Automation in Construction 57 (2015) 202–212

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

A fuzzy extension of the semantic Building Information Model

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ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form 3 April 2015
Accepted 13 April 2015
Available online 14 May 2015

Keywords:
Building Information Model
Ontologies
Fuzzy ontologies

ABSTRACT

The Building Information Model (BIM) has become a key tool to achieve communication during the whole building life-cycle. Open standards, such as the Industry Foundation Classes (IFC), have contributed to expand its adoption, but they have limited capabilities for cross-domain information integration and query. To address these challenges, the Linked Building Data initiative promotes the use of ontologies and Semantic Web technologies in order to create more formal and interoperable BIMs. In this paper, we present a fuzzy logic-based extension of such semantic BIMs that provides support for imprecise knowledge representation and retrieval. We propose an expressive fuzzy ontology language, and describe how to use a fuzzy reasoning engine in a BIM context with selected examples. The resulting fuzzy semantic BIM enables new functionalities in the project design and analysis stages—namely, soft integration of cross-domain knowledge, flexible BIM query, and imprecise parametric modeling.

1. Introduction

The use of Building Information Models (BIMs) in the architecture, engineering and construction industry has evolved from the early three-dimensional blueprints of the building geometry developed in the 70s to the complex representations of volumes, materials, and equipment that are nowadays more and more frequent. BIMs have proved very effective to increase building quality while reducing design and construction costs by enabling better interoperation between stakeholders [1].

According to the US National Building Information Model Standard Project Committee [2], "a Building Information Model (BIM) is a digital representation of physical and functional characteristics of a facility." A remarkable feature of this definition is that it highlights the relevance of the BIM as a "shared knowledge resource for information about a facility" that provides support for decision-making "during its life-cycle", thus expanding its utilization beyond the design stage. Nevertheless, full-fledged BIM applications covering the whole building life-cycle are still scarce, because it implies interfacing with heterogeneous users who have different background, objectives, and priorities.

For this reason, in the last years there is an increasing interest in the development of knowledge representations able to capture the semantics of BIM data models, but also more flexible and with enhanced query capabilities in order to express different perspectives on building information, to facilitate information retrieval, and to integrate the BIM with other information resources. Given its open and neutral character, the Industry Foundation Classes (IFC) standard, proposed by the buildingSMART alliance [3], has been typically used as the basis for these extended representations. The IFC specification defines an object-based data model written in the EXPRESS data definition language, and an accompanying text-based file interchange format based on STEP. It allows creating readable models and data validation rules, but it lacks a mathematical characterization of the semantics of its representation primitives. Consequently, querying the model is essentially an informal procedure supported by ad hoc implementations.

Not surprisingly, Semantic Web technologies have been proposed to address the challenges of the next generation BIMs [4], since they offer a complete framework for the management of the knowledge published in the Web, arguably the most heterogeneous information environment of our days. The envisioned Linked Building Data cloud, based on the Semantic Web technology stack [5], increases interoperability during the building life-cycle by connecting distributed pieces of BIM data [6,7] and cross-domain data [8]. At the core of the Linked Building Data cloud, ontologies encoded in OWL 2 (Ontology Web Language) [9] are used to define a formal conceptual schema for BIM constituents, and the RDF (Resource Description Framework) language [10] is used to encode BIM instances. We call *semantic BIMs* to these BIMs represented in OWL/RDF. The semantic BIM leverages classical BIM query capabilities by enabling automatic reasoning to retrieve information and to infer implicit knowledge.

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http://dx.doi.org/10.1016/j.autcon.2015.04.007
0926-5805/

The theoretical underpinnings of Semantic Web ontologies are strongly based on Description Logics (DLs), a subset of first order logic especially suitable for representing structured knowledge [11]. However, DLs cannot directly manage imprecise knowledge, which is inherent to several real-world problems [12]. This is the case of the semantic BIM, in which we may like for instance to represent that a building element is *quite big*, two elements are *quite similar*, there are *several* elements inside a space, and so forth. It would be also convenient to allow querying the system in these same terms; for example, to retrieve all the elements with size *around* a dimension value, or those that have been built with *similar* materials.

Fuzzy logic and fuzzy set theory are appropriate formalisms to handle imprecise knowledge. Hence, several proposals of fuzzy Description Logics to support fuzzy ontologies have emerged [13]. Generally speaking, in fuzzy ontologies concepts denote fuzzy sets, relations denote fuzzy relations, and axioms and facts are not in general either true or false, but they may hold to some degree of truth. Fuzzy ontologies are represented by using fuzzy ontology languages, and can be queried by using fuzzy ontology reasoners, such as *DeLorean* [14]. Although fuzzy ontologies have been used in different information science research areas – e.g., information retrieval [15], knowledge merge and summarization [16–19], recommender systems [20,21], and decision-making [22] – , to the best of our knowledge they have not been yet applied to solve industrial problems in practice.

