2026 European Conference on Computing in Construction
Corfu, Greece
July 12–15, 2026

FROM INSPECTION TO DIGITAL PASSPORT: TRACING THE PROVENANCE OF TESTING DATA OF CONCRETE COMPONENTS FOR CIRCULAR REUSE

Lukas Guntermann[1], Nina Krautgartner[1], Hendrik Zielonka[2], Philipp Hagedorn[1],
Peter Mark[2], and Markus König[1]
[1]Chair of Computing in Engineering, Ruhr University Bochum, Bochum, Germany
[2]Institute of Concrete Structures, Ruhr University Bochum, Bochum, Germany

Abstract

Circular reuse of construction components, prioritized by the EU over recycling, is limited by the lack of legally reliable, element-specific information in BIM environments. This work proposes a literature-based parameter set for the reuse of reinforced concrete elements as part of a product passport. Data from legally signed inspection certificates are integrated with digital BIM representations using established ontologies (BOT, Metadata4ing, ISOProps). Information is extracted from signed PDF certificates and linked to IFC models. Feasibility is demonstrated through a case study, enabling an interoperable, auditable workflow supporting End-of-Life-to-reuse information continuity for reinforced concrete elements.

Introduction

To reduce the negative environmental impact of the construction industry, the reuse of structural components is increasingly important regarding waste reduction (Sakthibala et al., 2025) and is assigned a higher priority in the waste hierarchy of the European Commission (2008). Reinforced concrete is particularly relevant in this context, as its high mass, significant greenhouse gas emissions, and long service life offer considerable potential to reduce environmental impacts through targeted reuse. Within the Circular Economy (CE), when planning with components that are reused at their End-of-Life (EoL), it is necessary to capture and store component- and reuse-specific information, e. g. from Pre-Demolitions Audits (PDA) according to DIN SPEC 91484. Information requirements for circular components have already been documented in general terms (cf. Akbarieh et al. (2023); Al-Qazzaz (2024)). However, for solid construction and structural components, additional information on the condition of components from detailed inspections and reuse-oriented component testing is necessary, since these typically need to be verified prior to reinstallation in order to determine structural properties such as load-bearing capacity.

For a Building Information Modeling (BIM)-supported reuse workflow, inspection data must be linked with Industry Foundation Classes (IFC) in a machine-readable form (Hagedorn et al., 2025), while the signed inspection certificates for the components must remain available for legal reasons so that it can be determined with certainty which properties can be assumed in subsequent structural planning. These inspection certificates ensure liability for the structural properties of the components for reuse, and are already being used for the reuse of steel components, as defined in EN 10204:2004 and EN 10168:2004. However, the reuse of reinforced concrete (RC) involves other product tests for which no reuse-specific material parameters or inspections have yet been established. This necessary flow of information leads to the following Research Question (RQ).

RQ: *How can information be extracted from PDF-based inspection certificates for RC elements and reliably transferred to the BIM model, ensuring a continuous flow of information in the components lifecycle?*

To answer the RQ, the remainder of the paper is structured as follows. Related work on reuse, product passports, ontologies, and information extraction is gathered. A methodology and workflow is proposed and implemented. Eventually, the workflow is demonstrated and validated before discussing the results and drawing conclusions.

Related work

Reuse of reinforced concrete (RC)

Küpfer and Fivet (2024) examine the structural reuse of concrete pieces, a relatively new practice evidenced by scarce yet diverse built projects. They trace the slow evolution of precast reuse since the 1980s and the recent emergence of cast-in-place reuse, driven by sustainability and design exploration, emphasize reliance on local knowledge and better case documentation, and advocate viewing soon-to-be-demolished structures as material stock. Mark et al. (2025) describe modular reuse of existing structures and focus on component testing in order to overcome usage restrictions and building regulations. Rose et al. (2025) investigate efficient reuse of RC using optimization algorithms and highlight the relevance of load-bearing capacity. Consequently, M–N (Moment-Normal force) charts may be pertinent for future structural assessment of reused components. Krautgartner et al. (2025) propose a network-based approach that integrates GIS (Geographic Information Systems) to manage building deconstruction and match demand for reuse elements. They derive requirements for system components, parameters, and process flows from the literature and formalize them.

