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AN ONTOLOGY INTEGRATING AS-BUILT INFORMATION FOR INFRASTRUCTURE ASSET MANAGEMENT USING BIM AND SEMANTIC WEB

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ABSTRACT

The as-built information is rarely stored in a structured, machine-readable, and model-based way. Semantically enriched IFC models can help to achieve vendor-neutral storage and processing of information from the construction phase. This paper analyses exemplarily the documentation of concreting during construction and specifies the Building Concrete Monitoring (BCOM) ontology using ABox statements for monitoring concrete work and laboratory testing. Utilizing the ICDD, a container is created to capture the information about concrete work with semantic web technology and to link this information with the IFC-based building model. The feasibility of this approach is evaluated in a specific use-case with a web-based platform implementation.

INTRODUCTION

The recording and exchange of relevant construction information is an important part of the construction process. Depending on the technical specification, quantity measuring, construction diaries, delivery notes, photos, test reports, etc. are required for acceptance and invoicing of the construction work. This information is recorded by the contractor during construction and handed over to the construction supervisor or client.

However, most of this information is still stored in paper-based form or non-machine-readable files. Hence, the verification of the construction work and the communication between contractor and client in case of discrepancies are often associated with additional effort. The transfer of the as-built data into an asset management system (AMS) for operation after construction can lead to uncontrolled loss of information due to the complexity of the documentation (Yuan et al. 2016). With the extensive use of model-based design using Industry Foundation Classes (IFC), model-based storage of construction information and documents is possible. Nevertheless, the IFC schema only covers a limited set of semantics and properties and is less flexible for an extension. To overcome the current issues in interoperability using IFC, the information relevant for construction and operation can be recorded as machine-readable and interpretable data using domain ontologies. In these ontologies, the structured information can be recorded, managed, and queried regarding specific logic definitions which achieves a more interoperable cross-domain data exchanging. Moreover, the data integration can be facilitated using distributed data with semantic web technologies.

Regarding current research presented in the literature review, there are two possible approaches for modeling construction documentation data, namely (1) modeling in the original construction data, e.g. the building model, and (2) modeling in a superordinate structured common data model, e.g. using semantic web technologies. The essential prerequisite in both approaches is the availability of an IFC building model. The IFC schema gives the possibility of individual extension to store the building information directly as part of the building model in IFC. However, the more comprehensive the captured information is, the more difficult it is to edit and transfer the building model.

Alternative modeling principles have emerged for construction data over the last few years, of which semantic web technologies are one relevant example in the research (Pauwels et al. 2017). Semantic web technologies are, for instance, employed in the standardized Information Container for linked Document Delivery (ICDD). The information can be captured and structured as instances of specific standardized ontologies inside this container. The combination of this information with the building model and other file-based data can be realized by the ICDD. In this way, the information retains its domain-specific data structure and offers domain-specific data despite the link to the building model. Therefore, a container created at the construction phase can capture the as-built data and be transferred for operation (Fig. 1).

The scope of this paper is the construction phase, while the operation phase is considered in further research. As a specific use-case from the construction phase, the documentation of on-site concrete work and off-site laboratory quality testing is taken into focus in this research. The required information is collected and modeled in a machine-readable way with the help of the developed Building Concrete Monitoring (BCOM) ontology using ABox statements. The ontology provides a schema for monitoring the concrete work, checking the fresh concrete properties, and testing the compressive strength of hardened concrete.

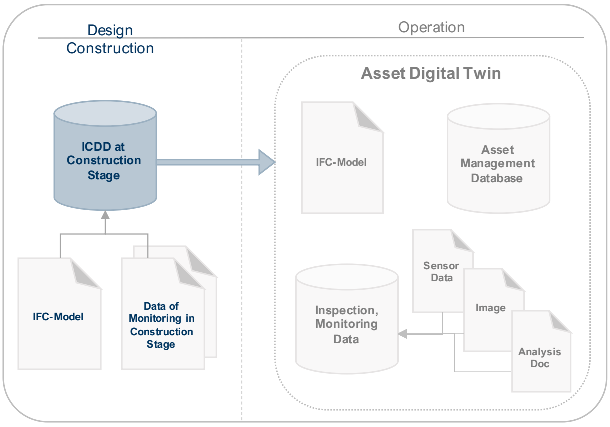

Figure 1: Overview of the information flow of as-built data between the construction and operation phase for asset management

Succeeding the **Introduction**, relevant research is presented in the section **Related Work**. The research approach for the development of the ontology for the demanded information management of construction documentation is presented in the section **Methodology**. In the section **Experiment**, all the development steps to prepare the information container are presented. In the section **Result Analysis and Evaluation**, the usability of the created ICDD is tested and evaluated with data from the practice. Finally, an overview and possible improvements and extensions for future research are presented in the sections **Discussion** and **Conclusion**.

