A First Approach to a Semantic Process Model for Enabling an Information Flow for Reuse of Building Materials

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Abstract. As climate change intensifies and materials become scarcer, there is increasing pressure on the construction industry to find more sustainable solutions for controlled deconstruction and the recovery of building components as a future source of secondary building products. The technical implementation for a robot-assisted deconstruction process of concrete elements is already being investigated. At present, however, there is no continuous flow of information between the data of existing buildings, from which components are removed, and new buildings, into which recovered components are integrated. For the testing process and the approval of the components for reuse, it is crucial to know where the elements come from, how they have been constructed and in which context they are to be reused afterwards. The establishment of a semantic process model to extend the Building Information Model (BIM) is the basis for connecting the information from the different buildings and intermediate inspection processes to enable the approval of the components.

Based on existing achievements, a semantic process model was conceptualised, which enables a linking of the information of the building component along the entire process chain. The process model not only connects the information of the existing building and the new building, but also enables the representation of the intermediate process, for example the testing and transport of the component. It can also be connected with the control system of the cutting robot, hence tool position data can be generated out of the process model. A holistic tracking of the component history, the testing and transport process up to the reinstallation in a new building is feasible.

Keywords: Secondary Building Parts · Semantic Web · Circularity · Process Model

1 Introduction

Today, concrete is the most widely used building material in the world. Besides water, sand, rocks and additives, cement is one of the main components of concrete. Every year, four gigatons of cement are produced [1], releasing 8% of the global CO^2 [2]. With the

J. Fottner et al. (Eds.): CLEaR 2023, LNCE 390, pp. 23–32, 2024.
https://doi.org/10.1007/978-3-031-44021-2_3

constantly growing demand, the need for raw materials is also increasing. In addition to extraction, the disposal of concrete also presents our society with new challenges: The dumping of concrete in repositories endangers ecosystems and biodiversity [3].

Current research has been concerned with the non-destructive recovery of building components from demolished buildings as a source for new building parts [4].

By precisely cutting out concrete parts from the buildings to be demolished, new building parts can be produced, which can then be used in new buildings.

For reuse, however, the extracted components must be subjected to intensive special testing [3]. One of the reasons for this is that today's planning models do not allow a connection between demolished and newly constructed buildings, as the current IFC model do only allow one ifcSite [5]. Since the data cannot be transferred to the new model, component information such as construction, reinforcement and installation location of the original component are lost. The aim of the paper is to address this problem by means of a semantic process model. This not only enables the transfer of the original component information into the new component, but also the consistent capturing of the cutting, the inspection and the assembly process.

2 Background and Related Works

Currently, the time-consuming and safe extraction process of concrete components for reuse is a major challenge, here the *Robot-assisted deconstruction for reuse using the example of the concrete wall* (ROBETON) project attempts to accelerate the process by a (semi-) automated cutting process by means of a construction robot with a mounted concrete saw [4]. The approach to a semantic process model to enable a new flow of information for the re-use of building materials beyond BIM is based on the development of the ontology.

2.1 Robotic Deconstruction Process

The ROBETON research project utilizes the knowledge acquired from a demolition machine, which has been established for over four decades to develop an intelligent robot via digital enhancements to its system control. Digital models of the construction planning are connected to the robot control via a newly developed user interface. Additionally, the (semi-) automated construction robot is supported by a mobile robot for environment perception and component detection. The collected data is used for collision-free planning and execution of the controlled demolition and directly transmitted to the robot control for data synchronization with the planning model.

To execute a planned movement in a controlled manner, a complex coordination of several hydraulic axes is required. The individual axis movements are detected by sensors, and the resulting tool movements for a wall saw are predictively planned before actual execution and adapted to the user requirements and actual construction site environment. The (semi-) automated construction robot is able to precisely, automatically, and minimally invasively cut out the components. The cut-out components can afterwards be reused for further construction and renovation measures [4]. Figure 1 shows the a sketch to demonstrate the cutting process in buildings and the real deconstruction machine with the saw.

