Providing Query Support to Leverage BIM for Construction

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ABSTRACT

Building information modeling (BIM) is an emerging technology and process that provides rich and intelligent design information models of a facility, enabling enhanced communication, coordination, analysis, and quality control throughout all phases of a building project. Although there are many documented benefits of BIM for construction, identifying essential construction-specific information out of a BIM in an efficient and meaningful way is still a challenging task. This paper presents a framework that combines feature-based modeling and query processing to leverage BIM for construction. The feature-based modeling representation implemented enriches a BIM by representing construction-specific design features relevant to different construction management (CM) functions. The query processing implemented allows for increased flexibility to specify queries and rapidly generate the desired view from a given BIM according to the varied requirements of a specific practitioner or domain. Central to the framework is the formalization of construction domain knowledge in the form of a feature ontology and query specifications. The implementation of our framework enables the automatic extraction and querying of a wide-range of design conditions that are relevant to construction practitioners. The validation studies conducted demonstrate that our approach is significantly more effective than existing solutions. The research described in this paper has the potential to improve the efficiency and effectiveness of decision-making processes in different CM functions.

INTRODUCTION

The continuing development of building information modeling (BIM) facilitated by *Industry foundation Classes* (*IFC*) has enabled the sharing, exchange and reuse of building information across multiple disciplines and software applications. BIMs contain a rich information model (geometric, topology and semantic details) related to the life cycle of a facility, and enable enhanced communication, coordination, analysis, and quality control (McGraw-Hill Construction 2008). BIM results in a faster and more cost-effective project delivery process, and higher quality buildings that perform at reduced costs (Eastman et al. 2008). Although much focus has been given to designer's use of BIM, contractors are also using BIM to support various CM functions.

There remain, however, many challenges when trying to fully leverage BIM for construction. The reality is that construction practitioners view a project differently from designers, and hence, require a different type of model; in effect, one specifically tailored to construction practitioners (McGraw-Hill Construction 2008). For example, the location and dimensions of penetrations is important for concrete and drywall construction (Bisharat 2004), the spacing of columns is important for formwork selection (Fischer and Tatum 1997), and the variability of wall sizes impacts productivity (Thomas and Zavrski 1999). These kinds of design conditions result from complex spatial relationships between components, which are not explicitly represented in BIM today. Emerging BIM applications such as *Solibri Model Checker©* (SMC) and *Autodesk® Navisworks®* are addressing aspects of the problem, but offer limited support for construction practitioners needing to identify these more spatially complex design conditions from a BIM.

The research presented in this paper aims to address these limitations by providing a novel approach that combines feature extraction with query processing to leverage BIMs for a broad range of CM functions. The approach supports the automatic extraction and querying of construction-specific features from a given BIM according to the preferences of a particular practitioner or domain.

The next section describes several examples from projects we have studied that illustrate the different kinds of design conditions practitioners consider. We then describe the research framework, and finally outline the results and conclusions.

MOTIVATING CASE EXAMPLES

In this section, we describe case examples that illustrate the variety of design conditions that are important for different CM tasks, including cost estimating, method selection, scheduling, productivity analysis, trade coordination and project management. We focus on those design conditions that are relevant in the process of constructing columns, walls and slabs and building service components.

Openings in building components and their properties (e.g., the location and size) impact construction productivity and methods of construction. Similarly, ***penetrations*** of building components by building services are an important design condition occurring frequently in components, such as walls and slabs. Failure to detect these design conditions can result in a considerable amount of rework as well as site coordination problems. Today, construction practitioners often spend a significant amount of time analyzing and interpreting the different drawings to identify these kinds of design conditions. Figure 1 shows hand drawn sketches created by the site superintendent documenting the size and location of openings and penetrations on a portion of the floor plan of a project we studied.

Current BIM analysis tools provide some support to check for openings and penetrations in a given BIM. For example, clash detection mechanisms in *Autodesk® Navisworks®* Manage can be used to find penetrations on building components. These programs, however, do not differentiate between a conflict, an intersection, or a penetration; they often identify false positives when performing clash detection; they cannot find specific types of intersections, such as intersections between drywall and round columns; and they are unable to provide information about the location and uniformity of these design conditions, which are relevant from a construction and constructability perspective.