RELATED WORK

Recent research has shown the need for systematic information management in the Architecture, Engineering, Construction, and Operation (AECO) industry to achieve an optimized lifecycle asset management of buildings and infrastructure utilizing existing Building Information Modeling (BIM) methods and recent digital twin approaches (Boje et al. 2020, Sacks et al. 2020, Lu et al. 2020). Boje et al. (2020) stated that the capacities of BIM especially in interoperability issues cannot sufficiently close the gap between the traditional document-based construction lifecycle and the next generation of web-based and data-centric information management. This next generation of information management requires a dynamic and extendable semantic environment to overcome the complexity of data and harnessing information in the operation phase. Regarding Boje et al. (2020), semantic web technologies and ontologies are a promising approach for modeling lifecycle information in the digital twin. Sacks et al. (2020) performed a conceptual analysis of the usage of digital twins as a lifecycle information system in design, construction, and operation phases to provide data-centric information management. The study shows the need for a graph-based cloud approach to information management, compares existing approaches, and identifies impediments to the implementation of such systems. Lu et al. (2020) have shown that the operation phase of building asset management lacks information and have reviewed limitations of BIM-based asset management focusing on technology, information, organization, and standards. These recent publications show the relevance of data-driven information management in construction and building operation.

Yuan et al. (2016) emphasize the importance of comprehensive and complete construction records and as-built documentation of assets for data-driven information management in the operational phase, especially for transportation infrastructure like roads and bridges. They describe a data loss in the transfer of information between construction and operation phases, which relies on the extensive use of paper-based data during construction, and propose electronic and machine-readable data flow of construction information as the ideal information accumulation. For road infrastructure management, Luiten et al. (2018) employed semantic web ontologies to realize a common European asset information management to provide information on the lifecycle of infrastructure. The authors evaluated their concept also for the alignment of national specific guidelines and frameworks like the ASB-ING in Germany.

Generally, there are two approaches for modeling lifecycle data of a building, namely (1) modeling in the original data, e.g. the building model, and (2) modeling in a superordinate structured common data model, e.g. using semantic web technologies. With the ubiquitous usage of BIM, the Industry Foundation Classes (IFC) have been established as a common vendor-neutral exchange format and have been standardized for model-based data exchange in ISO 16739. The domain layer of the IFC contains definitions for special areas of building lifecycle (architecture, construction, structural engineering, asset management, etc.).

On the one hand, research has shown that the domain layer does not suffice the full information requirements and needs to be extended (1), for instance with specific information for the design phase employing information for cost calculation (Zhiliang et al. 2011) or information for delay claim (Hammam & El-Said 2018). Ding et al. (2017) presented a comprehensive extension of the IFC schema for modeling quality management information and information on the work schedule inspection. To monitor the structural health of a building, Theiler & Smarsly (2018) proposed an extension of the IFC schema enriching the building model with physical information from sensor networks. Moreover, Krijnen & Beetz (2017) demonstrated the extension of the schema with point cloud data. Tanaka et al. (2016) proposed an extension to capture inspection data of bridges in a web-based prototype. Nevertheless, the IFC standard has mainly been developed for information exchange in data delivery purposes (Lee et al. 2015). It has sophisticated handling of the model view definitions for application domains (1) but is not suitable for dynamic extension Boje et al. (2020).