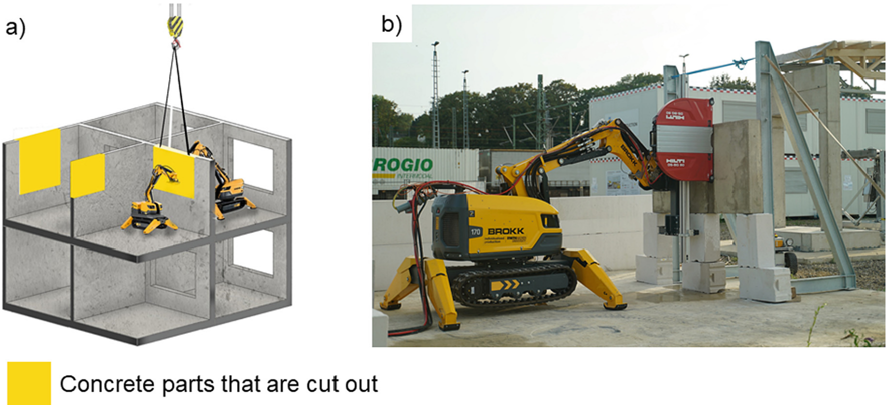

Fig. 1. a) sketch to demonstrate cutting process in buildings, b) real set up of deconstruction machine and saw

2.2 Ontologies in Construction

Ontologies have emerged as a potential solution to address the problem of semantic interoperability [6–9]. An ontology is a formal specification of concepts in a particular domain, involving a logical theory and reasoning capabilities to deduce new knowledge [10]. They provide explicit data semantics, enabling semantic interoperability by representing entities, concepts, and their relationships in a clear and unambiguous manner [11]. Several ontologies have been developed for the construction domain, with approaches including the translation of existing models [12, 13] or the development of new mapping techniques[14].

For instance, the Internet of Construction (IoC) ontology connects different subdomains of construction, including steel construction [14, 15]. There are several approaches to enable a digital information flow throughout the construction lifecycle. The Digital Construction Ontologies (DiCon) consist of six modules for specifying construction domain knowledge. The purpose of the ontology is to address the semantic level of this challenge, by providing essential concepts, terms and properties for construction and renovation projects, representing the evolution of information about a building over successive building lifecycle stages. In addition, the ontologies define the necessary relationships between building elements, construction details, materials, and their properties. It is paving the way to ultimate the integration of information from different decentralized sources over the construction lifecycle [14].

Lee et al. developed an ontology model to assist information handling for prefabrication and on-site assembly processes in construction [16].

The shared ontology for Logistics Information Management in the Construction Industry by Zheng et al. is a presentation of a domain-level ontology as a common information reference for standardizing and integrating construction logistics information. It provides information interoperability between logistics management and construction workflow management and improves the efficiency and transparency of logistics information management. As such, it links construction material with locations, statuses, users and equipment and is evaluated using actual schedule and delivery data of a construction project [17].

The Building Product Ontology (BPO) defines concept to describe building products in a schematic way. It provides methods to define assembly structures and component interconnections and attach properties to any component [18]. Janakiram et al. are concentrating on an efficient representation of various building lifecycle stages in their ontology approach for building lifecycle Stages (BLS). Additionally, it shows stages and sub-stages in the lifecycle of built assets [19]. Thus, focusing on non-geometric descriptions allows manufacturers to benefit from Semantic Web methods without restricting the modelling process of their products [20].

The ifcOWL ontology is built around ifc:root, which contains attributes that enable its association with construction resources, subtasks, and components. The Construction Tasks Ontology (CTO) defines tasks related to construction ventures, including installation, removal, modification, inspection, and repair [12].

The ifcOWL-DfMa ontology is an expansion of the ifcOWL ontology and strives to interpret the lexicon of offsite construction domain in a machine-readable manner, as per reference [21].

Looking at the use of ontologies in construction so far, they can allow linkage of heterogeneous and unstructured data, including various sources of information like BIM or scheduling data. Furthermore, it is advised to have the ontology focus on a specific use-case or problem statement defined as the scope of the ontology. However, previous works have primarily focused on describing general construction processes and do not focus on enabling an information flow for the reuse of concrete components. Therefore, the following methodology focuses on developing a semantic process model for linking the information of concrete components along the entire process chain.

3 Methodology

In the following, the developed process from extraction to installation of the extracted components is described. This description serves as a basis for the further development for the description of the reuse process in the semantic process model. The process is adapted to the German standards for the reuse of concrete components.

