concrete composite slab production is within 5 mm, and the permissible installation position deviation range is also within 5 mm. The designed length of DHB-01 is 7300 mm, while its production length is 7304 mm, resulting in a quality deviation of 4 mm, which does not constitute a quality defect. When DHB-01 is installed, a 4 mm deviation occurs along its centerline, which also does not constitute a quality defect. However, due to the 4 mm length deviation inherent in DHB-01, when combined with the 4 mm position deviation, the actual position deviation becomes 6 mm, exceeding the 5 mm limit and forming a quality defect. Therefore, the combination of DHB-01's production length deviation and installation position deviation results in a quality defect. If this defect is not resolved before concrete pouring and entering the usage phase, the position quality defect may prevent proper integration of the reinforcing bars and concrete in the load-bearing system. This could lead to the detachment of one end of the slab, resulting in a quality accident.

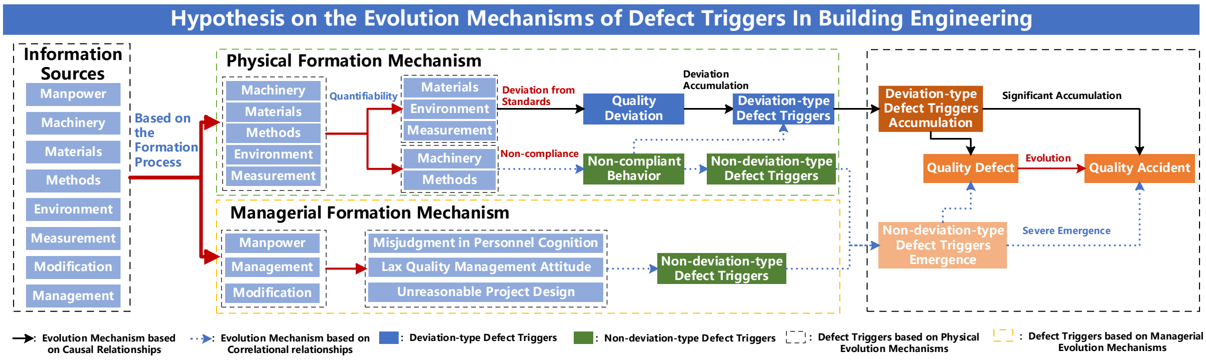


Figure 2: The evolution mechanisms diagram of defect triggers

The architecture of the quality linked-data and process patterns for identification of defect triggers

Overview

The construction site was characterized by multiple participants, complex construction processes, and significant overlap between various construction processes. Therefore, the sources of defect triggers are numerous and complex. A defect trigger identification process pattern based on quality linked-data was designed in this study. The process pattern begins with the most basic construction process units and incorporates quality linked-data to identify potential defect triggers.

The study considered the construction of the defect trigger identification process pattern from four layers: the quality standards layer, the quality data layer, the quality defect triggering layer, and the quality process layer, as shown in Figure 3. Defect trigger identification was based on the requirements of quality standards, so the quality standards layer must take quality management requirements into account. Quality standards include both international quality management standards and national construction quality standards commonly applied in the construction industry, as well as specific quality standards for division construction works quality of the project. Next, the study considered the actual construction quality by examining the quality data layer. The quality data includes information from various sensors, detection equipment, and manual inspections, as well as quality linked-data constructed through structured logical standards.

With the quality standards and actual project quality data in hand, the study focused on the quality defect triggering layer, which encompassed both physical triggers of quality defect during the construction of the project entity and managerial triggers of quality defect during the implementation of construction. Finally, the quality process layer for quality defect trigger identification was considered. The study proposed that the quality process layer can be divided into sub-division and sub-item construction works of the project, construction processes, and basic process elements. It is suggested that the quality defect trigger identification process pattern can be constructed based on the process elements.