On the other hand, the modeling approach in a superordinate common data model (2) requires domain-independent modeling utilizing a stack of technologies, which is delivered, for instance, with the semantic web. Besides the usage of IFC, semantic data can be modeled using ontologies making data more accessible, queryable, and inferenceable (Pauwels et al. 2017). The usage of the semantic web in the AECO industries has been analyzed by Pauwels et al. (2017). Several construction-specific ontologies exist that have been modeled using the Web Ontology Language (OWL). This common vocabulary for ontology modeling (Motik et al. 2012) makes these ontologies and their instance data easily machine-interpretable. One of the construction-specific ontologies is the Building Topology Ontology (BOT) presented by Rasmussen et al. (2020), which provides a high-level approach to model the topology of buildings. As an addition, Hamdan & Scherer (2020) demonstrated an alignable sibling of the BOT for bridges, which is available as the Bridge Topology Ontology (BROT) including components and materials. For modeling damages of buildings, the Damage Topology Ontology (DOT) has been presented by Hamdan et al. (2019), which allows to describe, classify, and evaluate damages and technical degradation. Along with this, further ontologies for the description of material and components were published. Kim et al. (2018) proposed ontologies for a semantic web-based facility management approach linking BIM and information from the facility management database.

Combining ontology-based data with model-based BIM-data, the ICDD has been described and standardized in ISO 21597. The information container enables an exchange of heterogeneous original data embedded in a semantic web meta-layer that provides metadata and linking capabilities. With this approach, model data, documents, images, and ontology-based data can be linked, stored, and exchanged. Moreover, information can be queried from containers using semantic web query languages like SPARQL or GraphQL (Werbrouck et al. 2019). The ICDD can be implemented as a partially or fully equipped common data environment providing specified web services for interaction with software applications (Senthilvel et al. 2020).

METHODOLOGY

In this research, a methodology is defined for creating a domain ontology and a corresponding container template to facilitate information exchange in the specific use-case. The first step for the development of a use-case-specific ontology is the definition of the use-case (1), which is reproducible in a defined environment. (see Fig. 2). The use-case includes a characteristic set of actors and sequences and delivers observable results. Technical and legal boundary conditions are considered. After a process defined together with all possible sub-processes, the information flow between participants is analyzed regarding process steps, information artifacts, and communication procedures. For this analysis, a construction company has been interviewed and several information artifacts have been examined. The data of the analysis has been aggregated in a process map.

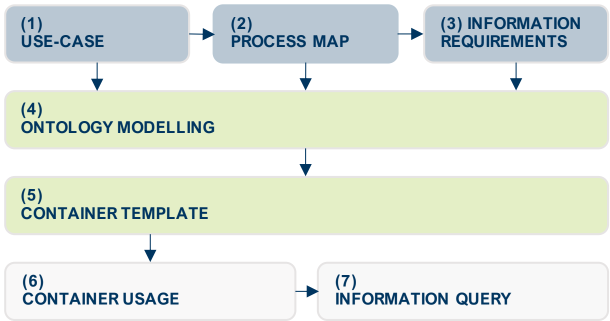

Figure 2: The methodology of gathering required information (blue), creating an ontology and a container template for the use-case (green), and the evaluation in a web platform (grey)

The process map (2) delivers the information requirements (3) for the ontology. The information requirements consider all information that is acquired and exchanged in the process, especially that is available only in paper-based documents. This allows for the creation of the classes and properties in the ontology (4), enables the definition of semantic relations between the model-based data and the decoupled file-based data, and determines the information container used for the evaluation. The technical framework for modeling and publishing the ontology is handled according to common methods presented by Garijo & Poveda-Villalón (2020). With regard to the process map, at this stage, the information container is defined as a template (5) to request specific information from the actors in the workflow. For the evaluation of the ontology and the template, this container will be used and populated with the requested information (6). To prove the feasibility of this research approach, in the last step specific information from the documentation is queried (7) employing a query language.

The first three steps of the workflow shown in Fig. 2 are prerequisites for the ontology modeling and the container template. Together, these steps are presented as the main contribution in the section Experiment. In the section Result Analysis and Evaluation, the use of the container with information collection and queries of information are evaluated.

