ANALYZING AND DEFINING INFORMATION REQUIREMENTS OF KNOWLEDGE INTENSIVE CONSTRUCTION MANAGEMENT TASKS ON BIM

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ABSTRACT

With the increasing popularity and adoption of building information modeling (BIM), the amount of digital information available about a building is overwhelming. Enormous challenges remain however in identifying meaningful and required information from a complex BIM model to support a particular construction management (CM) task. Detailed specifications of information required by different construction domains and expressive and easy-to-use BIM reasoning mechanisms are seen as an important means in addressing these challenges. This paper analyzes some of the characteristics and requirements of component-specific construction knowledge in relation to the current work practice and BIM-based applications. It is argued that domain ontologies and information extraction approaches, such as queries could significantly bring much needed support for knowledge sharing and integration of information between design, construction and facility management.

Keywords: construction management, BIM, digital model, building, information management

1. INTRODUCTION

The Architectural, Engineering and Construction (AEC) industry is a knowledge intensive industry, with complex networks of project organizations and stakeholders. It generates large volume of project information - product and process related information. With the increasing use of BIM to plan, design, construct, manage and operate the built environment facilities, the amount of digital information that is generated during these different phases of a construction project is overwhelming. The richness of information provided by BIM also comes with increased challenges and complexity on how to effectively integrate and manage that information in the existing work process. Moreover, it takes significant amount of time and efforts of BIM users, such as cost estimators and site personnel to find the right information, only the required and relevant information, in an appropriate level of details or granularity in a BIM model.

There has been an increasing focus on top-down, technology push approach to bring meaningful changes in the entire supply chain of the construction industry through the adoption of BIM. This approach alone, however is not sufficient, as any new technology such as BIM should consider the existing work practices and business processes for its successful implementation (Hartmann et al. 2012). There needs to be an alignment of technology push strategy with technology pull approach, and the BIM should not be seen as the "disruptive technology" by organizations and actors in the construction industry. Attention needs to be paid to defining services and supporting business processes through service oriented approaches such as ontology-based knowledge structures and semantic services (Rezgui et al. 2011). Detailed specifications of information required by different construction domains and expressive, flexible and easy-to-use BIM reasoning approaches can significantly leverage BIM in support of construction and other downstream business processes.

The purpose of this paper is to highlight the component-specific knowledge that construction practitioners care about and that needs to be represented in the BIM environment and/or identified from a BIM model. The paper uses the observation of case studies, existing work practices or processes and BIM tools to critically examine the construction requirement for such information in the context of BIM. It then provides a discussion and implications for future research, including the related research on information retrieval. We also provide a brief discussion of the recent research undertaken for enriching BIM and extracting useful and relevant information from a BIM model using ontologies and queries.

2. CAPITALIZING THE DOMAIN KNOWLEDGE AND EXISTING BUSINESS PROCESSES

2.1 Building component-specific information and flexibility to define component types

Construction practitioners, such as the cost estimators have different ways of defining component types, and grouping or categorizing them. Table 1 shows some of the criteria cost estimators use to define wall types that we identified through a detailed a case study of two institutional and one commercial buildings in Vancouver, Canada. Traditionally, architects or designers define wall types generically and provide detail drawings and specifications of components and components materials. They employ pre-defined symbols, assembly details, and descriptions, and annotate the 2D drawings to convey design intent and requirements (see Figure 1). Construction practitioners, such as cost estimators manually or semi-automatically derive the required construction information from the available design documents. In BIM applications, such as *Revit*, designers use pre-defined wall types, or define new wall types, derived from the family of wall types already defined in that application, and add assembly details, and type properties (parameters) of walls (Figure 2). Cost estimators, schedulers, and other practitioners must manually work to filter and group similar wall types, based on criteria, such as those listed in Table 1.

