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Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry

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A B S T R A C T

In building information modeling (BIM), the model is a digital representation of physical and functional characteristics of a facility and contains enriched product information pertaining to the facility. This information is generally embedded into the BIM model as properties for parametric building objects, and is exchangeable among project stakeholders and BIM design programs – a key feature of BIM for enhancing communication and work efficiency. However, BIM itself is a purpose-built, product-centric information database and lacks domain semantics such that extracting construction-oriented quantity take-off information for the purpose of construction workface planning still remains a challenge. Moreover, some information crucial to construction practitioners, such as the topological relationships among building objects, remains implicit in the BIM design model. This restricts information extraction from the BIM model for downstream analyses in construction. To address identified limitations, this study proposes an ontology-based semantic approach to extracting construction-oriented quantity take-off information from a BIM design model. This approach allows users to semantically query the BIM design model using a domain vocabulary, capitalizing on building product ontology formalized from construction perspectives. As such, quantity take-off information relevant to construction practitioners can be readily extracted and visualized in 3D in order to serve application needs in the construction field. A prototype application is implemented in Autodesk Revit to demonstrate the effectiveness of the proposed new approach in the domain of light-frame building construction.

1. Introduction

A building information model (BIM) is a digital representation of physical and functional characteristics of a facility. It is a product-centric and object-oriented information model whereby enriched building information is hosted by parametric building objects (e.g., walls and floors) as properties. This information can be retrieved from a BIM design model for building design analyses, such as energy analysis and structural analysis. Hence, the BIM model has the ability to support decision making in various aspects of the AEC industry, and boosts work efficiency by minimizing the rework of modeling or collecting building information for different purposes. As such, a large body of research has been focused on leveraging BIM models with discipline-specific information and information exchange between a BIM authoring program and discipline design tools. Nevertheless, it remains a challenge to tailor BIM to suit construction management tasks such as quantity take-off in connection with workface planning, *which is* "*the process of organizing and delivering all the elements necessary, before work is started, to enable craft persons to perform quality work in a safe, effective and efficient manner*" [8]. This is due to the fact that the BIM product model and the construction process model rely on different schemas to organize product and process data. A BIM model, including the Industry Foundation Classes (IFC) based open BIM model, is product-centric and represents an assembly of parametric building objects with properties, whereas a process model is a collection of processes usually organized by a material and method classification system (e.g., the MasterFormat developed by Construction Specifications Institute and Construction Specifications Canada) on the basis of material information, construction method, product design feature, and so forth. For this reason, one activity with a particular construction method (unique production rate and unit cost) in the process model might be only applicable to a specific group of building elements or for a portion of one building element or for a group of non-explicitly modeled building design features in a BIM product model. It is challenging for construction practitioners to obtain quantities in connection with construction activities from a BIM design model. Considerable

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human intervention must thus be involved to interpret the process model and to manually quantify the BIM product model in accordance with the process description.

Quantity take-off (QTO) is "*a detailed measurement of materials and labor needed to complete a construction project*" [13]. It serves as the foundation for other tasks in construction management such as cost estimation and schedule planning, and its accuracy can directly affect downstream analyses and decision making. The QTO process is an information extraction process during which quantities of building elements or features are measured based on the design drawings or the 3D model. BIM offers perhaps the best automatic approach to generating accurate QTO directly from 3D product models [33]. Indeed, BIM-based QTO is currently the most widely used BIM-based application in the AEC industry. Most BIM tools are able to support the QTO feature, including the "Schedules" function of Autodesk Revit. However, the quantities extracted from a BIM design model usually consist of tabular data of explicitly modeled building element dimensions and are product-oriented. This quantity information needs to be further manipulated by means of formulas or filter/aggregation functions in order to obtain construction-oriented QTO information for use by construction planners and trades personnel. Such a cumbersome manual process poses a challenge from the perspective of construction practitioners who take off work packages for detailed construction planning. Furthermore, some information that is relevant to construction practitioners is only implicitly represented in the BIM model, such as the topological relationships and various intersections among the building elements. It is challenging for construction practitioners to extract such specific building information from a BIM design model when it has not been modeled explicitly. For instance, although the open BIM IFC schema defines objectified relationships such as "IfcRelConnectsPathElements" in order to describe the connectivity between building elements, various connections (e.g., L-connection or T-connection), as well as their detailed properties (e.g., connection angle), are not explicitly defined in either IFC or the Autodesk Revit schema. Hence, instances of "T-connection" or "L-connection" representing the connection of walls are not explicitly present in the BIM design model. For this reason, information pertaining to connections (e.g., L-connection) cannot be readily extracted. Such implicitly modeled information restricts space-related information extraction (e.g., quantities of specific types of intersections); hence, the BIM design models are insufficient to account for the details necessary to serve the intended purpose. Additionally, existing BIM design models lack standardized industrial BIM object definitions in specific building domains. For example, studs and plates in light-frame walls are usually represented as "Structural Column/Framing" in the Autodesk Revit BIM design model and as "IFCMember" in the IFC-based BIM design model. These representations are not sufficient for construction practitioners (e.g., trades personnel) in taking off their work packages. As such, BIM design models lack domain semantics in connection with specific building trades. Construction practitioners need to understand the various complex BIM schemas or BIM object definitions in terms of their specific decomposition structure in order to obtain the desired QTO. This would considerably increase the workload and difficulty in their daily planning work. Given this reality, the varying object definitions at present make the BIM models less useful to construction practitioners in performing their specific tasks, while retrieving QTO information relevant to construction practitioners from a BIM design model without domain semantics is still far from efficient.