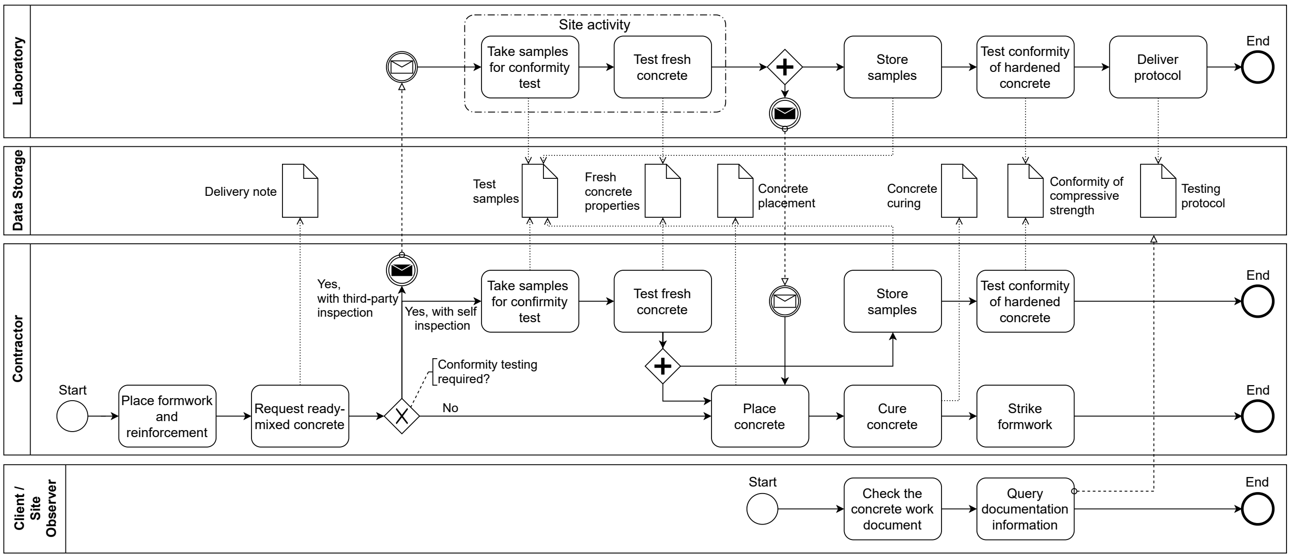

Figure 3: Process map of concreting and documentation with information exchange

EXPERIMENT

Use-case definition

For testing the usability of ontologies for model-based information storage according to the defined methodology, the frequently occurring task concreting in a construction project is taken as the use-case. In practice, concrete casting requires the contractor to document detailed information regarding concrete work on the construction site. Depending on the concrete properties in design, conformity checks must be carried out continuously during construction. This information must be presented to the client or construction supervisor in a verifiable manner for each concreting section and construction component. The following prerequisites apply to this use-case: concrete composition based on properties, placing ready-mixed concrete in situ, conformity test for concrete compressive strength, and testing by a third-party laboratory.

This use-case is specific for construction projects located in Germany and meets the national technical contract conditions and guidelines for structural engineering (ZTV-ING). This German guideline provides information for documentation on delivery, casting, and testing of ready-mixed concrete. The ready-mixed concrete must be tested and documented for fresh concrete properties and hardened concrete conformity in accordance with the standard series DIN EN 1045, DIN EN 206-1, and DIN EN 13670.

Process analysis

The use-case involves the client, the contractor, and, if applicable, the concrete testing laboratory, which are modeled in the process map in Fig. 3. A separate lane is introduced hosting the information artifacts. The whole process is part of the project documentation and the concreting diary.

The actions of the client, contractor, and third-party laboratory are depicted in the process map for performing the work, inspecting the material properties, and recording the data. The process begins with the preparation and delivery of the concrete, which creates the first information artifact to be managed, namely the delivery note. The contractor is responsible for collecting the required information. The inspection of the material properties can either be conducted as a self-inspection or by a third-party laboratory depending on the guidelines and the requirements of the concrete.

The whole casting and testing process creates several information artifacts, which must be considered in the modeling of the ontology. Only after verification of the data of concrete work by the contractor can the performed work be accepted. The client or construction supervisor is authorized to check the concrete work documentation and therefore needs comprehensive access. The documentation is usually done with paper forms. This shows the enormous need for solutions for model-related information management on the construction site.

Information requirements

The information requirements can be directly derived from the processes and information artifacts. The process map in Fig. 3 shows the acquired information: the delivery of the concrete, the test samples of the fresh concrete, the tested properties of the fresh concrete, the conditions of the concrete casting, the conditions of the concrete curing, the conditions of the concrete test storage, the tested properties of the hardened concrete and the documentation of the test of the hardened concrete properties.

