www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

SUPPORTING KNOWLEDGE-INTENSIVE CONSTRUCTION MANAGEMENT TASKS IN BIM

REVISED: September 2015
PUBLISHED: March 2016 at http://www.itcon.org/2016/2
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SUMMARY: *The delivery of products and services for construction-based businesses is increasingly becoming knowledge-driven and information-intensive. The proliferation of building information modelling (BIM) has increased business opportunities as well as introduced new challenges for the architectural, engineering and construction and facilities management (AEC/FM) industry. As such, the effective use, sharing and exchange of building life cycle information and knowledge management in building design, construction, maintenance and operation assumes a position of paramount importance. This paper identifies a subset of construction management (CM) relevant knowledge for different design conditions of building components through a critical, comprehensive review of synthesized literature and other information gathering and knowledge acquisition techniques. It then explores how such domain knowledge can be formalized as ontologies and, subsequently, a query vocabulary in order to equip BIM users with the capacity to query digital models of a building for the retrieval of useful and relevant domain-specific information. The formalized construction knowledge is validated through interviews with domain experts in relation to four case study projects. Additionally, retrospective analyses of several design conditions are used to demonstrate the soundness (realism), completeness, and appeal of the knowledge base and query-based reasoning approach in relation to the state-of-the-art tools, Solibri Model Checker and Navisworks. The knowledge engineering process and the methods applied in this research for information representation and retrieval could provide useful mechanisms to leverage BIM in support of a number of knowledge intensive CM/FM tasks and functions.*

KEYWORDS: *BIM, Ontology, Design Features, Knowledge Management, Knowledge Specification, Construction Management*

REFERENCE: *Madhav P. Nepal, Sheryl Staub-French (2016). Supporting Knowledge-Intensive Construction Management Tasks in BIM. Journal of Information Technology in Construction (ITcon), Vol. 21, pg. 13-38, http://www.itcon.org/2016/2*

1. INTRODUCTION

The construction industry is characterized by, and often criticized for, fragmentation, low productivity and inefficient work processes as well as its culture of poor communication, especially in terms of information exchange and sharing. The industry relies heavily on services from complex networks of project organizations and professionals, which employ different communication platforms to produce and consume facility information to and from a range of information outlets, such as drawings, specifications, and models. As such, a plethora of knowledge-intensive endeavors are required as prerequisites for interacting with different knowledge-dimensions in the Architectural, Engineering and construction (AEC) industry. Such dimensions of knowledge have been shown to materialize in two forms: as tacit (or implicit) knowledge or explicit knowledge (Polanyi, 1958; Nonaka & Takeuchi, 1995). Specifically, such knowledge in construction project environments may relate to one or more of three categories: domain knowledge, organizational knowledge and project knowledge (Rezgui, 2001). While project professionals have the same goal of fulfilling the client's project objectives and needs, they have differing preferences, viewpoints, and rationale for expressing and representing the requirements of facility information. This situation has made project-based ventures in the AEC and facilities management (FM) industry challenging from an information management perspective, particularly in terms of information sharing and knowledge reuse within a project and across series of projects.

Building Information Modelling (BIM) is an emerging technology and process that facilitates digital representation, exchange, use and reuse of all pertinent information about the life cycle of a building or facility from planning, design, construction, FM, and to the ultimate disposal. Eastman et al. (2011) define BIM as: "*A verb or adjective phrase to describe tools, processes, and technologies that are facilitated by digital machine-readable documentation about a building, its performance, its planning, its construction, and later its operation*". With the rapid adoption of BIM, the current outlook of the construction industry is one that is undergoing transition from culturally-ingrained redundant practices to a new era of digital information. This transition has, in part, been attributable to the extent of knowledge dynamics in the construction domain. Yet, the dominant form of working knowledge within the domain still exists in the form of tacit knowledge (Lowendahl, 2000).

BIM adoption is enabling practitioners to achieve explicit representations of facility design, construction, operations and management information. However, the management of such information presents a unique set of challenges as the volume of information derivable at any one time from digital building models may increase exponentially. Practitioners using BIM need the right information, only the required and relevant information, and the information at the appropriate level of details or granularity (Luth et. al., 2014; Pulaski & Horman, 2005). The formalization and effective management of design, construction, and FM knowledge is therefore very critical for widespread use of BIM in the AEC/FM industry.

Emerging BIM applications provide some support for extracting construction-specific information. Autodesk Revit, Innovaya, and Solibri Model Checker (SMC), for example, can identify explicitly defined geometric and material information in an underlying BIM using schedule or information/material takeoff tools. SMC provides constraints or rule-based support for interference checking, model checking, space checking and quantity takeoff, and for extracting explicitly defined dimensional and component property information. Navisworks is a widely used tool in the AEC industry for clash detection and conflict management. However, most of these tools lack flexibility to encode domain specific knowledge, and they provide limited support to extract construction-specific information (Nepal et al., 2013). The uptake of BIM by designers and contractors has increased significantly in the last few years. However, in many circumstances, BIM models authored or created by designers do not meet the needs of contractors and other downstream users as they are meant towards developing the design and producing construction drawings. Contractors often end up having to recreate the models because the BIM model and its content (data, relationships defined in the data, etc.) that they get from the architect and designers is often incomplete, inaccurate, and ill-defined in scope (Aram et al., 2014; Pilehchian et al., 2015; East, 2013). In many cases, construction practitioners use cumbersome, manual and error-prone processes for analyzing and interpreting 2D and 3D drawing or models to identify construction-specific information (Nepal et al., 2012, Eastman et al. 2011; Aram et al., 2014).

In order to increase the efficiency in the AEC industry, there is an urgent need for a well-defined interface between the designer's world of BIM and construction knowledge domains and easy to use, flexible and customizable reasoning approaches for extracting implicit knowledge held by practitioners and explicit product information represented in designer-specified BIM. In order to overcome these shortcomings, this paper describes a research study that identified a subset of construction relevant knowledge and developed a formal way to express that knowledge explicitly in a computer-interpretable way in order to query a digital model. The domain knowledge is captured through a critical and comprehensive review and synthesis of literature, which is supported by other information gathering or knowledge acquisition techniques, namely: case studies, interviews with industry experts and an observational study. The knowledge thus acquired or captured is then formalized in terms of an ontology of design conditions and query specifications, which is used to extract domain-appropriate information based on user-defined queries. The formalized construction knowledge is validated through interviews with domain experts in relation to four case study projects. Additionally, retrospective analyses of several design conditions are used to demonstrate the soundness (realism), completeness, and appeal of the knowledge base and query-based reasoning approach in relation to the state-of-the-art tools, Solibri Model Checker and Navisworks. In the context of this research, knowledge is viewed from a domain-specific standpoint and is understood to be largely implicit. Such knowledge can be viewed contextually, especially in terms of its use in the context in which it is presented (Carrillo et al., 2000), its primary use being, as a support mechanism for decision-making and problem-solving tasks in construction. This research provides the following contributions:

1. It identifies a subset of building components related construction knowledge through a critical and comprehensive review and synthesis of literature and other knowledge acquisition techniques.
2. It applies knowledge engineering methodology for the acquisition, representation, validation and inferencing (reasoning) of construction relevant knowledge to support knowledge-intensive construction management (CM) tasks within a BIM environment.
3. It leverages ontologies of design conditions and query vocabularies as mediums for encoding construction knowledge and specifying user-defined queries for extracting construction-relevant information from a designer-specified digital building model or BIM.