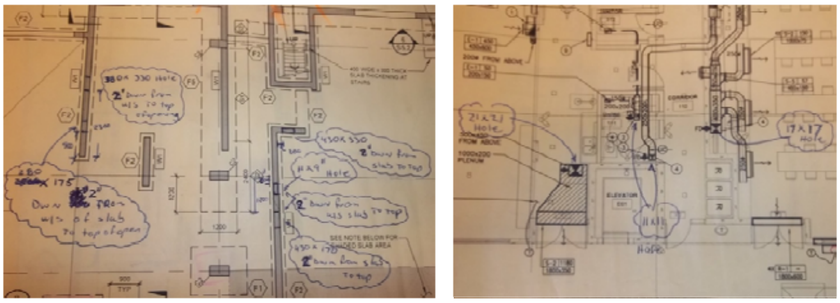

Figure 1. Annotated drawings created by a superintendent identifying the size and location of openings and penetrations

Grouping components is another type of important task required by construction practitioners, particularly cost estimators. Figure 2 shows a typical example of the current practice in which an estimator marks appropriate conditions on 2D drawings (in PDF format) of the building plans using tools like *On Centre*'s *On-Screen Takeoff*, to group and categorize components. This process is inefficient and prone to error. Emerging BIM tools, such as *SMC* and *Innovaya* provide support for grouping components and quantity take-off but lack sufficient flexibility to filter components by variety of criteria (other than size/dimensions and material properties) to meet the varied needs of practitioners, such as cost estimators.

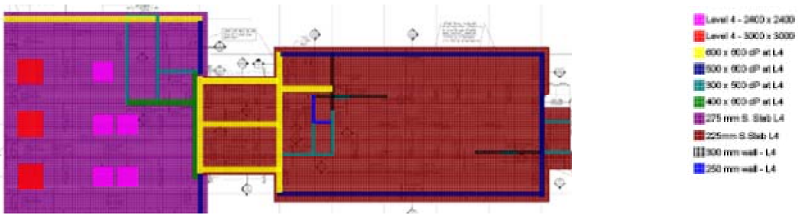

Figure 2. Colour marking of different design conditions by an estimator on a 2D drawing

Uniformity in the design, such as uniform column spacing, allows regular bay size and a regular grid of columns and frames that facilitates more efficient construction of columns and other components. Figure 3 shows the variation in size, shape, and location of columns within a single floor and across the first three floors of a complex engineering laboratory building we studied. Lacking enough computer support, practitioners today have a difficult time identifying these design conditions manually, typically analyzing variations in column schedules or using overlays of 2D drawings for the different floors.

These case study examples illustrate the diversity of design conditions that are critical for assessing construction methods, productivity, costs, etc, and that may occur in every building project. Emerging BIM tools provide some support for identifying these kinds of construction-specific design conditions (e.g., clash detection can be used to find penetrations), but lack the flexibility, comprehensiveness, and formal structure to support the requirements of construction practitioners.

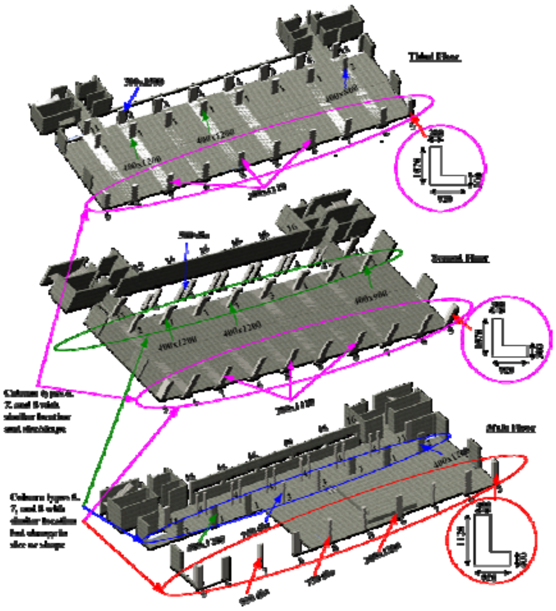

Figure 3. Variation in column size, shape, and location in a floor and from floor to floor

LITERATURE REVIEW

Many research efforts involving reasoning about 3D building or BIM models have been undertaken. They add representation schemas and utilize task-specific reasoning structures in order to construct specific views out of a BIM model. Some related studies use *IFC*-based model or *IFC* model server to generate application-specific views (e.g., Chen et al. 2005). Reinhardt et al. (2005) proposed a navigational model framework to enable the use of the *IFC* model to support data access and collection tasks on construction sites. Other studies have developed ontologies on top of *IFC* model to access *IFC* data (Katranuschkov et al. 2003), support knowledge management (Scherer and Schapke 2011), and to provide generic query and reasoning algorithms for processing building information (Beetz et al. 2009). While our approach and the existing research share the similar goal, which is to support the data access or information extraction from a BIM model, the existing approaches do not appear to combine customized representations a *priori* and at run time to fulfill the required information needs of construction practitioners.