Table 1: Different criteria for defining wall types by cost estimators

Wall typing criteria	**Example/s (with type italicized)**
Generic wall name	*Masonry* wall, *Dry*wall, *Concrete* wall
Constituent materials	*Steel stud* drywall, *Brick veneer* wall
Material properties	5/8" drywall, Wall concrete-35Mpa
Location in relation to interior or exterior of a building	*Interior* steel stud walls, *Exterior* wall 8' to 16 high
Shape (plan view)	*Straight* wall, *Curved* wall
Shape (elevation view)	*Vertical* wall, *Battered* wall
Change in height	*Clipped* wall, *Non-clipped* wall
Dimensions (height/length/thickness)	*190 mm* concrete block wall
Wall height relative to slab and ceiling	*Full height* wall, *Ceiling height* wall
Location on the floor	*Basement* wall-300 mm, *Foundation* wall-concrete block
Location on the floor space	*Classroom* wall, *Corridor* wall, *Theater* wall-300 mm
Generic wall properties	*Fire-rated* wall, *Acoustically-rated* wall, *Load- bearing* wall
Type of construction	*Precast* wall panel, *CIP* concrete wall
Wall function/usage	*Shaft* wall, *Core* wall, *Fire* wall

Cost estimators have different queries about wall types. For instance, estimators often want to formulate a query: "*Group all walls by type and height, and then calculate the total linear foot and area for each wall type*." This query is of interest to them, because different wall types may have differing productivity rates and require different construction operations. For example, estimators use different productivity rates or equipment for different ranges of wall heights. In order for estimators to flexibly define and extract right information, such as wall types, two requirements need to meet: (1) richer information about components (attributes, properties), such as walls needs to be provided in a BIM model, or (2) there needs to be a way for practitioners to flexibly define, manipulate or derive information from the model without much difficulty.

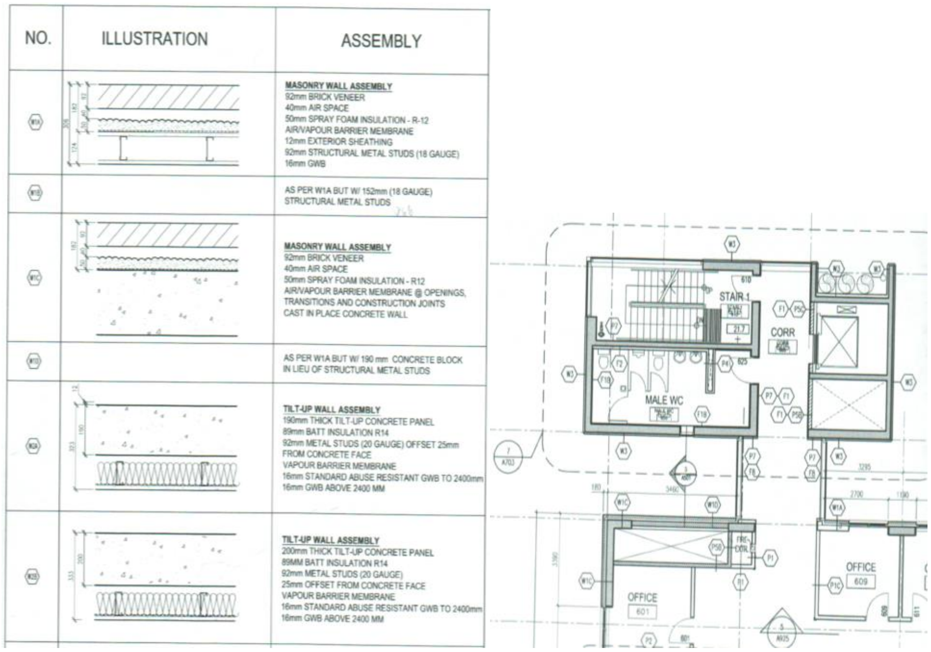


Figure 1: Style of designating and defining wall types and applying it to an actual design