The following sections describe the relevant literature and methodology, and subsequent sections describe how we acquired, represented and reasoned about construction knowledge.

2. RELEVANT LITERATURE

According to Costa and Lima (2014), models of building and construction knowledge fall into three broad categories: classification systems and thesauri, product and process models, and ontologies. Classification systems, such as *Uniformat*, *Masterformat*, and *BS6100*, are the most prominent and widely used vocabularies in the AEC/FM industry and are primarily focused on product categorization. They provide a vocabulary of concepts and a classification of building and construction information. Product models, on the other hand, provide a semantically rich representation of objects or entities of a building (geometry, properties, object hierarchy and their relationships, etc.) according to standard data structures. The ongoing development of open BIM standards and specifications is one of the major international efforts to support increased collaboration and integration of the AEC/FM industry through standard data models or *Industry Foundation Classes* (IFC), data dictionaries and business processes (*buildingSMART*, 2014).

Ontology-based knowledge modeling allows the semantic modeling and integration of data, knowledge management and reasoning about domain concepts (Lima et al., 2005). Several research efforts have led to the development of a taxonomy or vocabulary and semantic dictionaries for building and construction information, including OCCS (OmniClass Classification Systems for Construction Information), bcXML (an XML Vocabulary for Building and Construction), BARBi (The Norwegian Building and Construction Industry's Reference Data Library), and IFD (the International Framework for Dictionaries). IFD library is one of the core components of the buildingSmart technology and is intended to provide increased usability of an IFC-based BIM and improved interoperability in the building and construction industry (buildingSmart, 2015).

Many researchers have focused on formalizing design and construction knowledge through domain ontologies and knowledge management tools and systems (e.g., Lima, et al. 2005; El-Diraby and Osman, 2011; Costa and Lima, 2014; Zhang et al. 2015). While the open BIM standard, such as IFC, defines model schemas for representing semantically rich information about a facility and provides a common format for the exchange of such information, the vocabulary and grammar provided by IFC alone are not sufficient to define the set of information needed by any specific construction and FM discipline or practitioner (East et al., 2013; Graphisoft, 2004). One of the IFC's main problems is that the IFC attempts or pace at standardization have failed to align 'time-to-standard' with 'time-to-market" goals. As such there is not enough market demand for IFC and IFC-based integrated BIM. As a result proprietary BIM software and applications have evolved at rapid pace (Laakso and Kiviniemi, 2012). Emerging BIM applications such as Solibri Model Checker (SMC), Navisworks, Innovaya provide some support to interrogate BIM for finding spatial and non-spatial design conditions. However, state-of-the-art BIM tools provide little support for interrogating different spatial queries or conditions such as those listed in Table 1 and extracting semantic, domain specific knowledge.

In order to address the afore-mentioned shortcomings, many research efforts have leveraged BIM frameworks in structuring the needed information using ontologies, and have provided reasonable support in facilitating the extraction of construction specific information (Scherer & Schapke, 2011; Wang et al., 2011). Query-based approaches or query languages provide increased generic support to rapidly generate task-specific views of a BIM model (Borrman & Rank, 2009; Beetz et al., 2009). However, they are not widely used in AEC practices (Haymaker et al., 2004) possibly because they lack a simple, generic, formal and expressive specification of queries that would enable practitioners to explicitly define construction relevant queries. This research is an attempt to provide rich, expressive and flexible query support for subsets of knowledge-intensive construction tasks. The capture of domain knowledge held by practitioners and the detailed and explicit specification of such knowledge could provide more intuitive discipline-specific view or abstraction of BIM (Rezgui et al., 2011). Moreover, the explicit specification of domain knowledge in the form of common vocabularies or ontologies provides semantic integration of construction information.

The research presented in this paper was motivated by the need for well-defined knowledge specification layers between BIM design models and construction requirements on these models in the form of ontologies and sematic modeling of construction knowledge. Next section provides an overview of the knowledge engineering methodology and its application to this research study.

TABLE 1: State-of-the-art tools supporting querying a subset of spatial queries

Relevant Design Conditions	**State-of-the-Art Tools**		
	Full Support	**Partial Support**	**No Support**
Maximum and minimum spacing between columns			√
Clear vs. center-to-center spacing of columns			√
Spacing of façade columns			√
Horizontal and vertical alignment of columns			√
Uniformity in column size/shape from floor to floor			√
Uniformity in column location from floor to floor			√
Uniformity in the spacing of columns in a floor			√
Uniformity in the spacing of columns from floor to floor			√
Off-grid vs. on-grid columns			√
Uniformity of off-grid columns from floor to floor			√
Column offset distance			√
Location of exterior columns from the slab edge			√
Intersection or connectivity of building components	√		
T-, L, end-to-end, or overlapping wall intersections			√
Non-perpendicular intersection of walls			√
Location of intersection			√
Depth of intersection		√	
Size of intersection			√
Existence of wall/slab penetrations	√		
Horizontal and vertical location of wall penetrations			√
Horizontal location of slab penetrations			√
Uniformity in the size and location of wall/slab penetrations			√
Size/dimension, area, perimeter of wall/slab penetrations			√
Spacing of penetrations			√
Uniformity in spacing of penetrations			√

3. RESEARCH METHODOLOGY

This research adopts knowledge engineering methodology, which is the process of acquiring and specifying knowledge in a reusable form and building a knowledge base (Shabolt & Smart, 2015). The knowledge engineering process includes five major activities: knowledge acquisition, representation, validation, inferencing, explanation and justification (Figure 1).