Many researchers have developed specialized algorithms to derive different topological or spatial relationships among building components from a 3D solid model (e.g., Nguyen and Oloufa 2002) and used query-based approaches to provide increased generic support to rapidly generate task-specific views of a BIM model (Borrmann and Rank 2009). However, existing query-based approaches and languages are not widely used in AEC practice today (Haymaker et al. 2004), possibly because they lack simple, generic, formal and expressive framework which enables practitioners to explicitly define construction queries. Our research builds on and shares many common features with previous research to provide a rich, expressive and flexible query support for a variety of design conditions. The next section describes our framework.

RESEARCH FRAMEWORK

Figure 4 graphically illustrates a generic research framework of the system developed. In the first step (*Create Feature-based Model*), the prototype application, '*Feature Extractor*' transforms the input *IFC*-based BIM model into a project-specific feature-based model (FBM) that explicitly represents the features that are important to a particular construction practitioner or domain. For this step, we formalized a *feature ontology* to generically represent construction-specific design conditions.

In the second step (*Query Features*), users configure queries that operate on the project-specific feature-based model. The system takes the query input from the user and executes the application '*Feature Query Analyzer*' to process queries. For this step, we developed *query specifications* to formalize the language and structure of the user-driven queries in relation to a BIM. The query specifications define a query vocabulary and attributes to specify different types of spatial and non-spatial queries.

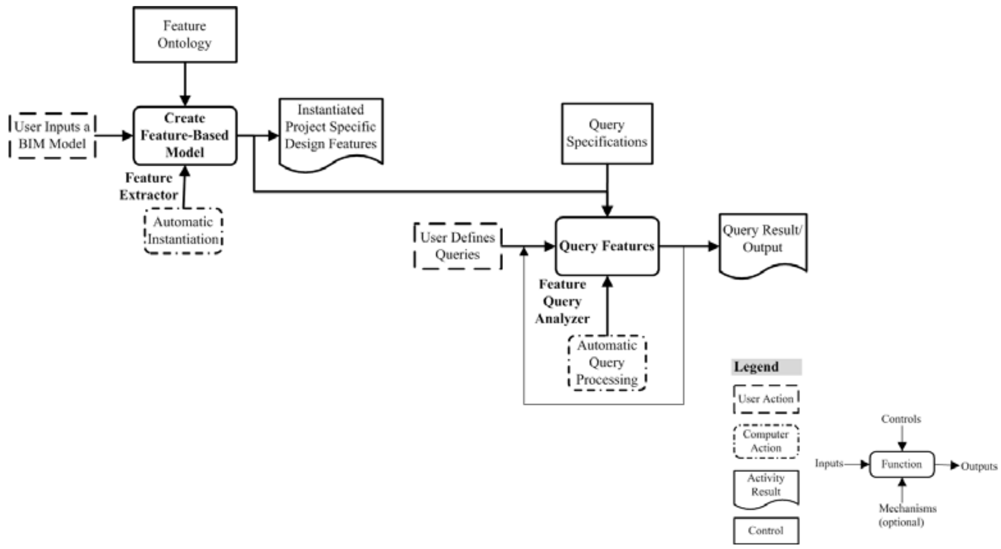

Figure 4. A generic research framework

We used an XML representation of BIM data converted the *Autodesk® Revit®* model for feature extraction and querying. The required BIM data was extracted from *Revit* in two different ways. We made use of ifcXML data as much as possible, as it offers the most comprehensive coverage of the relevant features represented in the feature ontology than other XML formats (Zhang et al. 2011). However, much of the spatial information and relationships between features (e.g., location of ducts on walls), and other geometric information (e.g., area, volume of component intersection and penetration) was not available in the ifcXML. Such data, not available in ifcXML, was extracted from the *Revit API*. We used standard XML query language, XQuery, and custom implemented XQuery spatial query predicates to extract and query features. Zhang (2008) and Webster (2010) provide more details on the prototype implementation focusing on ifcXML data and spatial data extracted from the Revit API, respectively. Nepal (2011) describes a detailed description of the framework and the process and methodology used to support the extraction and querying of BIMs.