Quality linked-data

The purpose of quality linked-data was to transform multi-source heterogeneous quality data of building projects into structured quality data. This enabled the comparison of construction quality data with standard quality requirements, thereby facilitating the identification of quality deviations. The study adopted the RDF to construct quality linked-data.

Quality linked-data primarily comes from multi-source heterogeneous project quality data and the linking relationships between them. The study referenced the Information Container for Linked Document Delivery (ICDD) to structure the quality linked-data. Therefore, the quality linked-data is constructed using the ICDD, which consists of the "Index.rdf" file, "Ontology resources" folder, "Data resources" folder, and "Linked-Data" folder.

Given the content clarification in the "Index.rdf" file, it ensures that resource location can be found and loaded from multiple sources. The "Data resources" folder contained multi-source quality-relevant data, including design, specification, and as-built data. The "Linked-Data" folder included structured as-built linked-data, criteria linked-data, construction deviation, and external links to standards. The “Ontology resources” folder held container ontology, linkset ontology and the domain specific ontology "Construction-quality-onto.rdf". This "Construction-quality-onto.rdf" is developed to represent the information of quality issues introduced previously. The Protégé is used to construct the "Construction-quality-onto.rdf". The relationship between construction process and quality data in construction projects was defined, encompassing data related to building components and spatial relationships, material acceptance, environmental condition monitoring, construction result testing, quality inspection standards, quality deviations and defect triggers. The structure of quality linked-data and the "Construction-quality-onto.rdf" are shown in Figure 4.