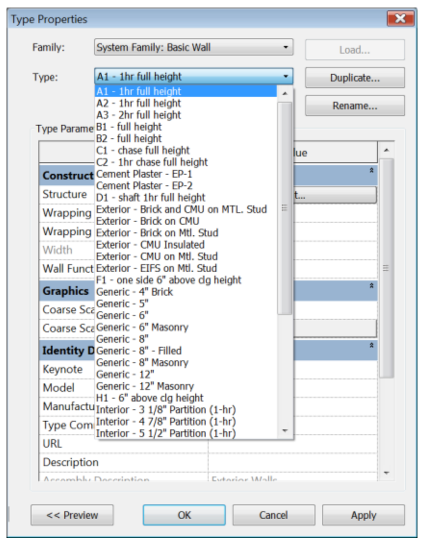


Figure 2: Methods of defining wall types in *Revit Architecture*

Majority of estimators group walls and take-off quantities using non-BIM based interactive and semi-automated processes. For instance, the estimators that we interviewed spend a significant amount of time colour-marking appropriate conditions on pdf drawings of the building plans using computer tools, such as *On-screen Take-off* in order to categorize components by material and other component properties. For example, in one of the projects that we studied, estimators marked the types of building components on floor plans (Figure 3), different types of floor/slab finishes on components, and different ceiling types and finishes in the reflected ceiling plans (Figure 4), and different types of exterior elements, such as curtain walls, sunscreen systems, and vents, in elevation views (Figure 5). When a design changed, the estimator had to repeat the whole process of color-marking for the components affected, which is very inefficient.

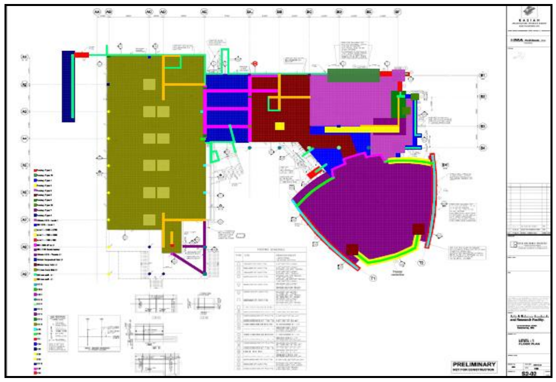


Figure 3: Colour-marking of the appropriate type of components – walls, columns, slabs on grade, suspended slabs

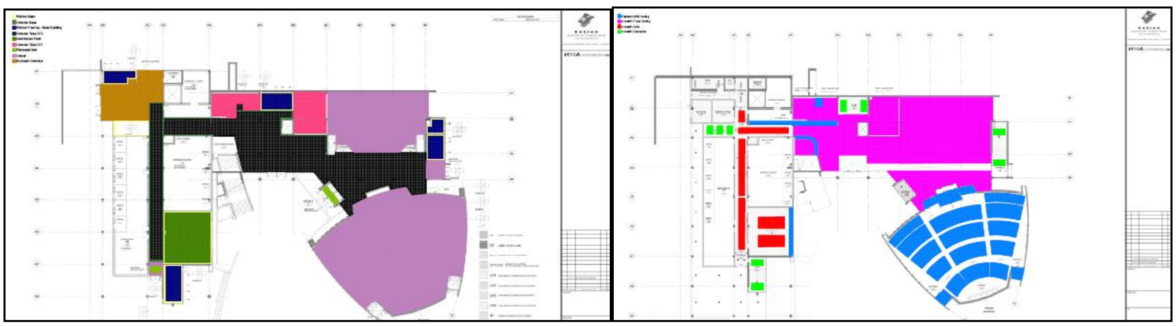


Figure 4: Colour-marking of different (a) floor finishes in the floor plan, and (b) ceiling types and finishes in the reflected ceiling plan