Creating a Feature-Based Model

A feature-based model or modeling (FBM) is an explicit representation of design information from a specific viewpoint using the set of features. In the context of our research, the set of features apply the set of semantics to the geometry, topology and other characteristics or attributes of building components, and the related entities or elements that exist on building components.

Feature Ontology

The feature ontology formalizes a common vocabulary, or language, to describe design conditions that are important from the construction perspective. It explicitly represents construction-specific design conditions relevant to different construction practitioners such as cost estimators, construction planners, and site coordinators. The feature "*component*" refers to common building elements and is further categorized into more specific concepts, such as *wall*, *column*, *slab*, and *beam*. The feature type "*intersection*" describes the physical/geometric interaction between objects in a building, and is further classified as *component intersection, opening*, and *penetration*. They represent the specific type and/or the nature different intersection relationships.

Feature attributes characterize the different types of features. They consist of relational attributes and feature-specific properties. Relational attributes establish relationships between features. Feature-specific properties, on the other hand, are distinct attributes that are generally assigned to a specific feature. Table 1 shows generic attributes that characterize *penetration* feature along with some other details.

Table 1. Generic attributes for the feature "penetration"

Attribute	Explanation	Value Type	Cardinality
Depth	Indicates the depth of intrusion of a penetration onto the host component.	Float	Single
Size	Refers to the size of a penetration measured as the combination of two linear dimensions on the surface of the host component.	Float	Double
Area	Represents the area of a penetration obtained by converting size measures into area measures.	Float	Single
Volume	Refers to the volume of a penetration and is calculated as the product of the area and depth of the penetration.	Float	Single
Host component	Indicates the component (e.g., wall, slab) where a penetration exists.	Class	Single
Penetrating element	Building services element that forms a penetration on the host component.	Symbol	Single
Perimeter	Represents the perimeter of a penetration on the plan or elevation view or on the surface of the host component.	Float	Single

Automatically Extracting Features from a BIM Model

The prototype application '*Feature Extractor*' first abstracts and analyzes the relevant geometric, topological, and other attributes and characteristics of objects in the input *IFC*-based BIM and maps them to the concepts defined in the feature ontology (Nepal 2011). This process instantiates the feature ontology to create a project-specific FBM, which the users can interactively browse, navigate and, subsequently, query the project-specific FBM. Figure 5 shows the prototype user interface for browsing the FBM, with some of the instantiated attributes of the instances of *wall* and *wall to wall intersection* features.

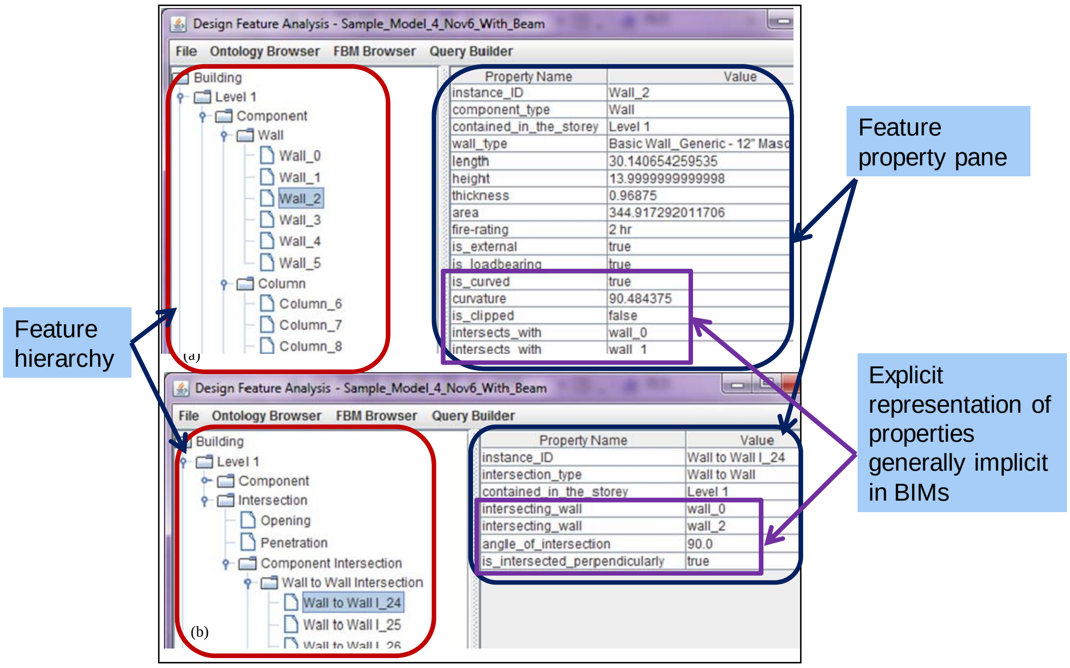

Figure 5. Browsing construction-specific features in the FBM

Query Features

Construction practitioners ask specific questions about features in a BIM model and require answers that are filtered, organized, documented or quantified in a way that is useful for their particular purpose. Our framework enables the user to easily and flexibly specify queries that meet construction practitioners' unique requirements.