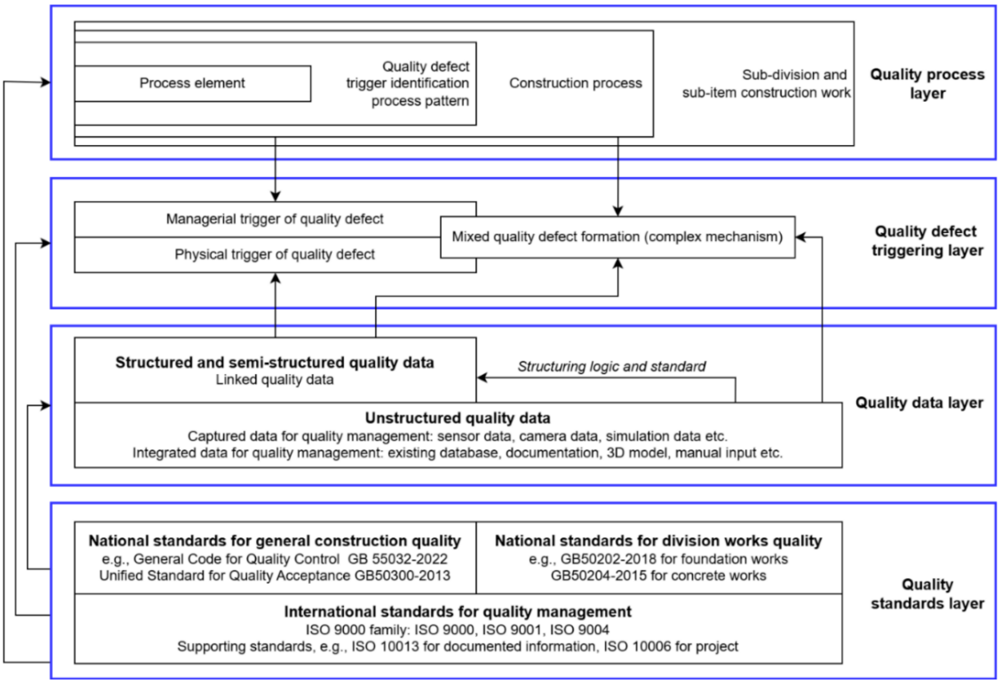


Figure 3: Hierarchy of quality data and quality defect triggers

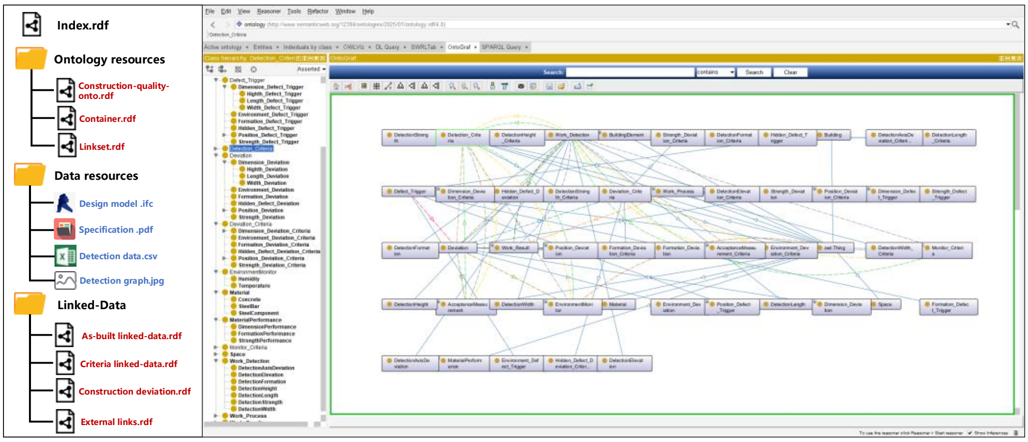


Figure 4: The structure of quality linked-data and graph of "Construction-quality-onto.rdf"

Identification criteria of quality defect triggers

Identification criteria should be developed for deviation-type defect triggers based on their specific characteristics to support the automated identification of defect triggers. This study identified three key indicators: required value, reference value, and reference rate. The required value refers to the standard requirements for quality deviations. According to the GB 50204-2015 specification, when the quality deviation exceeds the required value, the deviation is identified as a quality defect. The reference value is a critical indicator for determining quality defect triggers. When the quality deviation exceeds the reference value but does not surpass the required value, it indicates a high probability of leading to a quality defect, and the deviation is thus identified as a defect trigger. The reference rate considers the accumulation of quality deviations. When the deviation value does not exceed the reference value, but the frequency of the deviation exceeds the reference rate, meaning the deviation occurs frequently, it also has a high probability of leading to a quality defect, and is thus considered a defect trigger. The reference rate is a self-iterative parameter, which is adjusted based on the specific application circumstances.

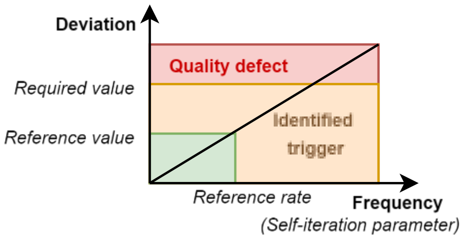


Figure 5: Identification criteria of quality defect triggers

Process patterns of defect trigger identification

To achieve comprehensive and accurate identification of quality defect triggers, the defect trigger identification process patterns should be based on the fundamental construction processes of a building project. According to the "Unified Standard for Construction Quality Acceptance in Building Projects" (GB 50300-2013), building projects are divided into division works, sub-division works, and sub-item works, with sub-item works representing the most basic construction processes required for completion. Quality acceptance of construction requires passing inspections at checkpoints within the construction process, followed by acceptance of sub-item and division works. Therefore, defect trigger identification should be based on the acceptance of checkpoints within the construction processes. A series of inspection items at these checkpoints should be compared, with as-built and criteria data extracted from quality-linked data to identify quality deviations. These deviations should then be analyzed, considering their deviation values and frequency, to determine whether they constitute a quality defect trigger.