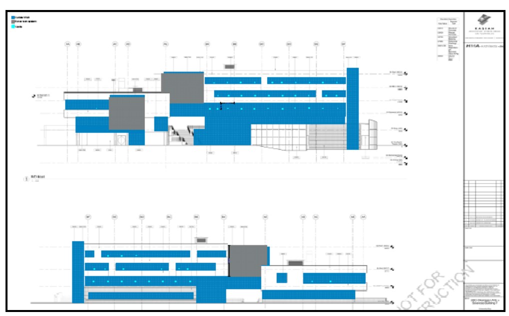
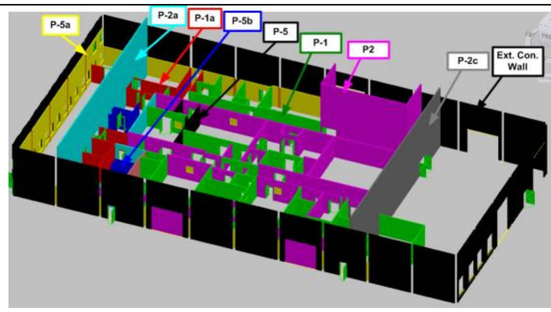
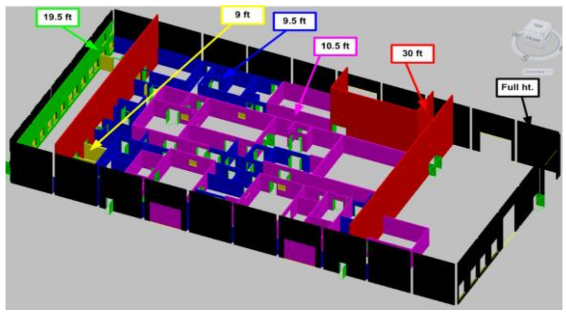


Figure 5: Colour-marking of curtain walls, sunscreen system, and vents, in elevation view

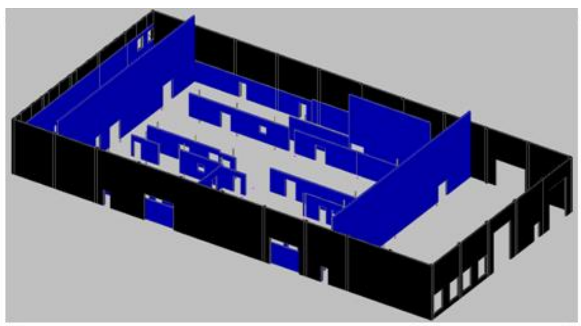
Estimators are better off if they can specify conditions (spatial and non-spatial) on a BIM model expressively and with ease of use rather than manually marking conditions on a pdf design. The systematic filtering and grouping of components can also aide to the better visualization and understanding of a given design to support construction. For example, estimators can categorize different types of walls (Figure 6 a) to accommodate the specific items needed in the cost estimate and base crew productivity. They can organize walls based on wall heights (Figure 6 b) to take into consideration of differing crew productivity and the methods required for their installation. They can identify the instances of wall connections with columns and exterior walls (Figure 6 c), since these require additional set-up and framing time.



(a) Different wall types as defined by an architect



(b) Corresponding walls of Figure (a) when categorized by wall height by an estimator



(c) Drywall instances (shown in blue) from Figure (a) connected to columns

Figure 6: Grouping of walls using different criteria

State-of-the-art BIM tools do provide limited support to flexibly query component types. *Solibri Model Checker* (*SMC*) provides some support to identify instances of components. However, the parameters defined in *SMC* are narrow and the knowledge encoded is not adequate to support a wide range of construction-relevant queries. *SMC* populates components with properties or attributes that are explicitly defined in the BIM application. *SMC* is however unable to identify component features with component specific and relational properties that are important to practitioners. While it allows the user to work with at the generic component level, such as wall, column, beam, duct, pipe, etc, it is not easy to specify a particular type of component based on its characteristics, such as material, dimensions, geometric shape, etc.