Query Specifications

Query specifications provide a formal and structured query vocabulary to specify different types of queries on features. Some basic queries manipulate features and their attributes instantiated in the FBM. Other more sophisticated queries build on and extend FBM to incorporate additional higher level design concepts or conditions, not represented explicitly in the feature ontology, and the resulting FBM. They currently include queries on spacing, location, alignment and uniformity of features. We define different query attributes for flexibly specifying different types of construction queries that meet the unique construction requirements and preferences of practitioners (Nepal 2011). Table 2 shows a list of attributes formalized to specify a penetration query including its location. Figure 6 illustrates some location-specific terminologies for duct penetrations on walls.

Table 2. Query attributes for specifying a penetration query including its location

Query Attributes	Sub-Attributes	Explanation
Query Name		This represents a practitioner's preference for naming a query.
Feature		This attribute allows a practitioner to select a feature to query.
Feature Property Constraint(s)		This attribute allows practitioners to filter the properties of the selected feature.
Target Floor(s)		This allows the user to specify a floor or a set of floors to run a query for.
Host Component		Enables to define the type of component where penetration occurs.
Host Component Property Constraint(s)		Allows to further qualify the penetration queries by constraining the type of host component (e.g., fire-rated dry walls)
Grouping Property		Allows to select a grouping property, or properties for grouping
Aggregate Function	*Count; Maximum; Minimum; Sum, Percent Count, Percent Variation*	We use this attribute to represent simple quantitative measures to allow users to quantify query results.
Location Type		Represents practitioner's preference for specifying the location.
	Horizontal Location	Location assessed horizontal from the frame of reference
	Vertical Location	Location assessed vertically from the frame of reference
Relative Reference	*Dist. from the:*	Allows practitioners to specify the reference/s for specifying the horizontal and vertical location of penetrations.
	Top of the wall	Location measured from the top of the host wall
	Bottom of the wall	Location measured from the bottom of the host wall
	Floor level	Location measured from the floor level
	Floor level above	Location measured from the floor above
	Edge of the wall	Location measured from the edge the host wall
	Wall to wall intersection	Location measured from the intersection of host wall with other walls.
	Wall to column intersection	Location measured from the intersection of host wall with column
Target Location		Location of penetration, either as the 'feature centre' or 'feature boundary.'
	Feature Boundary	Location measured to the proximate boundary of each penetration.
	Feature Centre	The location measured up to the centre of each penetration.

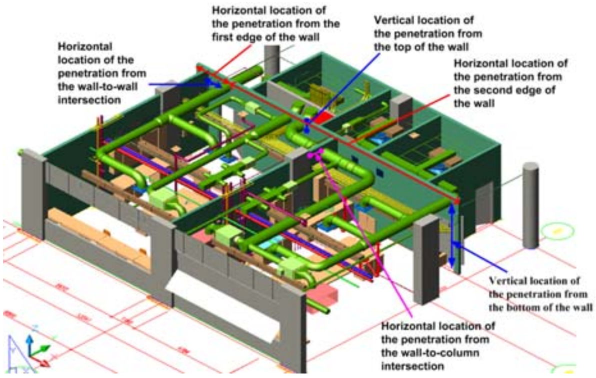

Figure 6. Illustration of location of duct penetrations on walls

Formulating and Answering Queries

Users make use of a series of reusable, customizable, expressive and computer interpretable form-based query specification templates to interactively formulate queries. Querying a BIM is easier for the end users who are familiar with the domain concepts but normally do not have sufficient knowledge of the *IFC*, underlying BIM data models, or query languages. A set of snapshots in Figure 7 highlights different query steps for formulating a query to identify penetrations and their locations. Figure 8 shows the corresponding query results in the form of XML output (the inset shows a mock-up of an instance of a penetration with location parameters).