According to the GB 50300-2013 specification, the acceptance requirements for division and sub-item works include material acceptance inspection, key construction process inspection, and sub-item work acceptance inspection. Material performance is assessed through material acceptance inspections, while key construction process inspections concentrate on concealed works, installation work, and measurement work. Sub-item work acceptance verifies the construction quality of the sub-item work. After the construction and acceptance of a sub-item work, the next sub-item work proceeds in the same manner until all sub-item works within a division are completed and accepted. Once all sub-item works are accepted, the entire division work is subject to acceptance inspections, typically through spot checks. Based on this, the study proposes that the fundamental unit for identifying defect triggers is the acquisition of linked-data at key inspection points, followed by the calculation of quality deviations. This process facilitates the identification of quality defect triggers. Additionally, the study developed a workflow with the decision logic for defect trigger identification, as shown in Figure 6 and Table 1.

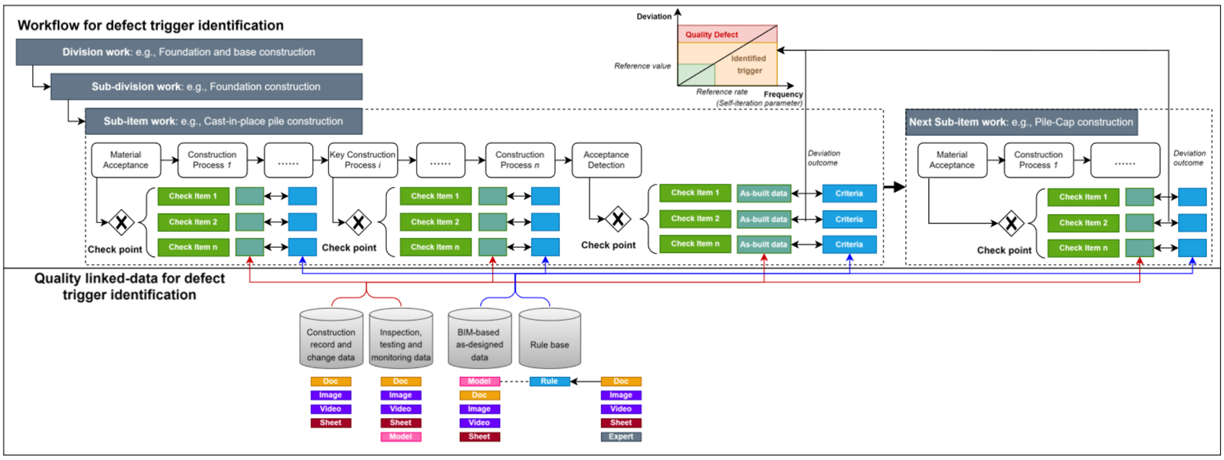


Figure 6: The workflow of defect trigger identification process pattern

Table 1: The decision logic for identifying defect triggers

```
Algorithm: Identification of Quality Defect Triggers
Input: $mad$: $material\_acceptance\_deviation$
       $maf$: $material\_acceptance\_frequence$
       $madr$: $material\_acceptance\_deviation\_reference$
       $mafr$: $material\_acceptance\_frequence\_reference$
       $cdd$: $construction\_detection\_deviation$
       $cdf$: $construction\_detection\_frequence$
       $cddr$: $construction\_detection\_deviation\_reference$
       $cdfr$: $construction\_detection\_frequence\_reference$
       $ced$: $construction\_environment\_deviation$
       $cef$: $construction\_environment\_frequence$
       $cedr$: $construction\_environment\_deviation\_reference$
       $cefr$: $construction\_environment\_frequence\_reference$
       $wad$: $work\_acceptance\_deviation$
       $waf$: $work\_acceptance\_frequence$
       $wadr$: $work\_acceptance\_deviation\_reference$
       $wafr$: $work\_acceptance\_frequence\_reference$
Output: $DeTi$: defect_triggers
Initialize: $DeTi$
for $i \in [1, n]$ do
    $division\_work\_i$
    for $j \in [1, m]$ do
        $sub\_item\_work\_j$
        $material\_acceptance\_j$
        if $mad \geq madr$ then
            $DeTi.add(material\_acceptance\_j)$
        else if $maf \geq mafr$ then
            $DeTi.add(material\_acceptance\_j)$
        end
        for $k \in [1, l]$ do
            $key\_construction\_process\_k$
            $construction\_detection\_k$
            if $cdd \geq cddr$ then
                $DeTi.add(construction\_detection\_k)$
            else if $cdf \geq cdfr$ then
                $DeTi.add(construction\_detection\_k)$
            end
            $environment\_monitor\_k$
            if $ced \geq cedr$ then
                $DeTi.add(environment\_monitor\_k)$
            else if $cef \geq cefr$ then
                $DeTi.add(environment\_monitor\_k)$
            end
        end
        $sub\_item\_work\_acceptance\_j$
        if $wad \geq wadr$ then
            $DeTi.add(sub\_item\_work\_acceptance\_j)$
        else if $waf \geq wafr$ then
            $DeTi.add(sub\_item\_work\_acceptance\_j)$
        end
    end
    $division\_work\_acceptance\_i$
    if $wad \geq wadr$ then
        $DeTi.add(division\_work\_acceptance\_i)$
    else if $waf \geq wafr$ then
        $DeTi.add(division\_work\_acceptance\_i)$
    end
end
return $DeTi$
```