1. **Preplanning:** The first step is to capture the existing data and identify the corresponding component. For this, the following required information from the new building must be available: Component size, concrete composition, position, number and type of reinforcement.
2. **Extraction of the concrete:** In the next step, the components are cut out from the wall and transported to the site storage or truck. For this process, the information about position, component and dimension are needed for the path planning of the (semi-) automated robot. In addition, the wall thickness must be known for the adjustment of the saw. After separating the component from the wall, the position of the component must be recorded for smooth removal.
3. **Testing process of the components:** Since each component requires a special release for further use, the component must be subjected to a special inspection. Post-treatment might also be required to ensure durability of the component.

4. **Assembly process:** It might be the case that some sub-components will be joined and assembled to one new component.
5. **Installation in the new building:** In the last process step, the components are installed in the new building. For this purpose, the position of the components in the new building must be known.

3.1 Scope and Competency Questions

The primary approach employed for creating the ontology is detailed in Noy and McGuinness' "Ontology Development 101: A Guide to Creating Your First Ontology" [22]. Using the selected guide, the initial step in the iterative process is to establish the focus and extent of the ontology. This is accomplished by answering three questions concerning the scope (SCQ).

SCQ1 What domain should the ontology cover?

The domain of deconstruction processes for reuse of concrete elements.

SCQ2 What is the purpose of the ontology?

The purpose of the ontology is to link building component information throughout the entire deconstruction process chain. This model not only connects information from the existing and new buildings but also facilitates the representation of intermediary processes, such as component testing and transportation. With this holistic approach, it becomes possible to track the component's history and the testing and transport process until its reinstallation in a new building.

SQ3 What kind of questions should the ontology be able to answer?

The ontology should describe the link between the element information from the original building, the intermediate processes for extracting and validating the element for reuse and the new building, where it will be reinstalled. This means that it should answer questions about the properties of the element and should provide information about the cutting process. At the same time questions about the transport and inspection process as well as the properties of the new building should be answered. The resulting dataset should be able to allow an ongoing information flow along the entire process chain.

Based on the specification of the scope, a set of competency questions (CQ) was developed, referring to the *ROBETON* project and previous research results in the field of Linked Data. They can be found in Table 1. The nature of these competency questions is technical and functional, outlining the precise queries that the ontology should be capable of addressing once it is established. The following list is a first summary of potential questions which cover different information areas. For example, details about the wall properties from the existing building as well as the requirements from the new building need to be accessible to determine the possible reuse applications. Other information are necessary to enable the deconstruction process itself, e.g. the location of the wall in the building need to be known to position the (semi-) automated construction robot. Furthermore, information about the process itself can be stored for quality control and documentation. So far, the component certification for further use is still challenging. Therefore, the ontology also need to include information to provide the basis for the approval process. During the implementation of the ontology it will be evaluated which questions are missing and need to be added to fully cover the process.

Table 1. Competency Questions

Type	Nr.	Questions
Wall properties	CQ1	What is the concrete composition of the existing building?
	CQ2	What is the reinforcement of the wall of the existing building?
	CQ3	What are the concrete and reinforcement requirements of the new building?
Wall location	CQ4	What is the location of the wall which is going to be cut?
Cutting machine	CQ5	Where are the cutting positions on the wall for the component?
	CQ6	What machine and tool will be used to cut the component?
	CQ7	Where are the locations of the machine on site to execute the cutting process?
	CQ8	What is the maximal process force for the machine?
	CQ9	What is the maximal force the machine is able to cover?
Process information	CQ10	How long does the cutting process take?
	CQ11	How much energy was consumed?
Inspection process	CQ12	How does the cutting surface of the component look like?
	CQ13	Is it required to do a post-treatment?
	CQ14	What component certificate is required for the further usage?
	CQ15	What is required for the component certification?
Transport	CQ16	Is the truck able to transport the element?
	CQ17	On which construction site will the component be reinstalled?
	CQ18	When does the component need to be at the new site?
Assembly	CQ19	Which components will be joined together?
	CQ20	What joining method will be used?

3.2 Reuse of Existing Concepts

The principle of Linked Data emphasizes the reuse of pre-existing ontologies. However, our investigation into the current status of ontologies in the domain deconstruction has revealed a lack of adequate approaches. None of the existing solutions can fully address the competency questions, especially in the context of (semi)-automatic deconstruction and reusability of elements. Nevertheless, there are mature ontologies available for concepts related to building elements, element metadata and construction processes, which we believe can be applied to this model. Our aim is to enhance interoperability by incorporating these ontologies. A summary of the ontologies that we will use or link is provided in Table 2.