While *Industry Foundation Classess (IFC)* and *Revit* provide rich information about a building and its components, some important construction-specific information is either not explicitly represented or missing. For instance, the designations of a 'full height wall' or 'ceiling height wall', and 'wall shape' are not explicitly defined. The categorization of components, such as wall type (or any building component typing, in general, for that matter), in the *IFC* model or *Revit* does not largely resonate the way practitioners think about different component types (Nepal 2011). It should be understood that *IFC* largely leaves the definition of component types (e.g., wall type) completely to the modeling application, and to other model extension software, through type definitions (*IfcDefinesByType*) and through the definition of properties. *IFC* is a weak (loose) typing system, allowing rich and multiple representations (Venugopal et al. 2012). *Revit* has some limited pre-defined wall types, which the user can edit to define instances of new wall types.

BIM tools provide another mechanism to structure their data by using classification schemes (e.g., Masterformat, Uniformat, etc.) which can be used to structure the domain information such as simple groups. This is a flexible and informal method implemented at the software user level as compared to typing, which is formal and implemented at programming language level (Venugopal et al. 2012). However, such classification schemes are not clearly defined in *IFC*. And, there can be many ways to classify building objects and/or information.

2.2 Requirements to provide better support for identifying component intersections, openings and penetrations, and real clashes

The existence of component intersections and characteristics of intersecting components are of interest to construction practitioners because they impact constructability, construction productivity, and costs. For example, the masonry and dry-wall contractors are interested in identifying dry-wall to column, masonry wall to column, masonry wall to slab, and block wall to beam intersections. Site superintendents that we spoke with in one of the projects wanted to know the intersections of concrete walls with other components, such as columns, pilasters, beams and slabs. The formwork contractor on the other project needed to know the numbers of T- and L-intersections of the concrete walls. Practitioners need to identify a specific type of intersection, based on specific properties or characteristics of intersecting components (e.g., intersections between concrete block wall and slab, intersections between dry wall and round columns, etc.). Additional relevant information, such as the size of the intersection, and the area and volume of the intersection is also required. However, component intersections are not always explicit in BIM models, such as *Revit* models, especially when the components are modeled by different professional domains, such as architects and structural engineers.

While the *IFC* provides objectified relationships to connect components in some way, it is up to the *IFC*-complaint software, or the modellers, to explicitly define these conditions in the 3D model. BIM based-applications provide some support to identify the intersections between different components. *NavisWorks*© provides an extensive set of options for selecting individual elements, or element groups, within the model. Objects in *NavisWorks* can be selected at different levels (an individual object, a group, such as a block or cell, a layer or level, or an entire model), as defined by the CAD application in which the model was first created. Unless the building components in the authored CAD application(s) are clearly and properly differentiated into different categories, the clash detective in *NavisWorks*© does not have the intelligence nor the knowledge about building components, other than the geometry of CAD objects. From that perspective, *NavisWorks*© falls squarely into the CAD category, rather than the BIM category (Khemlani 2008). *SMC* is a state-of-the-art BIM-based application, with sophisticated level of intelligence about building components. It, however, does not allow the properties of a component to be filtered in order to specify the intersecting component type.

Building components contain many openings and penetrations. It is a major challenge to find different kinds of penetrations on walls, slabs, etc. on each floor of the building. Practitioners spend a significant amount of time manually identifying the location, size, type and other pertinent details, of these penetrations. For instance, a site superintendent marks and annotates penetrations or openings and other relevant details on several drawing sets. The identification of slab penetrations by ducts (Figure 7 a) and wall penetrations and openings for pipes, ducts, cable trays etc., for instance in structural walls (Figure 7 b) is very time consuming and error prone tasks for site superintendents, especially for complex building projects with extensive mechanical, plumbing, electrical, and communication services. The information about the specific location (horizontal or vertical) of openings and penetrations is also critical for constructability analysis and for construction planning and execution.