Product passports in construction

Aftab and Agliata (2026) review the state of Material Passports (MPs) and discuss them generically, without addressing the complexity of composite, load-bearing materials such as RC. Their study characterizes BIM primarily as a dynamic repository, supporting the premise that BIM models serve as the starting point for Linked Data to consolidate additional information for reuse.

MPs address material-specific documentation, often in recycling, whereas Digital Product Passports (DPP) cover whole construction products; both rely on similar BIM- and Linked Data–based methods and can cover different scales from building materials to overall assessments. Ruismäki et al. (2025) examine stakeholder perspectives on DPPs for construction products and identify traceability, BIM integration, and resource efficiency as key benefits. Interviews show broad agreement on including EoL data and usage data (e.g., recorded damages). Stakeholders prioritized steel structures in a phased implementation owing to ease of handling, reuse, and major environmental benefits; concrete products were also considered suitable, but onsite modifications complicate information management. Ruismäki et al. (2025) further emphasize the complexity of concrete, which has contributed to the prevailing focus on steel. Senarathne et al. (2025) propose a concrete-specific DPP framework that includes physical properties and parameters across logistics, chemical, biological, cost, safety and health, among others. As it has not yet been validated in real-world settings, this paper adopts a smaller example focused on reuse-specific data instead. Vahidi et al. (2024) focus on recycled concrete and Radio Frequency Identification (RFID)-based MPs. As their work addresses crushed recycled concrete rather than component reuse, its relevance here is limited; however, RFID remains a potential option for tracking reused components. Bernier and Danash (2024) propose DPP based on ontologies. Blomqvist et al. (2023) propose a network of core ontologies for the CE and include process-, actor-, material- and product-information.

Ontologies for circular construction components

Ontologies and Knowledge Graphs (KG) enable machine-interpretable information for the built environment, typically represented in the Resource Description Framework (RDF) and the Web Ontology Language (OWL). The definition of terminology using ontologies is referred to as the TBox, while the instantiation and assertion of facts according to these ontologies is referred to as the ABox. (Pauwels et al., 2022, 2018)

Moreover, ontologies can be categorized as top-level ontologies for providing abstract generic concepts and domain ontologies for representing domain knowledge. Beyond domain-specific efforts, Li et al. (2023) investigate cross-industry general ontologies for the circular economy to create an ontology network that links core ontologies across multiple industry domains. To facilitate ontology discovery and reuse in AECO (Architecture, Engineering, Construction, and Operations), Akbarieh et al. (2025) developed the Built Environment Ontology Lookup Service (BE-OLS) (EC3 M&S Committee, 2025). Within the built environment, examples of domain ontologies include the Decommissioning and Reuse Ontology (DOR); for EoL decision-making, the Construction Circular Product Ontology (CCPO) provides a rule-based EoL product ontology that considers Product Health State, recyclability, and reference service life (Adu-Duodu et al., 2025). Additional ontologies relevant to DPP workflows include the Material Passport Ontology (MPO), the Steel Element Reuse Ontology (SERO), the Building Element Ontology (BEO) for classification of building elements, the Building Product Ontology (BPO), and a Concrete Damage Ontology (CDO). For data structuring and property description in the BIM-based information management, Zentgraf et al. (2026) developed the ISO 23386 Property Ontology (ISOProps), providing modular and reusable descriptions for properties and construction objects. Liu et al. (2021) introduced the Building Concrete Monitoring Ontology (BCOM) for maintaining testing data of cast-in-place fresh concrete properties on the construction site. However, their ontology is not a generic, extendable property dictionary but a strict, encoded TBox ontology with a fixed schema. In the context of managing arbitrary test data from the broader domain of engineering sciences, the Metadata4Ing ontology (Lanza et al., 2025) is relevant. It provides a framework for the semantic description of research data and the entire data-generation process, covering the object of investigation, sample and data manipulation methods and tools, the data files, and the roles of persons and institutions. Its structure and application follow modularity and inheritance, with the processing step as a central element. Ultimately, ontologies also serve information management by structuring extracted data from reports (Zentgraf and Zimmermann, 2025). In summary, existing ontologies already model circular processes and data structuring in AECO but do not address testing-level details for concrete.