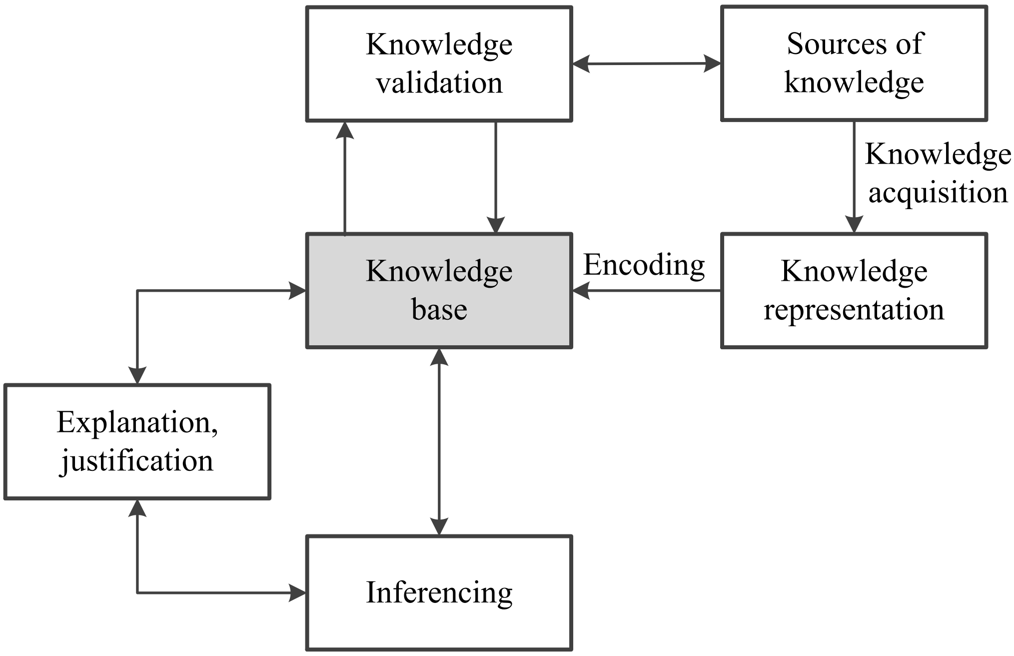


FIGURE 1: Process of Knowledge Engineering (Adapted from: Shabolt & Smart, 2015)

- Knowledge acquisition: Knowledge acquisition involves the acquisition of knowledge from experts and other variety of sources such as books, journal articles, and documents.
- Knowledge representation: This activity involves organizing the acquired knowledge in a form using the methods such as frames, decision trees, objects, and logic that is understandable to both humans and computers.
- Knowledge validation: This step involves validating and verifying the acquired knowledge and the system to ensure the quality, accuracy and performance. In terms of the knowledge base, it is necessary to ensure that the right knowledge base is acquired (i.e.., that the knowledge is valid) and that it was constructed properly (Shabolt and Smart, 2015).
- Inferencing: Inferencing is the process of reasoning based on the knowledge and the specifics of a problem at hand. It is the problem solving process using a computer program or software.
- Explanation and justification: This activity involves the act of clarifying and explaining the system's reasoning process, generated solution or recommendation. The type of explanation depends on the needs of the class of users, their knowledge and preferences, problem solving context and the structure of the underlying domain knowledge itself (Cawsey, 1995).

This research was developed mostly using the first four steps: knowledge acquisition, knowledge representation, knowledge validation, and inferencing. More procedural details about each of these steps are discussed in the relevant subsequent sections.

4. ACQUISITION AND ELICITATION OF KNOWLEDGE

The relevant domain knowledge comes from various knowledge sources (Turban et al., 2005). This research used a number of sources to acquire/elicit design-related, building components specific construction knowledge and included a synthesis of literature, case studies, observational study, and interviews with construction experts.

4.1 A Synthesis of Previous Research

This research gathered relevant terms and concepts through an extensive literature review on design constructability, value engineering, cost estimation, methods selection, construction planning and scheduling, and design coordination of building systems. These sources provide a considerable amount of construction knowledge about different design conditions that impact construction, FM and operation. Such knowledge, which relates to spatial elements of a building (e.g., site, floor/storey), different building systems, elements/components, and other design details, describes important design conditions, when they are important, and how they impact construction and/or FM. Previous research publications indicate that design conditions impact construction in a number of ways. For instance, they:

- Influence the applicability and suitability of specific construction methods, such as in the selection of formwork systems in concrete structures (Fischer & Tatum, 1997; Hanna et al., 1992; Thomas & Zavrski, 1999) and on the constructability of a design (Boeke, 1990; Glavinich, 1995; Burkhart et al., 1987; Skibniewski et al., 1997; Ugwu et al., 2004);
- Impact labor productivity (Smith & Hanna, 1993; Sanders & Thomas, 1991; Thomas & Zavrski, 1999);
- Relate to cost estimation via their impact on resource/method selection, construction activity requirements, and productivity (Hanna & Sanvido, 1990; Thomas & Sackrakan, 1994; Staub-French et al., 2003); and
- Influence the installation sequence, safety, coordination, operation and maintenance of mechanical systems (Korman et al., 2003; Tabesh & Staub-French, 2006).

A partial list of some important design conditions synthesized from the literature is summarized in Table 2. The table provides a non-exhaustive list of design conditions related to some major building components and their spatial conditions that impact construction. These design conditions exemplify the varied nature and characteristics of different design conditions at different levels of detail. For example, "spacing" is important not just at the component levels such as for beams, columns, but it can also be relevant at a more detailed level, such as the spacing of reinforcing bars (rebar) in beams, columns, and slab components (Nepal, 2011).

4.2 Knowledge Acquisition from Other Sources

A number of other techniques can be used for eliciting and acquiring design-specific construction knowledge. For this research, a detailed case study of the Chem-Bio building project at the University of British Columbia (UBC) along with three other projects - Life-Sciences Building, the Centre for Interactive Research and Sustainability (CIRS) and the Michael Smith Laboratories Building - at UBC was conducted to understand how different design features impact construction and how designers and construction practitioners describe or characterize them. A variety of design and construction documents (e.g., drawings, 3D models, construction specifications, cost estimates, and construction schedules) on these projects were also studied to elicit design conditions that impact construction. Over a six-month period, weekly observational studies based on design coordination meetings involving designers, suppliers, cost consultants, general contractors, and other specialty MEP trades, as well as owner representatives on the CIRS project was instrumental to the acquisition and documentation of construction knowledge. The meetings covered design parameters, building systems and subsystems, component typing and sizing, constructability analysis, value engineering, cost and schedule analysis, and design coordination issues. Seven different construction practitioners –consisting of cost estimators, superintendents, project managers, and a concrete foreman – were interviewed to better understand how practitioners describe and characterize the different design conditions that impact various construction trades and CM functions, and to substantiate concepts gathered from other sources including the extant literature. Table 3 shows some of the design conditions identified through the case studies which cost estimators utilize in the definition of wall types.

The knowledge about different design conditions identified from literature and other sources provided important domain concepts for developing the ontology of design conditions: entities representing higher level concepts, attributes that define concepts, relationships between the concepts, and any associated rules, conditions or constraints. As such, the identified concepts needed to be structured and represented (or formalized) in a generic and project-independent way to support other knowledge intensive tasks such as querying a project-specific BIM model to identify relevant construction information. The next section briefly describes the process of specifying or representing knowledge as a feature ontology and query vocabulary.