BIM analysis software provides excellent support to check for interferences and clashes of components, and helps to ensure the integrity of the 3D model. For example, *SMC* analyzes a BIM for its integrity and quality to ensure that there are no pertinent design errors, such as overlapping components. *NavisWorks*© provides a suite of applications that includes interference checking and clash detection of 3D models. The interference checking and clash detection module allows users to select the elements, or groupings of elements, that are to be checked against each other, to specify a tolerance value, and set the options for clash type and interference method. It thus helps practitioners to detect errors and coordinate designs, prior to construction. The clash detection mechanisms in *NavisWorks*© and *SMC*, can be used to identify penetrations on building components. Moreover, these mechanisms do not differentiate between a conflict, an intersection or a penetration (Nepal 2011).

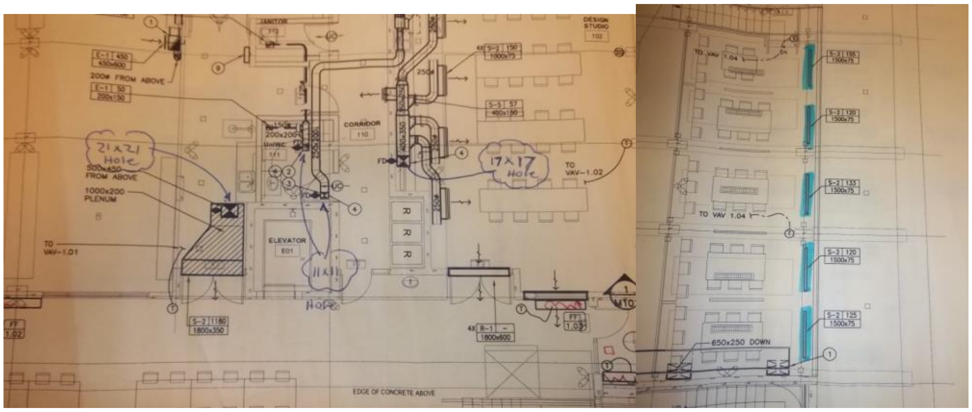


Figure 7: Hand marking of (a) the size of duct penetrations on a portion of a slab and (b) the openings in structural walls

The clash detection mechanism in *Solibri* and *NavisWorks*© is meant to detect errors, or interferences, such as a duct passing through a beam, and is useful to ensure the quality of the given model. These tools also provide support to check for clearances, and find hard and soft conflicts. They, however, do not provide sufficient support to locate the intersections, which are not conflicts themselves, but rather genuine intersections of interest to practitioners. Also the support for users to specify the host component, or the properties of the host component, in the analysis, is lacking. BIM users should be able to flexibly define a query to specify the host component, where the penetrations (or openings) have to be found, the type of penetrating elements, (i.e., duct, pipe, conduit, etc.), and relevant properties of interest, such as the dimension (size, area, perimeter, etc.) of each penetration. For instance, a drywall contactor should be able to automatically find penetrations on fire-rated walls; a roofing contractor should able to rapidly identify all existing roof penetrations, and their pertinent details. There needs to be a better BIM support for users to automatically identify the intersections between components of interest according to their preferences. This enables construction practitioners to identify meaningful information, and to better understand the design in support of their decision making process in the construction planning and execution. The issue of false positives generated during the clash detection process with the current BIM tools is in fact very alarming and requires lots of manual work and rework. In his keynote speech in CIB World Congress 2013, the manager for integrated building solutions, Turner Construction Company, acknowledged that only 28% of all clashes identified by clash detection tools actually turn out to be “real” clashes in their BIM projects.

3. DISCUSSIONS AND IMPLICATIONS FOR RESEARCH

The above discussion presented a context and some insights for enriching BIM and aligning BIM and BIM-based tools with the information needs of BIM users and existing business practices. It should be noted that there is a lack of clear understanding and agreement on whether:

- All information needed by end users should explicitly be represented in an *IFC* model.
- A designer or the specialty discipline downstream in a supply chain, should define all the needed information explicitly in the BIM tools.
- There needs to be a way for end users to specify conditions or compose information out of the primary representation provided in a BIM model.