Methodology

To answer the RQ proposed, the methodology is defined as shown in Fig. 1. First, relevant background and literature is gathered and analyzed regarding relevant component parameters for the reuse. Next, a methodology and concept are developed on how these parameters can be extracted from signed PDF certificates and be integrated with relevant metadata of the testing procedures for documenting the provenance. As a result, an ABox dictionary of properties assignable to concrete elements based on inspection tasks is developed, reflecting the parameters defined in the literature. This ABox dictionary is based on terminology from multiple ontologies, such as the Building Topology Ontology (BOT) for IFC model alignment (Rasmussen et al., 2021), Metadata4ing for test procedure metadata and material properties (Lanza et al., 2025), and ISOProps for maintaining the tested properties in accordance with ISO 23386 (Zentgraf et al., 2026). The proposed concept is implemented and demonstrated on a case study of a reinforced concrete element; results are discussed and conclusions drawn.

Component reuse data flow

Figure 2 outlines the workflow and data concept for component reuse. The process starts with deconstruction; components are tested in the laboratory, and a certificate is issued that must be handwritten-signed for legal accountability. This signature confirms that testing was performed, liability is assumed, and the described properties can be used for future planning in case of reuse. Information from the certificate is extracted and stored in a BIM model. The PDF inspection certificate is linked to the component's IFC model, ensuring that, in subsequent planning, information is available in two forms: within the IFC model for BIM-based design and as a linked PDF report that can be accessed at any time to provide planners with assurance for component reuse. The data linking the component and the inspection results can thus be transferred to the next life cycle of the component.

Inspection certificate for reuse of RC

Properties for a product passport for reinforced concrete are proposed, derived from the literature: Senarathne et al. (2025) present a DPP for concrete; Mecka et al. (2025) outline a framework for the reuse of reinforced concrete components; Ottosen et al. (2024) review non-destructive testing to document properties for reuse; Suchorzewski et al. (2023) propose a classification system for disassembled concrete elements (DCE). Relevant properties were compiled from these sources. The proposed inspection certificate can form part of a DPP and focuses on properties determined through laboratory testing and inspection of the elements. No claim to completeness is made; the proposal serves to demonstrate and model implementation and data flow in this paper. Table 1 lists and explains required parameters, and specifies the investigation methods by which they can be determined. These investigation methods are central to laboratory test reports. Section 1 of the table provides general information; Sections 2 and 3 present mechanical properties, geometry, damage, and durability.