TABLE 2: Synthesis of design conditions from literature

Design Entities	Design Conditions	References
Component Characteristics in General	Component dimensions (e.g., height, depth, width, thickness, length)	Burkhart et al. (1987); Boeke (1990); Fischer & Tatum (1997); Smith & Hanna (1993)
	Maximum/minimum dimensions and spacing of components	Fischer (1991)
	Component location in a floor (e.g., below grade, main floor, top floor)	Sanders & Thomas (1991); Udaipurwala & Russell (2005)
	Repetition of component dimensions/sizes and distances in a floor and from floor to floor	BCA (2001); O'Connor *et al*. (1987); Fischer & Tatum (1997); Burkhart *et* al. (1987); Boeke (1990)
	Shape of components (e.g., round column)	Burkhart *et al*. (1987); Boeke (1990)
	Existence of blockouts, bulkheads, pilasters, drop heads	Burkhart *et al*. (1987); Boeke (1990)
	Changes in dimensions, shape, size/cross section of structural components	Boeke (1990); Burkhart *et al*. (1987); Fischer & Tatum (1997)
	Variation in the size and location of components (e.g., columns, structural walls)	Hanna *et* al. (1992); Fischer & Tatum (1997); Burkhart *et* al. (1987); Boeke (1990)
	Component spacing	Fisher &Tatum (1997); Bisharat (2004)
	No. of components attached or connected to the component	Skibniewski *et al*. (1997)
	Type of component material/s	Ruby (2006); Thomas & Zavrski (1999); RS Means Inc. (2004)
	Material characteristics of a component (e.g., concrete strength)	Fischer & Tatum (1997)
	Component finish type	Thomas & Zavrski (1999); Smith & Hanna (1993)
Component - Column	Existence of column head/drop panels	BCA (2001); Boeke (1990)
	Uniformity in the layout and spacing of columns	Ugwu *et al*. (2004)
	Variation in the size and location of columns from floor to floor	Hanna *et al*. (1992)
	Horizontal and vertical alignment of columns	Fischer (1991); Allen & Iano (2002)
Component - Wall	Wall type	Staub-French *et al*. (2003); Sanders & Thomas (1991); Smith & Hanna (1993); Bisharat (2004)
	Presence of sloped walls	Thomas & Zavrski (1999)
	Straight walls	Sanders & Thomas (1991); Thomas & Zavrski (1999)
	Presence of curved walls	Fischer & Tatum (1997)
	Exterior or interior walls	Sanders & Thomas (1991)
	Ceiling or full height walls	Bisharat (2004)
	Length of wall; minimum and maximum wall length	Fisher & Tatum (1997); Sanders & Thomas (1991); Thomas & Zavrski (1999); Smith & Hanna (1993)

Design Entities	Design Conditions	References
	Wall height	Fisher & Tatum (1997); Staub-French *et al*. (2003); Smith & Hanna (1993); Bisharat (2004)
	Wall curvature	Staub-French *et al*. (2003); Peurifoy & Oberlender (1996)
	Existence of wall corbels, ledges, and pilasters	Thomas & Zavrski (1999); Peurifoy & Oberlender (1996)
	Variation in the size, height and shape of walls	Thomas and Zavrski (1999)
Component-Intersection	Intersection or connectivity of building components (e.g., a beam connected to a column)	Burkhart *et al*. (1987); Thomas & Zavrski (1999); Nguyen and Oloufa (2002); Fischer (1991), Skibniewski *et al*. (1997); Haymaker *et al*. (2004)
	Wall turns (corners)/no. of wall turns	Sander & Thomas (1991); Peurifoy & Oberlender (1996); Staub-French *et al*. (2003)
	Wall to wall intersections	Smith & Hanna (1993)
	Intersection of masonry wall with structural steel elements	Thomas & Sanders 1991); Thomas & Zavrski (1999)
	Non-perpendicular wall turns (orientation of wall turns)	Staub-French *et al*. (2003); Sander & Thomas (1991); Thomas & Zavrski (1999)
	No. of intersecting components	Sanders & Thomas 1991); Skibniewski *et al*. (1997)
	Property of intersecting components (e.g., material type)	Thomas & Zavrski (1999)
	Type of intersecting components	Thomas & Zavrski (1999)
	Relative dimension of intersecting components	Boeke (1990); Luth *et al*. (1991), Ruby (2006); Fischer (1991)
	Complexity of intersection (e.g., complex slab-beam intersection)	Burkhart *et al.* (1987)
	Horizontal location of intersection	Haymaker *et al*. (2004)
	Reinforcement ratio of the attached or connected components	Skibniewski et al. (1997)
Penetration	Existence and extent of component penetrations	O'Connor *et al*. (1987); Bisharat (2004)
	Vertical location of wall penetrations	O'Connor *et al*. (1987); Bisharat (2004)
	Uniformity in the location of wall penetrations	O'Connor *et al*. (1987)
Opening	No. of wall openings (e.g., window and door openings)	Thomas & Zavrski (1999)
	Existence of openings	Sanders & Thomas (1991)
	Size and location of component openings	Fisher & Tatum (1997)
	Uniformity in the size and location of openings	Fisher & Tatum (1997); Thomas & Zavrski (1999); Smith & Hanna (1993)
	Uniform spacing of openings	Hanna & Sanvido (1990); Thomas & Zavrski (1999)

TABLE 3: 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, *Theatre* 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

5. KNOWLEDGE REPRESENTATION

The systematic depiction of knowledge of a domain is essential for representing information about the domain and for making inferences about it (Galambos, 1986). Knowledge structures provide the systematic schematization or organization of knowledge of a domain (Galambos, 1986). Ontologies – the explicit specifications of concepts (Gruber, 1986) – provide machine-readable representations of human knowledge that specify knowledge structures of interest in some domain (Shadbolt & Smart, 2015). They are highly useful for representing domain-specific knowledge, such as knowledge about construction-specific design conditions. They also provide the means for defining or representing knowledge about a domain of interest, and include a set of concepts, their definitions, relationships and semantics (Genesereth & Nilsson, 1987).

In the context of this research, feature ontologies and query specifications provide knowledge structures, or schemas to formalize the construction knowledge about different design conditions and a medium for specifying user-defined construction queries on the BIM models.

5.1 Feature Ontology

The feature ontology, irrespective of project type, explicitly defines vocabularies or concepts to characterize a broader set of design conditions relevant to construction practitioners; cost estimators, construction planners, and site coordinators. It enables the systematization and explication of knowledge which, oftentimes, is implicit in construction design, using a structured set of terms (concepts) that are general, computable, and easily understood by practitioners. It generically and flexibly defines concepts in order to provide a common language for practitioners from different CM functions to characterize a design and to account for the varying needs and preferences of practitioners.

The manufacturing concept of "features" (Shah, 1991) was used to define different entities in the ontology. Features in the context of this research refer to meaningful real world entities (objects) to which one can associate construction-specific design information. They include physically identifiable entities, such as walls, columns, beams as well as the concepts representing the physical/geometric interaction or relationship of physical entities such as intersections, openings, and penetrations (Nepal et al., 2013).