Nevertheless, retrieving meaningful information to meet the unique need and preferences of BIM users and practitioners, and flexibility and ease with which the required information can be extracted from a design-centric and product-oriented BIM model, remains a challenge to realize the full potential of BIM (Nepal 2011). In an effort to address this challenge, we employed a declarative approach to extract construction-useful information from a BIM, using domain ontologies and queries. This approach involved the following steps:

- Knowledge elicitation and acquisition about generic components of a building.
- Formalizing concepts - entities and their attributes - and representing them in an object hierarchy.
- Formally represent the ontology on *Protégé Frame Editor*.
- Instantiating the ontology by mapping the concepts defined in the Ontology with the concepts defined in the *IFC* model and/or BIM authoring tool (in our case, *Revit*) using XQuery.
- Developing a query vocabulary.
- Developing query specifications and encoding query-specific domain knowledge into query templates, and
- Leveraging XQuery and custom developed spatial query predicates to answer spatial and non-spatial queries.

Nepal et al. (2013) describe the development of a feature ontology and the process for querying a BIM model by leveraging the concepts defined in the feature ontology. The feature ontology specifies important domain concepts, which are formalized into a set of features and attributes (properties and relationships) and are represented hierarchically. It provides a domain specific concepts or information that the experts in that domain care about, which then can be used to generate project specific views. In addition, the features and attributes defined and represented explicitly in the ontology enable the BIM user to expressively define component types at query run time to extract tailored information from a BIM. Cost estimators can use these predefined properties and relationships to characterize a specific type of component, define grouping criteria, and quantitative functions. The estimator can use a range of wall properties, such as dimensions (thickness, length, height), wall type materials (masonry, stud, concrete), shape (curved, clipped, straight, battered), and other properties (load-bearing vs. non-load-bearing, exterior vs. interior, fire-rating, acoustic-rating, etc.) to define wall types. A variety of quantitative functions such as count, percent count, sum (total), average, maximum, minimum, and range further enable estimators to obtain the required aggregated information.

Querying a BIM for spatial queries is very challenging as many spatial relationships are not explicitly defined in an *IFC* model or underlying BIM model. Moreover, there is a lack of support to answer spatial queries on BIM (Borrmann and Rank 2010). Nepal et al. (2012) describe a framework that integrates ifcXML data and other spatial data and that employs custom 2D topological XQuery predicates to answer a variety of spatial queries. Providing declarative query support for BIMs are particularly important not just for searching a BIM but also for extracting partial models or views from a building model (Borrmann and Rank 2010). They can be extremely useful to support a range of design and construction purposes and tasks listed above. Many researchers have used rule-based reasoning for automated code checking in Australia, Norway, Singapore and the USA (Eastman et al. 2009). We would expect the use of more such systems to increase significantly in the future. Borrmann and Rank (2010) provide an overview and comparison of currently available different query technologies for BIM and state that native Express-X, SQL and XQuery are the most commonly used languages.

The usability of BIM-based applications from the end user perspective is another important issue. End users, such as the construction or facility management professionals need not be required to have the knowledge of query languages or underlying data representation or schemas of *IFC* or BIM tools. In fact, the seasoned construction BIM users should be able to formulate queries in an easy, flexible and interactive way, without bogging down on the complexity of codes and query expressions. They should be able to define conditions on the fly using pick and choose approach. In order to facilitate such requirement for extracting domain-specific information from a BIM model, Nepal (2011) has developed query specifications. Query specifications define a query vocabulary that is encoded into the sets of expressive and user-customizable query templates. The users can use such templates to easily and interactively formulate customizable queries in order to extract the meaningful and required information (Nepal 2011).

Much of the information retrieval or search systems in information science literature focus on retrieving information from an unstructured or semi structured large collections of textual data or document collections. However, in reality, almost no data are truly "unstructured" – even textual data has some sort of structure (Manning et al. 2008). Information retrieval also involves browsing or filtering document collections and further processing a set of retrieved documents. The spectrum of information retrieval or search can range from (a) web-based search, (b) enterprise, institutional and domain specific search to (c) personal information retrieval such as integrated information retrieval built-in within the personal computer or applications (Manning et al. 2008). The approaches generally fall into three categories: statistical approaches (e.g., classic Boolean model, vector model, probabilistic model); semantic approaches (e.g., morphological analysis, lexical analysis) and statistical/semantic hybrid approaches (Lin and Soibelman 2006).