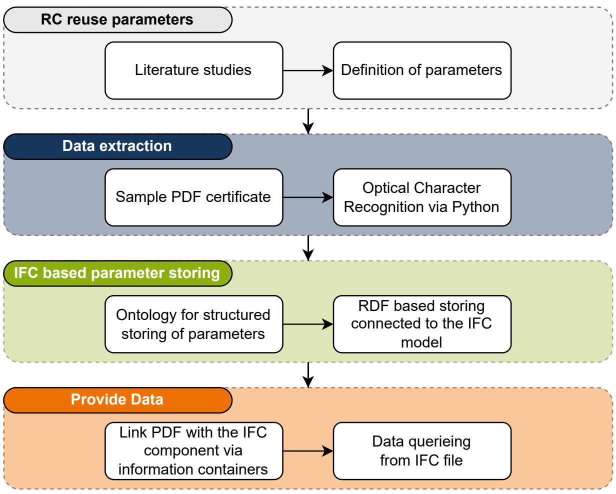

Figure 1: Methodology

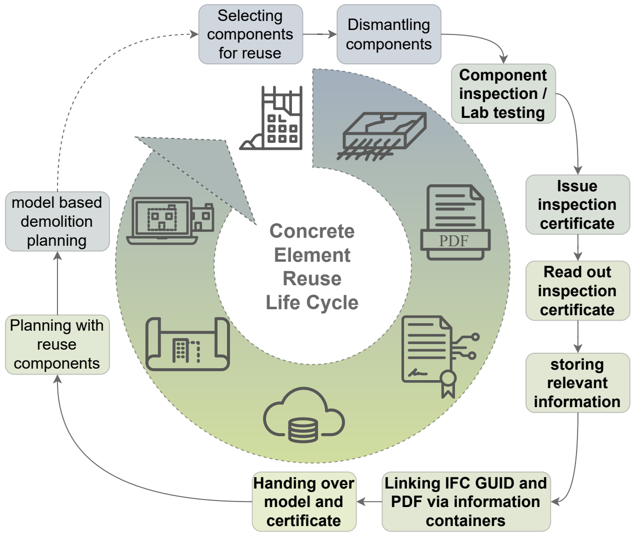

Figure 2: Data Concept for reuse components

Implementation

After having analyzed the literature and provided a template and parameter set for inspection reports according to the methodology in Figure 1, in this section, data extraction is performed. For the first testing of the procedure, a Python library for Optical Character Recognition (OCR) was used. The extracted parameters are ingested into a KG using the Concrete Element Reuse Ontology (CERO) published at `https://w3id.org/cero#` in previous work (Krautgartner et al., 2026). CERO provides standardized ABox properties as `owl:DatatypeProperty` instances annotated with standardized metadata according to the Metadata4Ing ontology and maintenance workflows for the property dictionary according to the ISOProps ontology and ISO 23386. Property values are assigned to concrete components represented in RDF graphs after being converted from the IFC model. Eventually, the extracted data is provisioned into Information Containers for Linked Document Delivery (ICDD) (ISO 21597-1, 2020) and linked to both the PDF and the IFC model to provide the provenance of the properties. Using the ICDD platform as it has been presented in Hagedorn et al. (2023), this interlinked data can be queried from the model and the PDF file of the inspection certificate.

Ontology for structuring the parameters

To embed Table 1 into the Linked Data concept, it must be converted into processable entities following a meaningful structure. Because BE-OLS does not contain an ontology for RC component inspection certificates (as of January 2026, (EC3 M&S Committee, 2025)) yet, a custom implementation of the parameter set into the CERO ontology was necessary. The namespaces used for the implementation are presented in Table 2.

This dataset inside CERO maps the entirety of the proposed information of the test certificates according to Table 1. The parameters from Section 1 are directly instantiated and persisted into the CERO ontology. The parameters from Sections 2 and 3 are also created as parameters in the CERO ontology, but are recorded via the Metadata4Ing ontology. This means that each test method (see Table 1) has been created there as `metadata4ing:Tool`. In addition, the possible test configurations (`metadata4ing:Configuration`) have been stored, which contain, which parameters can be recorded with which test methods. According to the Metadata4Ing Ontology, for each row, `metadata4ing:Configurations` were initially created to link instances of `metadata4ing:Methods` (e.g., `certificate:CompressiveStrengtTest`) with the testing tools (`metadata4ing:Tools`) (e.g., `certificate:Reboundhammer`) as shown in Figure 3. Numerical parameter Values are stored in the `metadata4ing:ProcessingSteps` in `metadata4ing:NumericalAssignments` in a `metadata4ing:NumericalVariable`. The `metadata4ing` Ontology uses the `qudt` ontology for storing units (as here MPa for the compressive strength).