The overarching objective of this paper is to present the fundamental characteristics and the applications of fuzzy ontologies that can be of interest to the BIM users. Rather than focusing on the formal description of the mathematical foundations of fuzzy DLs, we provide examples that show the representation and reasoning capabilities of such formalisms. To do so, we extend the *ifcOWL* and *ifcRDF* models obtained by the IFC-to-RDF conversion tool [23] with fuzzy information. In addition, we describe how they can be exploited in different use cases that illustrate common problems in the building design and analysis stages.

Accordingly, the main contributions of the paper are the following:

- We provide a description of the main features of fuzzy ontologies in the context of the Linked Building Data initiative, avoiding the cumbersome details of the underlying theoretical framework. For the interested reader, we also provide a selection of pointers to related works that elaborate on these topics.
- We present illustrative examples of the main representation primitives of a typical fuzzy Description Logic, and how they can be applied in different use scenarios. We also explain how to use a fuzzy ontology reasoner to query the resulting fuzzy semantic BIM for practical purposes.
- We discuss the advantages of using fuzzy ontologies over non-fuzzy (crisp) representations in the scope of the Linked Building Data research area, considering the current state of the art and the level of maturity of the existing tools, as well as their interrelation with the *ifcOWL* and *ifcRDF* technologies.

The remainder of the paper is structured as follows. First, we describe the materials, methods and tools used in this research work; namely: (i) ontologies as representation formalisms for the BIM; (ii) fuzzy logic and fuzzy DLs for the creation of fuzzy ontologies; (iii) reasoning with fuzzy ontologies. Next, we proceed to describe some relevant representation primitives of the selected fuzzy ontology language. We explain the meaning of each primitive with examples of their use to represent imprecise building data and to make fuzzy queries. We elaborate afterwards on the added value of such extensions in three specific use cases: soft integration of cross-domain knowledge, flexible BIM query and imprecise parametric modeling. We discuss the limitations of fuzzy ontologies and their implementation feasibility in a BIM context, especially from a performance perspective. Finally, the paper finishes with a summary of the most important conclusions achieved and some directions for future work.

2. Materials, methods and tools

2.1. Ontologies and the BIM

Ontologies are typically used for representing knowledge in scenarios that require interoperation between heterogeneous agents. As mentioned, this is the case of the BIM, where several individuals with different expertise are usually involved. Essentially, an ontology is developed from the following primitive elements: (i) classes (or concepts), which determine sets that classify domain objects; (ii) instances (or individuals), which are concrete occurrences of concepts; (iii) properties (also named relations or roles), which represent binary connections between individuals, or individuals and typed values (integers, strings, etc.); and (iv) axioms, which establish restrictions over classes, instances and properties that characterize their features.

Descriptions Logics (DLs) provide a formal substratum to ontology representation primitives by mathematically defining the constructors that can be used to form complex classes, properties, and axioms, as well as their semantics. In particular, the OWL 2 language, the current standard for Semantic Web ontologies [9], is based on the DL named $\mathcal{SROIQ}(\mathbf{D})$ (each letter corresponds to a constructor or set of constructors). A detailed description of DLs is out of the scope of this paper, but the interested reader can found a concise summary in [24].

Beetz et al. proposed in [25] a mapping from the IFC data model to OWL that generates an *ifcOWL* ontology. Later works have implemented procedures to convert a given BIM in STEP format to RDF instances in order to obtain a specific semantic BIM [26]. The IFC-to-RDF conversion software is a publicly available tool that performs both tasks [23]. In this section, we describe some aspects of the models obtained by the IFC-to-RDF tool that are relevant for our fuzzy extension. Notice that, as mentioned by the authors, the translation of a model is not unique, since different conversion strategies can be applied depending on the user needs. We will focus on a slightly modified version of the 'OWL 2 EL–RDF List' ontology.[1] To increase readability, we will use the OWL Manchester syntax in the following examples [27].

In the conversion, IFC EXPRESS classes are mapped into OWL classes, and subtype and supertype relations are represented with class inclusion axioms. For example, the `IfcWindow` entity is represented as follows:

```
Class: ifc:IfcWindow
    SubClassOf:
        ifc:IfcBuildingElement,
    ...
```

Analogously, attributes are translated into OWL properties. Due to some particular features of EXPRESS, such as the rich data type system and the capability to define attributes local to classes, the conversion of properties is not straightforward. Among the possible alternatives, the authors of IFC-to-RDF have successfully used property reification, wrapper classes for data types, and variant names for local properties.

The snippet below represents the `overallHeight_of_IfcWindow` attribute, which translates into a functional `DataProperty` property with defined domain and range. In OWL 2, it would be possible to define a range restriction based on a facet to delimit the values allowed for the attribute:

```
DataProperty: ifc:overallHeight_of_IfcWindow
    SubPropertyOf:
        ifc:overallHeight
    Characteristics:
        Functional
    Domain:
        ifc:IfcWindow
    Range:
        xsd:float[> 0.0f]    # strictly positive values
```

[1] http://ugritlab.ugr.es/r/ifc/schema-EL-RDFList.owl.