Implementation

This study selected the construction of cast-in-place piles as a case to validate the proposed framework of quality linked-data and process patterns for the identification of defect triggers.

Workflow of defect trigger identification in cast-in-place pile

Based on "Code for Construction Quality Acceptance of Building Foundation and Substructure Engineering" (GB 50202-2018) and the research of Ding et al. (2017), the main construction processes of cast-in-place pile include positioning calibration, protection tube insertion, drilling, cleaning the drill hole, measuring hole depth, setting up the reinforcement cage, setting up the catheter, pouring concrete, and cast-in-place pile formation. The key inspection points include pile foundation measurement and positioning, excavation quality of the hole, reinforcement cage, concrete material performance, and cast-in-place pile formation quality. The workflow of defect trigger identification in cast-in-place pile construction is shown in Figure 7.

Quality linked-data of cast-in-place pile

Based on the structure of quality linked-data, the "Quality Acceptance Checklist", "Concrete Sample Detection Report", "Design Model", "Pile Top Amplitude-Time Diagram", and the GB 50202-2018 specification for cast-in-place piles were used as sources of quality data. The "Construction-quality-onto.rdf" file for this section was constructed using Protégé, the "Container.rdf", "Linkset.rdf" and "Index.rdf" files were compiled by VScode. Based on the contents of the data sources files, the "As-built linked-data.rdf" and "Criteria linked-data.rdf" files can be compiled manually. The relevant data from the "As-built linked-data.rdf" and "Criteria linked-data.rdf" files was input into Individuals in the "Construction-quality-onto.rdf" within Protégé. Since the referenced specification is stored in the data sources folder, no "External links.rdf file" was needed. To enable the calculation of quality deviations, SPARQL is used within Protégé. Based on the SPARQL query results, the "Construction deviation.rdf" file can be compiled by using VScode.

Taking the reinforcement cage length of cast-in-place piles as an example, the design length of the reinforcement cage is 13,500 mm, while the detection length is 13,580 mm, with a frequency of 8%. "ReinforcementCage_Measurement_Length", "ReinforcementCage_Measurement_Length_Criteria", and "ReinforcementCage_Length_Deviation", were created in Protégé. Corresponding values were added to "ReinforcementCage_Measurement_Length" and "ReinforcementCage_Measurement_Length_Criteria". By running the SPARQL query, the deviation value and frequency for "ReinforcementCage_Length_Deviation" were obtained. The "calculatedDeviation" and "deviationFrequency" are 80mm and 8%, the results are shown in Figure 8.