Table 1: Proposed testing parameters for inspection certificates of reused reinforced concrete components

Section 1: General component and project information		
Parameter	***Description***	
Identification	Identification number/ID/serial number	
Origin	Original building, year of construction, pre-use	
Element type	Type of element (beam, column, slab, etc.))	
Overall dimensions	External geometry of the element, span after processing	
Load capacity	Reduced cross-sectional load-bearing capacity after taking into account all mitigating factors, e.g. via M-N interaction diagram	
Environmental actions	Relevant exposure classes	
Environmental impacts	Environmental data on the original element, on processing the elements after use, and on the cost of dismantling and transport	
Section 2: Condition assessment		
2.1 Mechanical properties		
Parameters	***Description and units, if applicable***	***Investigation method***
Concrete compressive strength	Characteristic compressive strength (fck) [MPa; N/mm²]	Core extraction; non-destructive testing (e.g. rebound hammer); as-built documentation
Concrete stiffness	Modulus of elasticity [MPa; N/mm²]	Core extraction; non-destructive testing (e.g. ultrasonic testing); as-built documentation
Reinforcing steel tensile strength	Yield strength (fyk) [MPa; N/mm²]; modulus of elasticity [MPa; N/mm²]	Reinforcement sampling with tensile test; as-built documentation
2.2 Geometry and damage		
Concrete cover	Minimum and mean concrete cover [mm]	Ground penetrating radar (GPR); as-built documentation
Reinforcement layout	Location, diameter and number of reinforcement bars; effective depth	Reinforcement scanner; covermeter; ground penetrating radar (GPR); as-built documentation; partial exposure of reinforcement
Cracks	Localisation and maximum crack width [mm]	Visual inspection; laser scanning; digital imaging
Internal defects	Presence of delamination, voids or flaws from loading history	CT scans; X-ray tomography
Section 3: Durability and remaining service life		
Carbonation depth	Measured depth compared to existing concrete cover	Phenolphthalein Indicator, Drill dust analysis
Chloride content	Concentration at reinforcement level [% by mass of cement]	Staggered drilling dust analysis
Remaining service life	[a]	Two-phase model according to Tuutti
Classification	According to DCE classification (Suchorzewski et al., 2023)	

Table 2: List of namespaces used in this study

Prefix	**Namespace IRI**
Existing namespaces used:	
rdf	`http://www.w3.org/1999/02/22-rdf-syntax-ns#`
rdfs	`http://www.w3.org/2000/01/rdf-schema#`
xsd	`http://www.w3.org/2001/XMLSchema#`
sh	`http://www.w3.org/ns/shacl#`
bot	`https://w3id.org/bot#`
props	`https://w3id.org/props#`
isoprops	`https://w3id.org/isoprops`
metadata4ing	`http://w3id.org/nfdi4ing/metadata4ing/1.4.0/`
cero	`https://w3id.org/cero#`
Defined namespaces:	
component	`https://example.org/component#`
certificate	`https://example.org/certificate#`

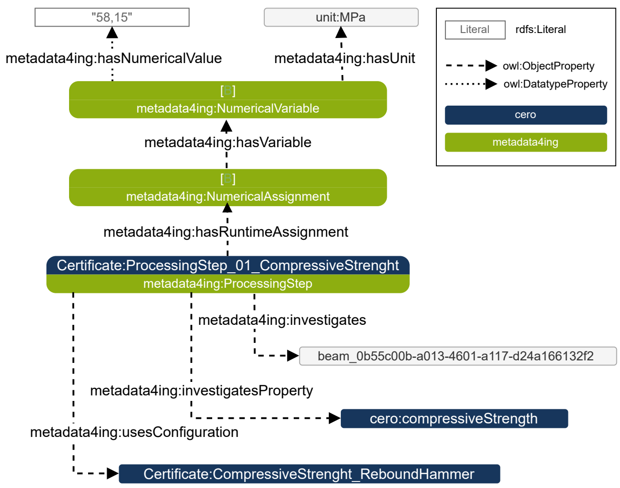

Figure 3: Property for concrete compressive strength

Information extraction of inspection certificates

The information extraction and ontology population for this workflow are inspired by existing research approaches. Sithisint et al. (2025) present engineering drawing interpretation, employing bounding box detection via YOLOv11n and text extraction via OCR with EasyOCR. Schönfelder and König (2025) provide an ontology based approach to structure extracted information from floor plans. Vaatz et al. (2023) show how to link semantic information to BIM using ontologies and ICDD.