This paper presents an ontology-based semantic approach to extracting construction-oriented QTO information from a BIM design model. It allows users to semantically query the BIM model using domain vocabularies, capitalizing on building product ontology formalized from a construction perspective. The proposed ontology addresses the limitation of BIM design models in terms of lacking domain semantics and aligns BIM design models with construction-oriented QTO. As such, QTO information relevant to construction practitioners can be easily extracted and visualized in 3D in order to serve practical needs in the construction field. A prototype application is implemented in Autodesk Revit to demonstrate the effectiveness of the proposed approach in the domain of light-frame building construction.

In the remainder of this paper, state-of-the-art research is reviewed with respect to BIM-based QTO. Subsequently, the ontology background and the research scope are presented, and the ontology-based semantic QTO approach is described in detail. The development of a QTO prototype system is then presented. A case study is also shown to validate and demonstrate the effectiveness of the methodology. Conclusions are summarized and limitations of the present research are identified.

2. Literature review

To date, various automated approaches have been explored by which to extract quantity take-off information from 2D drawings or 3D models, such as generating quantities using AutoCAD drawings [27] and Open BIM-based QTO systems [7]. Among these, BIM has emerged as the best automated approach to generating accurate QTO from 3D product models [33]. Most BIM authoring tools are able to support the QTO feature and allow the nearly seamless quantity information exchange for downstream analyses such as cost estimation. Nevertheless, BIM-based QTO may not provide all the necessary quantity data about the product model in the event that the BIM model is not designed with sufficient construction detail. To realize automatic QTO at a sufficient level of construction detail, the BIM model must be "redesigned", which demands even more effort than performing manual take-off. As such, some studies have sought to explore an automatic approach to designing the BIM model in performing a QTO. Kim et al. [15] explored an automated modeling method by which to model a building's interior. Monteiro and Poças Martins [27] proposed an add-on for ArchiCAD that would automatically generate the formwork model based on the structural model of the building. Liu et al. [22] studied an automatic approach to construction-centric BIM with the main focus on the sheathing and drywall modeling for a residential house. Noting that once the detailed information is represented in the BIM model, the thorough QTO in the form of tabular data could be generated by use of the routines in BIM tools. All these efforts pertaining to automatic modeling can improve the efficiency of QTO. Nevertheless, leveraging the BIM model may also result in a redundant information database and further pose challenges to retrieving specific QTO information. In this context, Monteiro and Poças Martins [27] reported that modeling guidelines enable users to extract a thorough QTO in accordance with existing specifications. Those modeling guidelines could filter the relevant information at the modeling phase, rather than at the quantity extraction phase, thus boosting the QTO efficiency.

One important factor impeding BIM-based QTO applications in the construction field is that some information, such as the spatial or topological relationships among building objects, is implicit in the BIM model. To tackle this problem, Borrmann et al. [6] developed a spatial query language for BIM models which enabled the spatial analysis of building and partial building information extraction. The newly developed query language covered spatial operators such as *mindist, maxdist, isCloser* and *isFarther*, which was proven to be a promising approach for partial model extraction that satisfied certain spatial constraints. Subsequently, this spatial query language was extended by adding other