In the context of BIM, the information extraction may serve one or more of the following non-exhaustive and non-exclusive categories: conformance analysis (e.g., building code checking), diagnosis (checks for model integrity, conflicts etc), basic search (may also include derivation), and higher-order reasoning (e.g., fire engineering simulation, energy simulation, acoustic simulation). Many researchers have used ontologies, or contend for their use as a knowledge-assisted gateway for retrieving information from different information sources, and to address the information and knowledge sharing requirements of the construction user community (Rezgui et al. 2011; Yurchyshyna and Zarli 2009; Anumba et al. 2008). The use of construction ontologies could act as a semantic abstraction layer above BIM and provide more intuitive discipline specific view or abstraction of BIM (Rezgui et al. 2011).

The schema represented by domain ontology such as *IFC* could serve as domain knowledge to support different construction management functions, such as cost estimating (Zhiliang et al. 2011) and information retrieval tasks, such as code checking (Eastman et al. 2009). However, there are many challenges in using *IFC*. The use of *IFC* model and file output representation implemented by the BIM tools may differ in details. The mapping process and consequently the information extraction is complicated as different BIM standards and applications use different geometric representations. For example, the placement origin of the wall in an *IFC* file is assumed to be on wall centerline. This assumption may not always be true, as certain BIM tools may have the default placement origin set on the outer or inner face of the wall rather than the centerline (Spearpoint 2010). Similarly, the representation of openings in *ArchiCAD* and *Revit* differ in that the reference point for the entity is not defined in the same manner. The Revit defines the x-coordinate local placement as the edge of the opening element entity whereas *ArchiCAD* uses the centre of the opening element entity. The software has to be able to deal with these differences in *IFC* files generated from different BIM tools (Spearpoint 2010).

There needs to be particular emphasis on the typing of components, classification, geometry, relationships, and rules. A model view definition (MVD) would ideally provide an environment to define and structure the semantic meaning of *IFC* entities, attributes, relationships, and PropertySets in a rigorous and formal manner. Implementation of MVD concepts developed that way can help in achieving a uniform mapping to and from the internal objects of BIM tools and *IFC* entities and relationships (Venugopal et al. 2012). Many Information Delivery Manuals (IDM) have already been developed, and a number of MVD projects are currently under development. MVD defines a subset of the *IFC* schema and 'use cases', that is needed to satisfy one or many exchange or end user requirements of the AEC industry such that different BIM users can focus on the information relevant to them (buildingSmart International 2013). However, the level of detail requirement of the model views as well as the clear definition and agreement of classification schemes is needed for further elaboration in the MVD development (Venugopal et al. 2012).

4. CONCLUSIONS

BIM has the potential to provide significant project efficiency and effectiveness to the AEC industry. As the BIM technology matures and its adoption increases, the need for automated information extraction and retrieval will increase dramatically. This paper argued that BIM-based applications need to capitalize the end user's requirements, existing business processes and work practices. It discussed some of the requirements for component specific information in order to highlight the importance of acquiring domain-specific knowledge to leverage BIM models for construction. The examination and analysis of how practitioners think of different spatial and non-spatial conditions present in a given design, and how they account for differing geometric, non-geometric and other relationships between components in cost estimating, constructability analysis and in the planning and execution of construction, can provide valuable domain specific information. Such information can provide insights for defining the requirements for model specifications, which could provide useful information for creating MVD and defining enriched objects in BIM applications. We expect to see the increasing use of construction oriented domain ontologies as a wrapper or semantic abstraction layer above current *IFC* or BIM models to bring much needed integration and knowledge sharing in the AEC industry.

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