In this article, the information extraction from the sample inspection certificates is done by a Python script and the PyTorch library EasyOCR[1]. To do this, the parameters were converted into different spellings in regex pattern, which are then used to search the imported certificates. The following values are then transferred into a template file according to the CERO parameter set.

[1]`https://github.com/JaidedAI/EasyOCR`

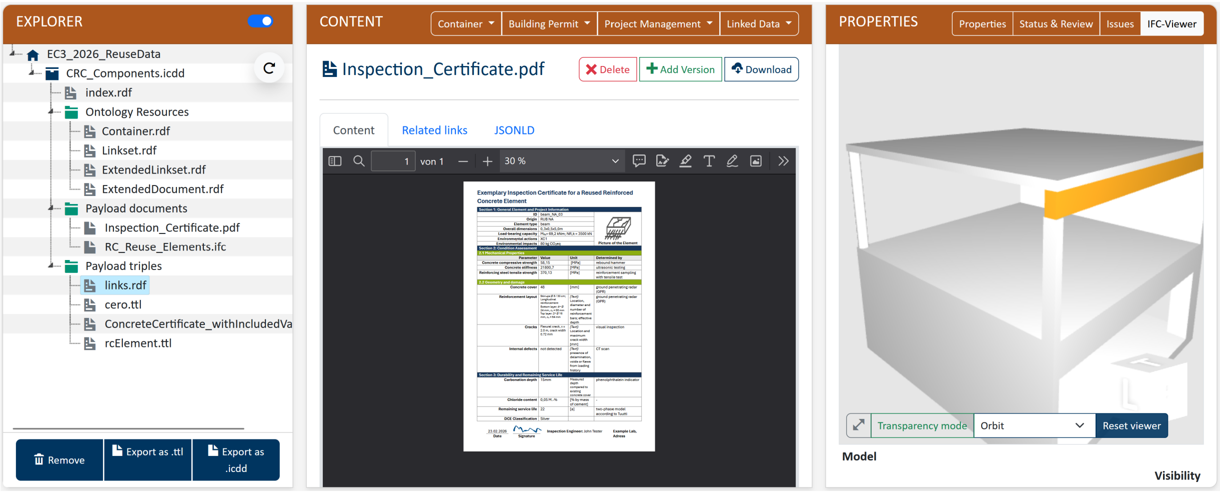

Figure 4: Link of PDF inspection certificate (middle) and RC reuse component (right)

Link of inspection certificate and IFC entity via ICDD

ICDD containers organize and link heterogeneous project data on a dedicated platform. Through Linked Data, documents and files can be associated with a project and with specific IFC elements in the central model. RDF/OWL semantics enable machine-readable linkage and integration with standardized BIM data (e.g., IFC). The ICDD platform has been used for a ReSource Marketplace, where individual components are offered and presented together with their IFC-based data (Hagedorn et al., 2025).
Consequently, the platform's Linked Data concept is suitable for establishing a connection between the PDF inspection certificate and the RC Reuse Element in the BIM model via the IFC GUID, as shown in Figure 4.