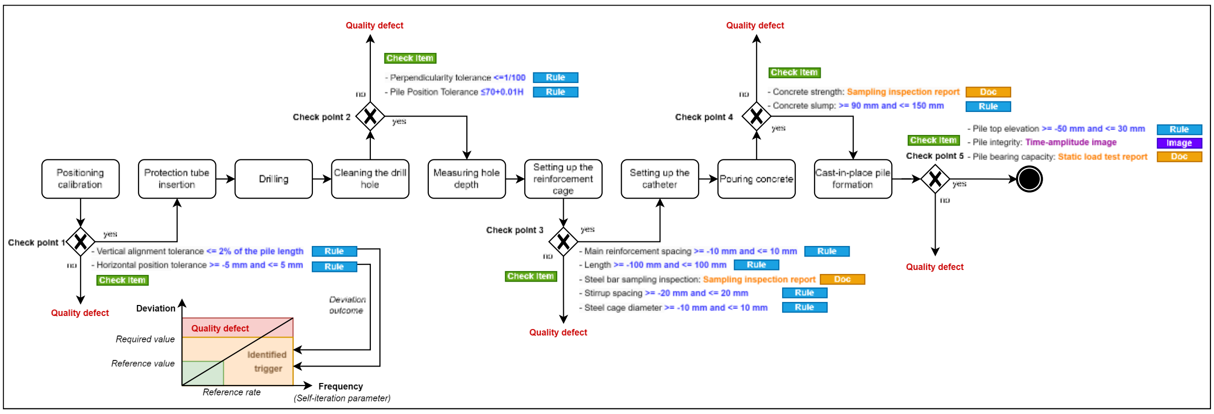
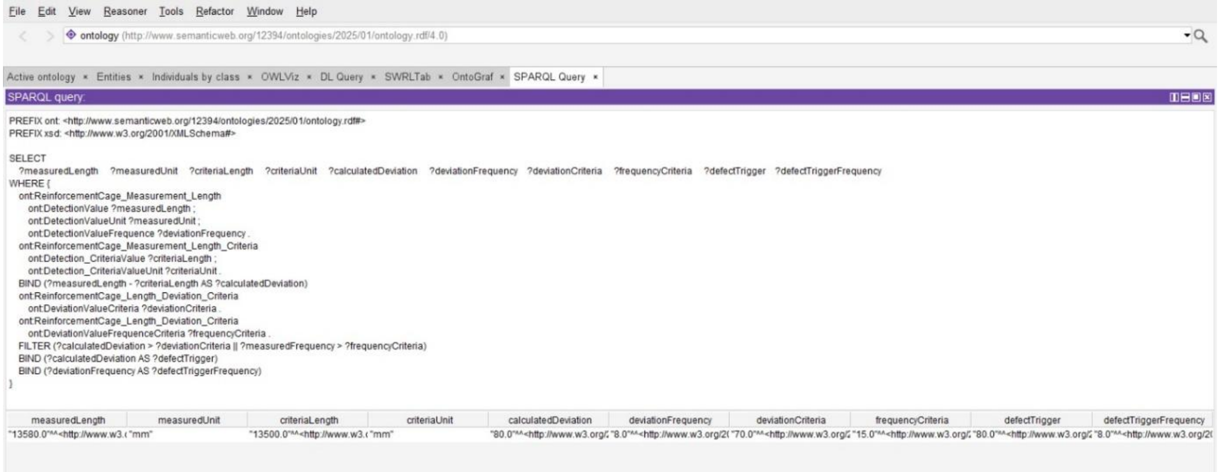