The frame-based knowledge representation (Protégé, 2008) was used to develop a feature ontology, which consists of a set of classes organized in a subsumed hierarchy to represent a domain's salient concepts, a set of slots associated with classes to describe their properties and relationships, a set of facets that describe properties of slots, and axioms to specify additional constraints. Figure 2 summarizes the classification of feature types formalized in this research.

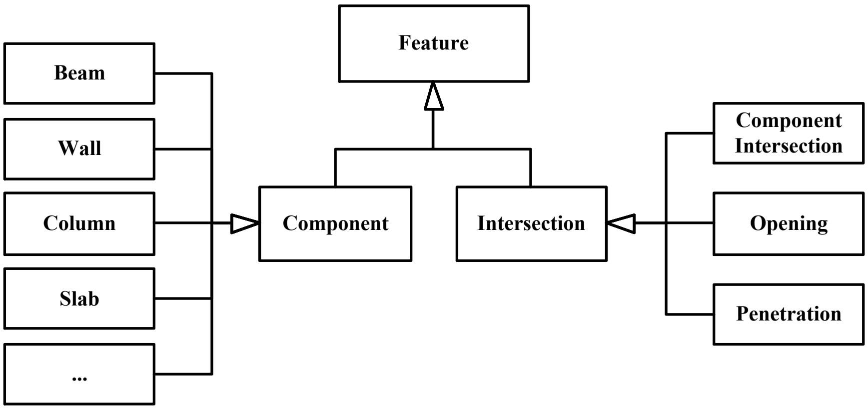


FIGURE 2: The feature hierarchy

The features are classified into two broad categories: component and intersection features. The feature "component" refers to common building elements and is further categorized into feature subclasses representing more specific concepts, such as walls, columns, slabs, and beams, etc. The feature "component" has similar connotations to what IFC defines as elements, but it has more of a construction meaning or usage than in the design thinking of a building. It is similar to the "component mode" of design thinking suggested by Lawson and Roberts (1991) in their formalization of different organizations of knowledge, or modes of thinking in building design. The feature type, intersection, is defined as the physical/geometric interaction between components that result in the formation of different types of intersections between components. The intersection features are further classified into three types, as component intersection, opening, and penetration, features. These subtypes characterize the type and nature of components involved in intersection relationships. The "component intersection" feature describes the physical/geometric interaction or connectivity between building components of the same type, such as intersections between walls (wall to wall intersection) or different types, such as wall to column intersection. The feature "opening" refers to door openings, window openings, and other types of openings on building components, such as walls, slabs, etc. Openings can be through or partial, void (or empty), or filled with elements (e.g., doors or windows). A "penetration" feature describes design conditions that involve building service elements entering or passing through building components, for instance a duct or pipe penetrating a wall or slab (Nepal et al., 2013).

The concepts in the feature ontology are represented generically as an object hierarchy which categorizes design conditions into different feature classes (types) or subclasses (subtypes), defines feature properties, and the relationships among features. The feature ontology acts as a knowledge repository representing domain-specific knowledge or the user's view of a design. It provides a richer representation of construction knowledge by explicitly representing concepts relevant to practitioners. Table 4 shows some concepts (attributes) explicitly defined for the component feature "wall".

The feature ontology was formally represented in Protégé Frame Editor, an open-source, ontology development platform. Protégé-Frame provides a suite of tools for building domain models and knowledge-based applications with ontologies (Protégé, 2008). The frame-based ontology consists of a set of classes organized in a subsumed hierarchy to represent a domain's salient concepts, a set of slots associated to classes to describe their properties and relationships, a set of facets that describe properties of slots, and axioms to specify additional constraints. As shown in Figure 3, different feature types are represented in a hierarchical structure. For each feature type (or class/subclass), different properties (relationships are also treated as a type of property in this research) and their data type are also defined. Several relational properties (e.g., has opening, has penetration, and intersects), establish links or relationships between different feature classes (for instance, the property has opening links "wall" component feature with "opening" feature). New properties can also be defined for each subclass.

TABLE 4: Some attributes defined for the feature "wall" - the existing IFC attributes and the extended attributes

Attribute	**Value Type**	**Cardinality**
Acoustic rated ±	Boolean	Single
*Acoustic rating**	String	Single
*Curvature**	Float	Single
Height ±	Float	Multiple
*Full height wall**	Boolean	Single
*Ceiling height wall**	Boolean	Single
*Is clipped**	Boolean	Single
*Is curved**	Boolean	Single
*Has penetration**	Instance	Multiple
*Is sloped**	Boolean	Single
*Is straight**	Boolean	Single
*Is vertical**	Boolean	Single
Length ±	Float	Single
Thickness ±	Float	Single
Wall type ±	String	Single

± IFC Attributes

* Extended Attributes

One of the major characteristics of the feature ontology is its explicit and flexible representation of design conditions as discrete properties and/or relationships of features. Such representation not only provides the flexibility to query a BIM, but also enables users to flexibly define features or component types (e.g., wall types) during query run time, without altering the original structure of the ontology. Such a flexible representation of building information allows the evolution and adaptation of information models to accommodate the specific requirements of the end users (van Leeuwen & Wagter, 1997), such as those of construction practitioners. Figure 4 shows a browser view of the actual instances of features and their attributes of the feature ontology for a simple BIM model. The user can navigate feature instances and view detailed information about their properties, as defined in the feature ontology. The explicit representation of features (e.g., intersections) and feature properties (e.g., different wall shapes, such as curved wall, clipped wall, etc.) serve to enrich a BIM as such information is not always explicit in BIM models, and their IFC representations.