Validation and discussion

To validate the concept, an IFC4 model of a solid construction support structure consisting of reinforced concrete components was used (see Figure 4). For this purpose, a sample inspection certificate with realistic values for an RC beam was created, containing all parameters proposed in Table 1 (see Figure 5). In addition, the test engineer's data is provided as an example. The information extraction of this sample inspection certificate was carried out as described, whereby it became apparent that the OCR algorithm has shortcomings with multi-line table entries. The extracted data is stored in the `certificate` KG template using Python by manipulating the text in the Turtle file of the KG. The ontology, the IFC Model and its RDF representation is then uploaded to the ICDD platform (see Figure 4).
To ensure the fundamental functioning of the ontology, Competency Questions (CQs) are formulated according to Bezerra et al. (2013) and checked using SPARQL (SPARQL Protocol and RDF Query Language) queries within the ICDD platform. The aim is to be able to retrieve all data contained in the PDF inspection certificate in the IFC model as well. Due to the different use cases of the data sections, two CQs are checked and the corresponding SPARQL queries are formulated (see Listings 1 and 2).

Exemplary Inspection Certificate for a Reused Reinforced Concrete Element

Section 1: General Element and Project Information			
ID	beam_NA_03		
Origin	RUB NA		
Element type	beam		
Overall dimensions	0,3x0,5x5,0m		
Load-bearing capacity	M_{Rk}= 69,2 kNm; NR,k = 3500 kN		
Environmental actions	XC1		
Environmental impacts	80 kg CO_2eq		**Picture of the Element**
Section 2: Condition Assessment			
2.1 Mechanical Properties			
Parameter	**Value**	**Unit**	**Determined by**
Concrete compressive strength	58,15	[MPa]	rebound hammer
Concrete stiffness	21800,7	[MPa]	ultrasonic testing
Reinforcing steel tensile strength	370,13	[MPa]	reinforcement sampling with tensile test
2.2 Geometry and damage			
Concrete cover	48	[mm]	ground penetrating radar (GPR)
Reinforcement layout	Stirrups Ø 8 / 30 cm; Longitudinal reinforcement Bottom layer: 4× Ø 24 mm, c_v = 68 mm Top layer: 2× Ø 16 mm, c_v = 64 mm	*[Text]:* Location, diameter and number of reinforcement bars; effective depth	ground penetrating radar (GPR)
Cracks	Flexural crack, x = 2.0 m, crack width 0.72 mm	*[Text]:* Location and maximum crack width [mm]	visual inspection
Internal defects	not detected	*[Text]:* presence of delamination, voids or flaws from loading history	CT scan
Section 3: Durability and Remaining Service Life			
Carbonation depth	15mm	Measured depth compared to existing concrete cover	phenolphthalein indicator
Chloride content	0,05 M.-%	[% by mass of cement]	-
Remaining service life	22	[a]	two-phase model according to Tuutti
DCE Classification	Silver		

23.02.2026 **Date**	**Signature**	**Inspection Engineer:** John Tester	**Example Lab, Adress**

Figure 5: Example of a printed reuse certificate based on the proposed parameters

CQ1: *Can all "General Element and Project Information" (Certificate Section 1) be queried in the model?*
CQ2: *Can all "condition assessment" and "durability and remaining service life" information be queried in the model? (Certificate Sections 2 and 3)?*
Both SPARQL queries were executed on the ICDD platform, returning all values from Figure 5 in tabular form

```
PREFIX inst: <https://icdd.vm.rub.de/converter-ws/model/ae874c60-a8ec-4915-a1a3-bc6d9b0df9ac#>
SELECT ?property ?value
WHERE {
?property isoprops:hasGroupOfProperties cero:Group_1_GeneralInformation .
  inst:beam_0b55c00b-a013-4601-a117-d24a166132f2 ?property ?value
}
```

Listing 1: SPARQL query for CQ1

```
PREFIX inst: <https://icdd.vm.rub.de/converter-ws/model/ae874c60-a8ec-4915-a1a3-bc6d9b0df9ac#>
SELECT ?procedure ?val
WHERE {
  ?procedure metadata4ing:investigates inst:beam_0b55c00b-a013-4601-a117-d24a166132f2> .
  ?procedure (metadata4ing:hasRuntimeAssignment/metadata4ing:hasVariable) ?var .
  { ?var metadata4ing:hasValue ?val .}
  UNION
  { ?var metadata4ing:hasNumericalValue ?val . }
}
```

Listing 2: SPARQL query for CQ2

and demonstrating that the proposed workflow enables information storage and querying in the model.