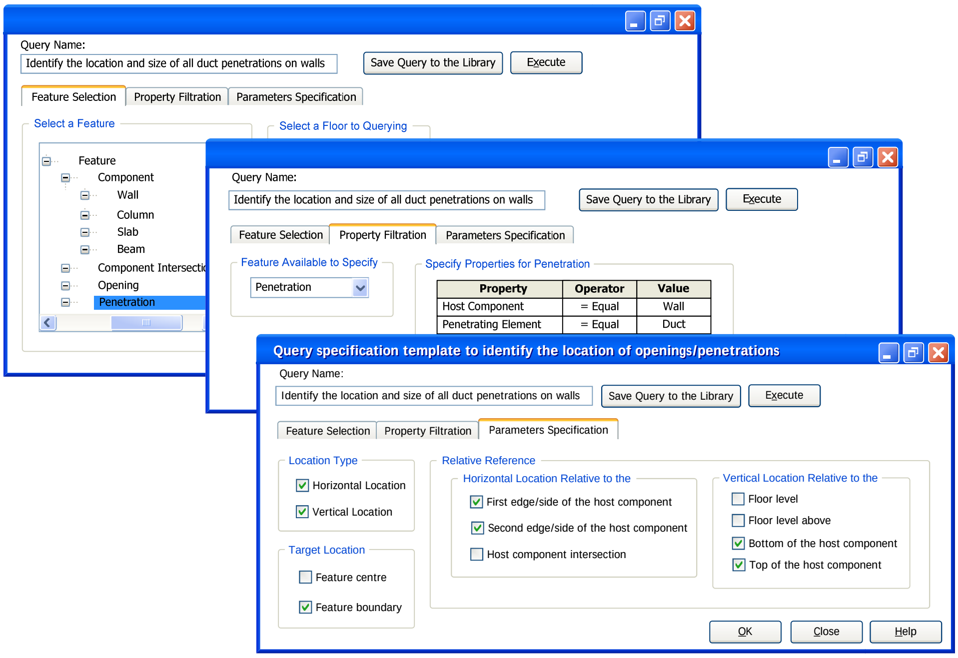

Figure 7. Query formulation interfaces for specifying a penetration query


```
<Penetration>
    <Wall gml:id="133152"/>
    <Duct gml:id="149164"/>
    <area uom=#sq-ft>0.39</area>
    <volume uom=#cu-ft>3.95</volume>
    <location>
        <gml:Point srsName="gml:CartesianCS">
        <gml:pos>-34.24 42.04</gml:pos>
            </gml:Point>
        <gml:Point srsName="gml:CartesianCS">
        <gml:pos>-34.24 40.54</gml:pos>
            </gml:Point>
        <gml:Point srsName="gml:CartesianCS">
        <gml:pos>-33.27 42.04</gml:pos>
            </gml:Point>
        <gml:Point srsName="gml:CartesianCS">
        <gml:pos>-33.27 40.54</gml:pos>
            </gml:Point>
    </location>
    <locationOnWall>
        <distanceFromWallTop uom="#ft">2.25
            </distanceFromWallTop>
        <distanceFromWallBottom uom="#ft">6.25
            </distanceFromWallBottom>
        <distanceFromWallLeft uom="#ft">8.75
            </distanceFromWallLeft>
        <distanceFromWallRight uom="#ft">19.75
            </distanceFromWallRight>
    </locationOnWall>
</Penetration>
```


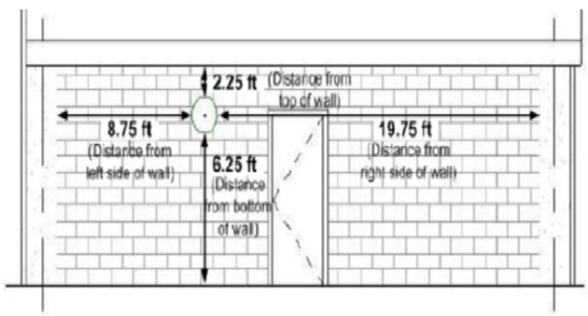

Figure 8. A sample output from the penetration query and an instance of duct penetration

CONCLUSIONS

Construction practitioners today have an increasing need for quick and easy retrieval of information from a BIM, delivered in a way that meets their expectations. This paper described the necessary representation and reasoning mechanisms to provide query facilities to leverage BIM for construction. The validation studies conducted, described in Nepal (2011), provide evidence for the relevance and importance of the concepts formalized in this research, the flexibility and the effectiveness of our approach compared to existing tools. The research described in this paper has the potential to support decision making in a broad range of CM functions, enabling practitioners to better plan, coordinate, estimate, and execute their work.

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