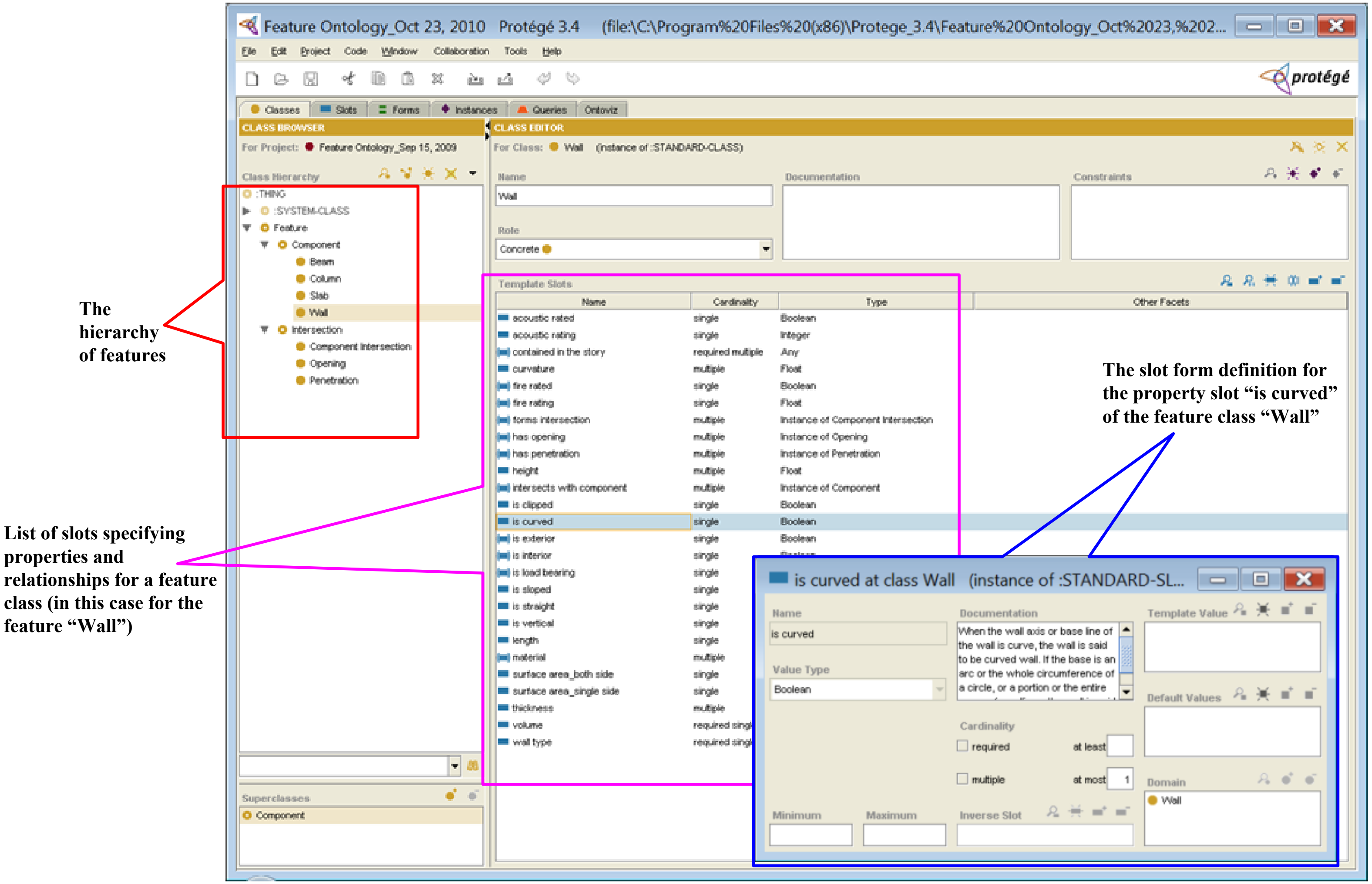


FIGURE 3: The Feature Hierarchy represented in Protégé Frame Editor

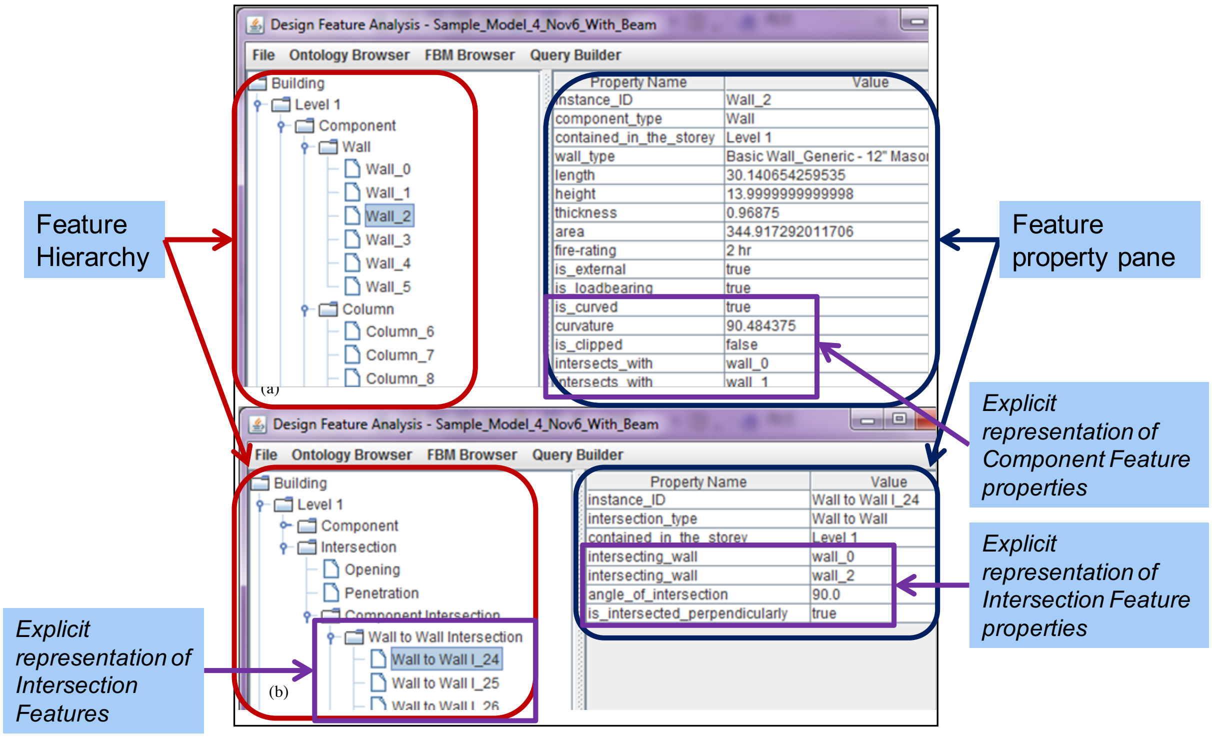


FIGURE 4: Some instantiated features and their attributes of the feature ontology for a simple BIM model

5.2 Query Specifications

Query specifications provide controlled and structured query vocabularies for end users to flexibly specify different types of queries on features formalized in the feature ontology. They provide additional information constructs and domain knowledge beyond what is represented in the feature ontology to query a given BIM. The knowledge is encoded in computable templates so that practitioners can easily and intuitively formulate and customize queries without the knowledge of the underlying data models of a BIM or of query languages. Some basic queries enable the manipulation of features and their attributes generically represented in the feature ontology and subsequently instantiated in the project-specific feature based model (FBM). Other more sophisticated spatial queries require the specification of other spatial concepts/conditions (or attributes) not represented explicitly in the feature ontology and instantiated in the FBM (Nepal, 2011). For each type of query, relevant domain concepts or attributes are defined, which are then used to specify a query on the BIM models. Table 5 shows a list of attributes formalized to specify a penetration query including its location. Figure 5 provides an illustration of some location-specific information/parameters for designating duct penetrations on walls.