These are the minimum requirements an information management solution must fulfill regarding guidelines and regulations. Additional information on the involved persons and organizations as well as their contact data should be captured in the ontology to create documentation that can be reliably used in the long term.

Building Concrete Monitoring (BCOM) ontology

The analysis shows that a specific ontology for concreting and quality of concrete is necessary for this use-case. In the review of literature, ontologies were considered that can represent materials for buildings or bridges, but these are limited to the typification of materials and are not mapped into a specific process. The required ontology is created in this paper as the Building Concrete Monitoring (BCOM) ontology using OWL vocabulary. BCOM is defined for capturing and linking the information of concrete work, concrete curing, and testing of concrete properties. In the following the namespace prefix *bcom* is used representing the ontology URI `https://w3id.org/bcom`. The OWL classes for delivery, placement, and curing of concrete and related classes for tests, test samples, and storage conditions are developed in the ontology. To capture the data of the test persons, test organizations, and the ready-mixed concrete plant, the ontology vCard from Iannella & McKinney (2014) is imported into the ontology. Fig. 4 shows the BCOM components and relations between the classes.

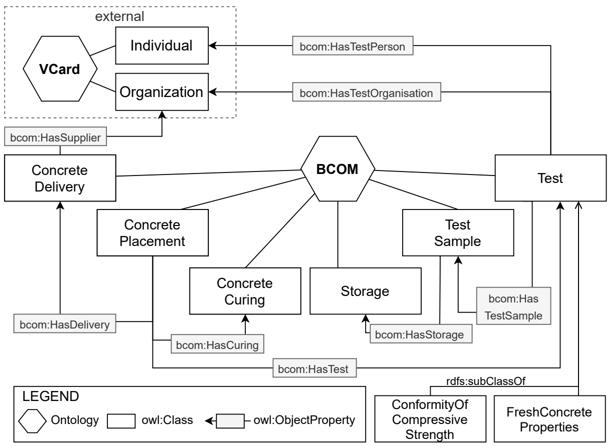

Figure 4: Overview of the BCOM ontology, its classes, and the relations between classes via object properties

To represent the information about concrete work, the classes *bcom:ConcreteDelivery*, *bcom:ConcretePlacement*, and *bcom:ConcreteCuring* are created. The instantiated data is recorded in the comparable scope of the practice-relevant concreting diary. For example, the placement date, quantity, air temperature, and duration of curing are defined as data properties. The delivery notes will later be stored, for legal reasons, in the information container. With *bcom:HasSupplier* the instances of *bcom:ConcreteDelivery* can be linked with the concrete plant as instances of *vcard:Organization*. With *bcom:HasCuring* the instance of concrete placement can be associated with the respective instance of concrete curing. The instance of *bcom:ConcretePlacement* can later be linked with the element of the IFC model in the information container. The material properties of fresh concrete and the conformity of the concrete compressive strength are represented by *bcom:FreshConcreteProperties* and *bcom:ConformitiyOfCompressiveStrength*. The information of test samples can be captured as instances of *bcom:TestSample* with a specific storage condition defined in *bcom:Storage*. In addition, the report of the conformity test should be stored as a document in the information container. With *bcom:HasTestSample* the instances of *bcom:TestSample* can be assigned to instances of *bcom:Test*. Through *bcom:HasTestPerson* and *bcom:HasTestOrganisation*, the test person as instance of *vcard:Individual* and the associated laboratory as instance of *vcard:Organization* can be linked to the tested fresh concrete properties or compressive strength.

Container template for concrete work documentation

The storage and exchange of information according to the BCOM ontology are proposed using the ICDD. The client delivers the container template with prepared data structures, the as-planned IFC model, and a link set template. The contractor supplements the container template with documentation data during the construction phase to create the as-built container. The content of the ICDD according to ISO 21597-1 is structured in three folders: *Ontology resources*, *Payload documents*, and *Payloads triples*. An overview of the content of the information container, the data types, the creation stages, and the creator of the information are presented in Table 1.