Whereas the first iteration of the ontology focuses mainly on a broader view of the processes and their relations further developments increased depth. For example, during the set-up of the competency questions and the analysis of the process chain it became clear that components size and weight are limiting factors for the transport. Additional

Table 2. Overview of the connected ontologies

Namespaces	Main classes/focus and purpose of the ontology	Reference
bot	*bot:Zone, bot:Element, bot:Interface* Ontology describing the core topological concepts of a building and the relationships between the concepts. One of the central ontologies introduced within the Linked Building Data (LBD) group	[23]
ifc	*Ifc:Root* Web Ontology Language (OWL) representation of the Industry Foundation Classes (IFC) schema	[24]
ioc	*ioc:process* Ontology developed within IoC to describe processes and process metadata	In print (not published yet)
opm	*opm:PropertyState* An ontology for describing properties that change over time	[25]
schema	*schema:Thing* Collaborative project to develop schemas for structuring data	[26]

requirements for the cutting process and the resulting joining of multiple elements are added to the ontology. Thus, the top-down approach for ontology development, starting with the definition of the most general concepts and refining those afterwards, was used according to Noy and McGuinness.

4 Outlook

This work represents the first conceptional approach for setting up a semantic process model to extend the Building Information Model (BIM) for connecting the information from the different buildings and intermediate inspection processes to enable the approval of the components. Previous studies have predominantly concentrated on outlining broad construction procedures, neglecting to emphasize the establishment of an information pathway to facilitate the reuse of concrete components. As a result, the proposed approach centers on the creation of a semantic process model that connects the information pertaining to concrete components throughout the entirety of the process sequence. Currently, concrete holds the distinction of being the most extensively utilized construction material worldwide. As the demand for concrete continues to escalate, so does the requirement for raw materials. The proposed approach facilitates the establishment of an information base that promotes the reuse of existing concrete components as a secondary resource for future construction endeavors.

In view of the increasing resource shortages [1], this approach to the still young field of concrete reuse offers the possibility of a process standardization. In this way, the individual solutions [1, 3, 4, 30] can be placed in a common context with the aim of: 1) Moving away from a special solution to a broad application 2) Developing new application tools for precise and simplified planning of the reuse processes 3) Developing appropriate tools for extracting the components 4) Standardized connection for assembling the components 5) Cost-effective testing processes for rapid evaluation of the component condition. In future works, the semantic web model will be set up to be able to answer the competency questions raised in this paper.

Subsequent studies must assess the different existing ontologies more extensively to streamline and enhance them to the semantic process model, while analyzing which classes and properties are not yet defined. Additionally, it ought to address the constraints and preconditions of this research, including the essential digital data and modeling proficiency or ways to overcome current drawbacks of utilizing the IFC data model, such as version conflicts or data loss.

4.1 Robotic Implementation

In the following project phase the technical implementation of the robot-assisted deconstruction process of concrete elements and the semantic web approach will be linked. The objective of robotic implementation use case is to connect the distinct process stages (Methodology) with the process model, as only by documenting each step a precise evaluation of the component's quality can be accomplished. The development of the semantic process model creates the basis for this. An instance of a specific process will be demonstrated, elucidating how the position of the component can be transmitted to the robot control of the disassembly robot [27] in ROS [28]. This query consists of three sub-actions.

1) Selection of the desired component. This can be done e.g. via a visual interface or directly via an Application Programming Interface (API).
2) Once the component has been selected, the robot's target positions must be queried. These are the positions where the robot positions the concrete saw to cut the components [4], for each component, positions have been defined adapted to the process requirements (saw, robot, cutting length). The query can be automated via an API that is directly connected to the database. In addition to the positions, the cutting sequence must also be queried, which is necessary for a successful process to hinder the jamming of the saw blade.
3) Subsequently, the data is translated into a geometry_msgs/PoseStamped message [29] in ROS, this can be passed to the robot as a target position. Such a PoseStamped consists of a position [X, Y, Z] in space and the orientation in quaternion format [x, y, z, W]. In addition, each pose is provided with a timestamp that is generated at the time of the query. The positions are passed to the robot controller according to their specified order in a geometry_msgs/PoseArray [30].

Acknowledgement. The ROBETON research project is funded by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) on behalf of the German Federal Ministry of Housing, Urban Development and Building (BMWSB) with funds from the "Zukunft Bau Forschungsförderung".

Furthermore, the development of the paper content was supported by Timur Kuzu.

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