The research challenge with respect to formalizing query specifications is that construction practitioners require different types of queries, have different ways of expressing queries, and different levels of knowledge specifications are needed for describing queries. In order to address these challenges, a richer, structured, and flexible mechanism is required to give practitioners the ability to specify and customize queries on features formalised in the feature ontology. This was achieved in part by defining query vocabularies and encoding them into customizable query templates. The users use computer interpretable query specification templates to specify queries that meet the unique construction requirements and preferences of practitioners (Nepal, 2011). Figures 6 (a) through (d) show an illustrative example of the use of such templates and different query steps - feature selection, property filtration, grouping, and quantification – involved in specifying queries.

TABLE 5: 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*	This attribute is used 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 center' or 'feature boundary.'
	Feature boundary	Location measured to the proximate boundary of each penetration.
	Feature center	The location measured up to the center of each penetration.

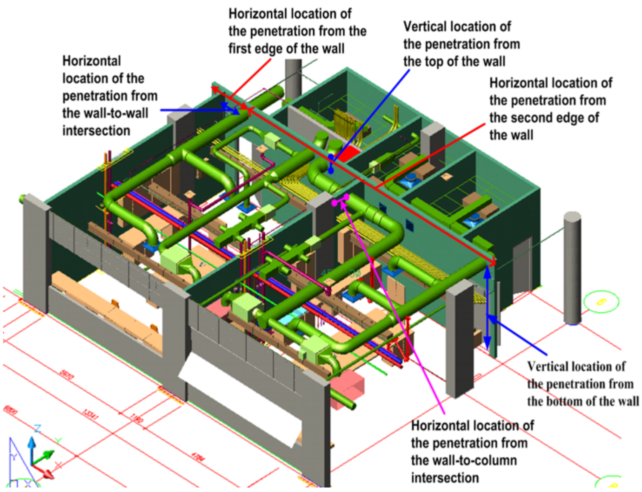


FIGURE 5: Illustration of location-specific information of duct penetrations on walls

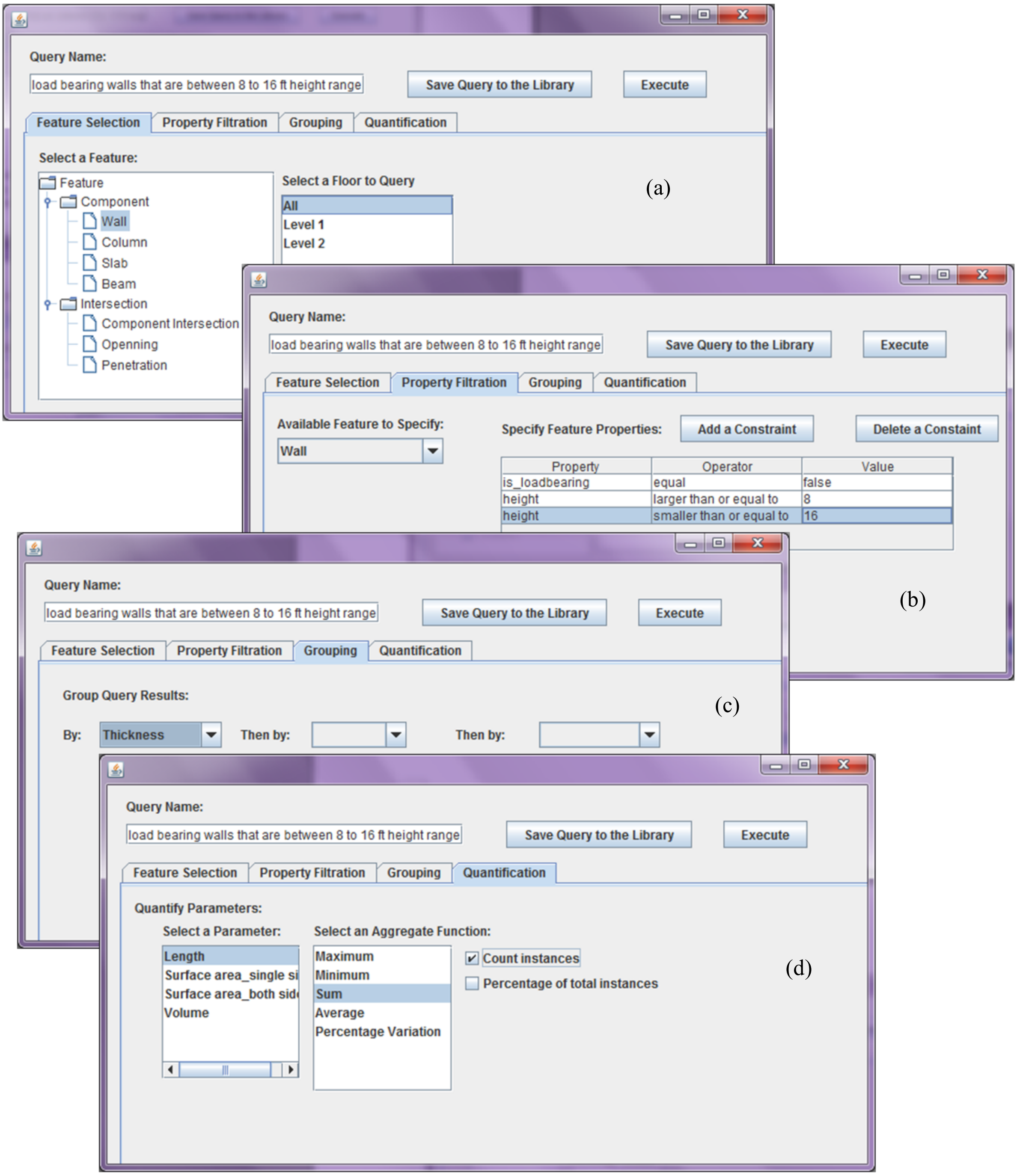


FIGURE 6 (a-d): An illustrative example of using templates and different query steps involved

This section provided an overview of the formalization of design-relevant construction domain knowledge in the form of feature ontology and query specifications. The next section briefly describes the method of deriving inferences about different design conditions using spatial and non-spatial queries.

6. INFERENCING – REASONING ABOUT DIFFERENT DESIGN CONDITIONS USING QUERIES

Extracting the information needed by construction practitioners is challenging as objects data in the BIM authoring tool such as Revit or BIM data extracted from pre-defined standard data schemas such as ifcXML require formalized mapping to the concepts in the domain model (i.e., feature ontology and query specifications). Mappings were created between ifcXML data obtained from Autodesk Revit to each of the concepts defined in the domain models by using XQuery, the standard query language for XML. The query processing involved the complicated process of how objects are represented and linked with different attributes and relationships in the IFC model and the resulting ifcXML file. The use of XQuery for ifcXML data enabled to answer most non-spatial construction queries as reported in Nepal et al. (2013). However, most of the spatial information about BIM objects needed to process spatial queries that are important to construction practitioners was not available in the exported ifcXML file. Such data was extracted directly from the Autodesk Revit API and represented in a GML application schema, which also stored non-spatial ifcXML data. The mappings from BIM objects to concepts in the domain model were implemented as XQuery spatial query predicates. The detailed reasoning process for querying BIM for construction-specific spatial information is provided elsewhere (Nepal et al., 2012).