As a result of the analysis of concrete work processes, the container must be equipped with the information of concrete work and the delivery notes of ready-mixed concrete of each delivery by the contractor. Conformity test reports are stored as documents in the folder *Payload documents* by the testing laboratory. These also might be stored in subfolders. The concreting documentation is continuously complemented by the contractor. The link set Ifc2BCOM in the *Payloads triples* folder is created as a template and supplemented by the link to the model at each information delivery. The ICDD provides several predefined types of links, of which the generic directed *m*-to-*n* link is utilized to link a set of *m* building elements from the IFC model to an instance of the *bcom:ConcretePlacement*. Furthermore, delivery notes can be linked to instances of *bcom:ConcreteDelivery* and conformity reports linked to *bcom:Test*. The other relations are managed inside the BCOM ontology.

ICDD user interaction platform

During the construction phase and in transition to the operating phase of a building, accessibility of data is one of the main impediments to a successful collaboration between the client and contractors. Therefore, in this approach, a web-based ICDD platform is used and extended to enable a CDE-like information ex-

Table 1: Content of the information container template for the documentation of concreting in construction

Folder	File	Type	Creation stage	Created by
Ontology resources	Container	rdf	container template	ISO 21579-1
	Linkset	rdf	container template	ISO 21579-1
	BCOM	ttl	container template	this paper
	VCard	ttl	container template	Iannella & McKinney (2014)
Payload documents	IFC Model	ifc	container template	as contract document by client
	Conformity Report [1...n]	pdf	during work process	captured by third-party laboratory
	Delivery Note [1...n]	pdf	during work process	captured by contractor
Payload triples	Ifc2BCOM	rdf	container template / during work process	as contract document by client / captured by contractor
	ConcretingDocumentation	ttl	during work process	captured by contractor

change so that the data presented in the data storage lane (see Fig. 3) is accessible to all parties involved.

For the evaluation of the ontology in the following section, the data from the defined ontology will be linked to model data and additional files for documentation. Therefore, the information containers are supplemented with the ontology description as an extension of the underlying ontological schema of the ICDD. Ontologies as well as their imported dependencies belong to the *Ontology resources* folder (see Table 1). For the evaluation of this approach, the existing web-based ICDD platform presented in previous research (Hagedorn 2018) is extended with a parser for payload data according to the delivered user-defined ontologies. Ontology-based payload data in the *Payload triples* folder can be stored within a container using Turtle or RDF/XML syntax. The referenced ontologies are parsed into classes and properties. Instance data from the payload is parsed into individuals according to the classes and properties from the ontology.

Instance payload triples can be viewed, edited, and added in the context of an information container on the ICDD platform using the web interface. Individuals from the payload can be referenced in any link type inside the container using the URI-based identifiers. Moreover, elements from the *Container.rdf* can be referenced from the ontology-based payload.

RESULT ANALYSIS AND EVALUATION

Container usage

To evaluate the developed ontology as well as the created information container on the ICDD platform regarding usability and feasibility, this section presents a practical example for the described use-case. A reinforced concrete bridge is introduced as the construction for the concrete work. The western foundation of the bridge is the element to be concreted. The date and the conditions of placement are recorded in instances of *bcom:concretePlacement* (see Fig. 5). For this concreted element, test samples are taken and stored for conformity testing. This information is generated as an instance of *bcom:TestSample*. In this process, the fresh concrete properties are tested and documented as an instance of *bcom:FreshConcreteProperties*. The curing of the element is documented. The result of the conformity test is also recorded in ICDD as an instance of *bcom:ConformitiyOfCompressiveStrength*, for which the third-party laboratory is responsible in practice. This practice common report is stored as a document in ICDD and is linked to the instance of conformity testing.