This research approach is limited by the availability of real inspection certificates, so a sample certificate was provided and validated. Moreover, the implementation of the OCR pipeline is limited because the focus of the study is not the employment of an optimized OCR but on the ontology implementation for inspection certificates with traceable test data provenance and the modeling of the information flow for a reuse RC Element. The OCR algorithm can be supplemented with segmentation to enable the correct reading of other layouts or the extraction of correct information from diagrams (e.g., M–N charts). Another avenue to improve information extraction could be to employ a visual–language model (VLM). However, since text recognition using OCR and VLMs involves uncertainties in data extraction, it should be noted that printed component certificates will be replaced by digitally signed inspection certificates in the long term. Currently, PDF-based certificates are used in the field of steel component reuse, as revealed in an expert interview conducted as part of the ''CLUE'' (Circular Building Design) research project.
The information flow from an inspection certificate to a digital passport, regardless of product or material passport, relies on the review of literature and has not yet been extensively tested in practice. Employing the proposed workflow is intended as a demonstration case on a reference reuse construction site in the next step. Moreover, an integration of the proposed inspection certificate parameters in addition with the the linking of the signed PDF Version into reuse Marketplaces such as this presented by Hagedorn et al. (2025) would be a meaningful next step in establishing the market for reused components.
Ontology alignment with other CE-specific ontologies remains to be addressed; particularly with the superior approach for CE ontologies across different industries by Blomqvist et al. (2023). The KG for inspection certificates requires further maintenance; missing test methods may need to be added, and additional parameters can be included if necessary. If CERO is further developed, adjustments must be made to the `certificates` KG.

Conclusion and outlook

This paper models the data flow for reused components. The proposed structure of inspection certificates was successfully used to (1) extract data using OCR and transfer it to the corresponding IFC model, and (2) maintain a persistent linkage to the reuse component using ICDD so that the signed PDF remains available at any time. The following research question was addressed as part of the prototype implementation of the workflow: *How can information be extracted from PDF-based inspection certificates for RC elements and reliably transferred to the BIM model, ensuring a continuous flow of information in the components lifecycle?*
To create the inspection certificate, a literature-based analysis of the required information was conducted; see Table 1. In addition to the necessary parameters, measurement methods are central, which is why possible measurement methods for parameter determination are listed. The compilation was implemented as an ontology using existing ontologies, including BOT, Metadata4ing, and ISOProps, in compliance with ISO 23386.
The information can be inserted into the ontology by text recognition (in this work with a simplified OCR algorithm) from PDF-based inspection certificates. To provide the information to users, the ICDD platform was chosen. This platform uses Linked Data to directly link different files to the corresponding IFC GUIDs, and the information can be queried directly on the model via SPARQL queries, which offers potential for further automation through the ICDD platform's API (Application Programming Interface).
The ontology was validated using two CQs. Although

CERO is still under development, the example presented here shows that CERO supports CE processes for RC reuse elements. The OCR algorithm employed to demonstrate the complete information flow (see Figure 2) is error-prone and cannot be recommended for future work; it would need to be improved or replaced, or it may become obsolete if fully digital product passports become established.

The concept is suitable and expandable to other reuse products, e.g., steel and timber. Future work should investigate approaches without upstream paper documents, i.e., fully digital product passports. There may be new regulations for product passports through the Circular Economy Act. The developed ontologies can also be aligned with the parameters of DIN SPEC 91525 (''Post-Use Concept (PUC) for construction products from existing buildings''), which was published in February 2026, after the implementation of this work was finalized.

Acknowledgments

The authors acknowledge financial support for this research as part of the ''CRC 1683'' funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 523205694 and financial support as part of the project ''CLUE'' (project number EFRE-20800305) funded by the European Union and the state of North Rhine-Westphalia as part of the EFRE/JTF program NRW 2021-2027. Further information can be found at www.efre.nrw.

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