Figure 7: The workflow of defect trigger identification in cast-in-place pile

Identification of defect triggers in the cast-in-place pile

Based on the decision logic for identifying defect triggers, SPARQL query was further developed to incorporate the functionality of quality defect trigger identification in the reinforcement cage length of cast-in-place piles. "ReinforcementCage_Length_Deviation_Criteria" and "ReinforcementCage_Length_Defect_Trigger" were created in Protégé. The reference value for defect trigger identification of reinforcement cage length in cast-in-place piles was set to 70 mm, and the reference rate was set to 15%. By running the complete SPARQL query, the identification of quality defects related to the reinforcement cage length in cast-in-place piles was successfully implemented. The quality deviation value of 80mm has been identified, which exceeds the reference value. Therefore, the reinforcement cage exhibits a quality defect. The results for the defect trigger identification of cast-in-place piles and the SPARQL code are shown in Figure 8.



```
PREFIX ont: <http://www.semanticweb.org/12394/ontologies/2025/01/ontology.rdf#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT
  ?measuredLength  ?measuredUnit  ?criteriaLength  ?criteriaUnit  ?calculatedDeviation  ?deviationFrequency  ?deviationCriteria  ?frequencyCriteria  ?defectTrigger  ?defectTriggerFrequency
WHERE {
  ont:ReinforcementCage_Measurement_Length
    ont:DetectionValue ?measuredLength ;
    ont:DetectionValueUnit ?measuredUnit ;
    ont:DetectionValueFrequence ?deviationFrequency .
  ont:ReinforcementCage_Measurement_Length_Criteria
    ont:Detection_CriteriaValue ?criteriaLength ;
    ont:Detection_CriteriaValueUnit ?criteriaUnit .
  BIND (?measuredLength - ?criteriaLength AS ?calculatedDeviation)
  ont:ReinforcementCage_Length_Deviation_Criteria
    ont:DeviationValueCriteria ?deviationCriteria .
  ont:ReinforcementCage_Length_Deviation_Criteria
    ont:DeviationValueFrequenceCriteria ?frequencyCriteria .
  FILTER (?calculatedDeviation > ?deviationCriteria || ?measuredFrequency > ?frequencyCriteria)
  BIND (?calculatedDeviation AS ?defectTrigger)
  BIND (?deviationFrequency AS ?defectTriggerFrequency)
}
```

measuredLength	measuredUnit	criteriaLength	criteriaUnit	calculatedDeviation	deviationFrequency	deviationCriteria	frequencyCriteria	defectTrigger	defectTriggerFrequency
"13580.0"^^<http://www.w3.(	"mm"	"13500.0"^^<http://www.w3.(	"mm"	"80.0"^^<http://www.w3.org/.	"8.0"^^<http://www.w3.org/2(	"70.0"^^<http://www.w3.org/.	"15.0"^^<http://www.w3.org/.	"80.0"^^<http://www.w3.org/.	"8.0"^^<http://www.w3.org/2(

Figure 8: The quality deviation, identified defect trigger and corresponding SPARQL code for cast-in-place piles

Conclusion an outlook

This paper presents ongoing work on the quality linked-data and process patterns for quality defect trigger identification, within the context of construction digital twins. The research refers to the principles of ICDD, utilizes RDF technology to convert multi-source heterogeneous quality data into structured quality linked-data. Based on the analysis for evolution mechanisms of defect triggers, the construction process of building projects was deconstructed, and a workflow for defect trigger identification in cast-in-place piles was developed. Subsequently, pseudocode for the identification of defect triggers was compiled. Furthermore, a case study of the reinforcement cage length during the cast-in-place pile construction process was conducted for defect trigger identification, demonstrating the logical validity of the proposed approach.

For the future works, the research will focus on three aspects. First, further theoretical research on the evolution mechanisms of quality defect triggers should be conducted to determine more reliable and accurate quality deviation reference values and reference frequency rates for defect trigger identification criteria. Second, automated processing tools such as computer vision and IfcConvert should be introduced to achieve the automatic conversion of multi-source heterogeneous data into structured RDF quality data, instead of manually compiling RDF files. Third, Ontext GraphDB should be introduced to enhance the scope and capability of RDF data comparison. These efforts will improve the efficiency of structuring multi-source heterogeneous data, quality deviation calculation and quality defect trigger identification. These efforts will provide a strong theoretical foundation for automating defect trigger identification in future building construction.

Acknowledgements

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