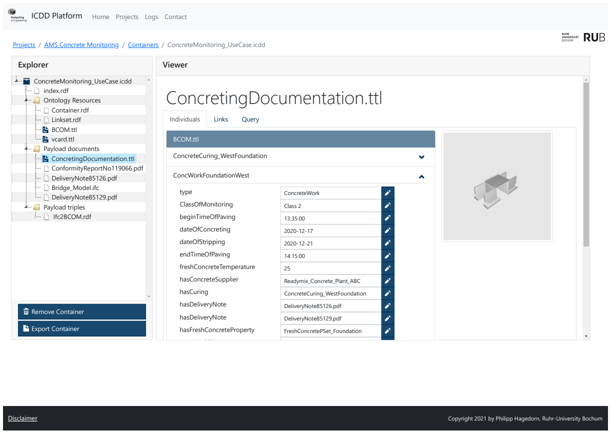

Figure 5: Editing documentation data on the ICDD platform

Information querying

One advantage of machine-readable semantic modeling of information for asset management is the ability to query data according to formal logic and semantic relations. The links between the IFC elements and instances of the ontology provided by the proposed container can be queried using SPARQL on the aggregated data set in a triple store. In a given scenario, all building elements cast from a specific batch of ready-mixed concrete need to be queried for a defect notification of the concreted foundation. A SPARQL query for this scenario can be executed as depicted in Fig. 6.

```
SELECT ?concreting ?ifcGuid WHERE
{ ?delivery bcom:hasSupplier bcinst:Supplier_01 .
  ?concreting bcom:hasDelivery ?delivery .
  ?identifierBcom ls:uri ? concreting .
  [... truncated link element queries]
  ?identifierIfc ls:identifier ?ifcGuid . }
```

Figure 6: Querying documentation data with SPARQL

This query delivers a result set with pairs of the concrete placement procedure and the GUIDs of the respective linked building elements for a specified concrete supplier. Further use-case-related queries are conceivable, for instance, querying over the conformity test to check if the conformity of the compressive strength is fulfilled.

DISCUSSION

The results of the evaluation indicate that the capture and management of information regarding concrete work through ICDD and the ontology BCOM provides significant added value for documentation in the construction process. Linking extensive information on the concrete of built assets to IFC elements has become possible with the presented approach. The implementation in a web-based environment enables participants to integrate information into the as-built data to facilitate lifecycle-oriented asset information modeling. Value creation for the operation phase can be achieved with subsequent use of the integrated data, e.g., by querying over the comprehensive dataset utilizing the ICDD and SPARQL.

The result of research in this paper shows that use-case-specific heterogeneous technical data can be captured reliably and with minimal effort by using the respective ontology. Creating a completely new ontology leads to extensive work, while the extension of the ICDD utilizing existing ontologies is feasible. Nevertheless, the presented approach delivers only a mid-term solution for information management. As it is oriented on the process in practice, it is still partly based on file exchange. Recent research (Senthilvel et al. 2020, Pauwels et al. 2017) has shown that in the future information management in the AECO industries will be cloud-based and decoupled from files. To achieve more interoperability between ontologies, alignments with existing ontologies such as BMAT, BROT (Hamdan & Scherer 2020) or BOT (Rasmussen et al. 2020) should further be considered. The BMAT ontology also describes materials in the context of bridges but has not been considered for the ontology development in this approach, as it does not fulfill the complex requirements of the documentation process.

In terms of data transfer from the construction to the operation phase, it is advantageous if the model data is classified in accordance with the Asset Management System. As classification is specific for projects and differs between nations, Luiten et al. (2018) provided a solution for classifying building elements creating an ontology of the respective classification and executing inferences on the data set. Especially considering the long-term development of as-operated models and digital twins, more building data needs to be captured and managed with domain-specific ontologies as mentioned by Terkaj et al. (2017), which can be used in connection with the IFC building model within a comprehensive ICDD.

CONCLUSIONS

In this research, the BCOM ontology has been developed based on a specific use-case, a process analysis, and information requirements. It consists of five classes, which provide capabilities to capture information of the concrete work and the conformity test of concrete compressive strength. For the evaluation of the ontology, a web-based ICDD platform is extended for the creation of an ICDD including the presented user-defined ontology. Therefore, a test case is applied in which the user-defined ontology is used and linked with an IFC-based bridge model in an information container. Instances of the developed ontology are generated for adding information on concrete work. SPARQL queries of certain information for the asset management confirm the added value of data collected in conjunction with the building model.

Furthermore, the presented approach can be optimized by connecting to other ontologies to give more compatibility when capturing construction information and transferring such information to an AMS. The developed ontology has to be aligned with existing ontologies in the adjacent domains. For a fully interoperable web-based lifecycle information management, further semantic web approaches need to be implemented for a cross-lifecycle use of information.

APPENDIX

Documentation and sources of the BCOM ontology can be found under `https://w3id.org/bcom` and `https://github.com/RUB-Informatik-im-Bauwesen/bcom`.

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