7. VALIDATING THE KNOWLEDGE BASE

Validation is part of evaluation, which is a broad concept that assesses the validity of a knowledge base as well as the overall value, performance or applicability of the system (Turban et al., 2005). Different measures of validation can be utilized, for instance, in ensuring that appropriate knowledge has been acquired from a knowledge base (Marco, 1987) and for determining that the knowledge base was constructed properly (Shabolt & Smart, 2015). In the context of this research, the adequacy or completeness (portion of the necessary knowledge included in the knowledge base), depth (degree of detailed knowledge), breadth (how well the domain is covered), face validity (credibility of knowledge), appeal (the usability; how well the knowledge base matches human intuition and stimulates thought; practicability) and realism (accounting for relevant variables and relations) are argued as some of the most applicable criteria out of many validation measures or criteria compiled by Shabolt & Smart (2015) for the validation of a knowledge base. This research used interviews with the domain (construction) experts as the main validation method of the knowledge base. Additionally, it used retrospective analyses of several design conditions in relation to the four case study projects and performed descriptive and interpretative analyses to demonstrate the soundness (realism), completeness, and appeal of the knowledge base and query-based reasoning approach for querying different design conditions.

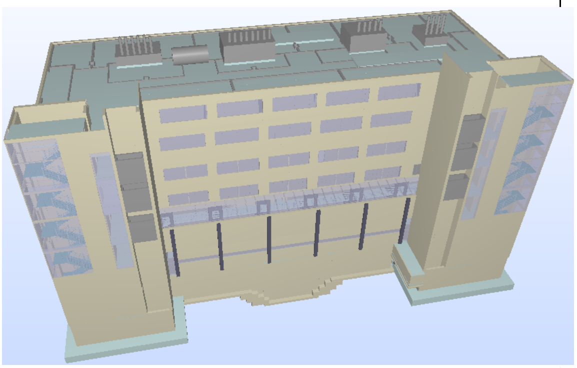
7.1 Interviews with Construction Experts

Interviews with four construction experts were conducted to assess the relevance of formalized concepts to experts and their domains. The experts in this study were identified wholly at arm's length via networking with authors' personal contacts. The interviews largely confirmed the adequacy, depth, breadth, credibility and appeal of the formalized knowledge in the feature ontology and query specifications. They also provided the opportunity to verify and better understand experts' rationale for "why", "when" and "how" different design conditions impact construction. The interviewed construction experts included a Project Manager, a Formwork Manager, a Site Superintendent, and a Chief Estimator. The following summarizes their particular expertise:

- ***Project Manager***: The project manager works at one of the world's leading planning, engineering, and CM organizations. He holds professional degrees in structural, architectural, and CM, with more than 30 years of experience in planning, scheduling, and estimating. For more than 20 years, he has worked in the capacity of project manager, and construction manager, for a range of infrastructure and facility projects. Examples of design conditions and scenarios from the Chem-Bio project at UBC (Figure 7a) were used as references for steering the interview with this expert. He played the role of the generalist, surveying the design conditions from the perspectives of component layout, component installation, constructability, cost estimation, construction planning, and scheduling.
- ***Formwork Manager:*** The formwork manager works for a company that specializes in the construction and erection of concrete formworks, serving commercial, high-rise and high-end residential homes corporations. He has over 20 years of construction experience. He has significant experience in estimating and managing concrete formwork. Several examples and scenarios from the Chem-Bio Project were used to facilitate interactions with him. He often used examples of the design conditions from the Discovery Place project (Figure 7b) in the interview.
- ***Site Superintendent:*** The site superintendent works with a medium-sized construction company, specializing in multi-residential, commercial, institutional and mixed-use projects. He has over 12 years of experience in construction site supervision and operation. In providing client-feedback on constructability, he displayed an outstanding flare for deciphering design issues that impact construction

operation. Specifically, he referred to examples from the Engineering Design Center (EDC) project (Figure 7c) during the course of the interview.

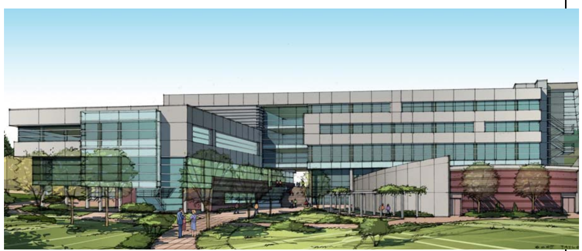
- ***Chief Estimator:*** The Chief Estimator works for a general contractor that provides CM services to clients. The stakeholder possessed extensive experience in quantity surveying and project controls. As such, he provided examples of relevant design conditions from a cost-estimating perspective, with particular reference to the Fipke Center for Innovative Research project at UBC Okanagan (UBC-O) (Figure 7d).



(a) Chem-Bio Building, at UBC, Vancouver, BC

(b) Discovery Place, Burnaby, BC

(c) Engineering Design Centre (EDC) at UBC, Vancouver, BC



(d) Fipke Centre for Innovative Research at UBC-Okanagan (UBC-O), Kelowna, BC

FIGURE 7 (a-d): 3D models of the projects used in the validation studies

These experts were asked about the impact, or relevance, of different design conditions related to different feature types. Sets of close-ended questions were used to interview the Project Manager. He was asked to indicate the relevance of each design condition (or factor). Open-ended explanations about the rationale for each factor, or any other factors not incorporated in the questions were also sought from him. Face-to-face interviews were conducted with three other experts to understand the relevance of different design conditions and to gather detailed information about the specific design conditions that were present, or of particular concern, in the referenced projects. A number of visual aids, probing questions, example scenarios, and structured sets of questions were used as interview guides and for reducing the potential of miscommunication in the course of the interviews. All interviews were recorded and, subsequently, analyzed as transcripts.

Rather than describe all of the results of the interviews in detail, due to space constraints, this paper only presents experts' assessments of the relevance of design conditions related to the component feature "column" (Table 6). Tables like this were used to receive expert opinion on design conditions for other features and are available in Nepal (2011). The discussions of the results of the interviews with respect to the component feature "column" are provided below.

TABLE 6: Expert opinion on design conditions related to the component feature "column"

Design Conditions	Relevance/Importance				Experts' Comment, if any
	Significant	Moderate	Little	Irrelevant	
Column size/dimensions	■ □ ○	●			
Column shape	■ □ ○	■ ●			Estimators understand that forming circular columns may be more costly than square columns of a certain size range. Tradesmen may be concerned about the shape of smaller, round columns to a lesser degree.
Existence of column head/drop panels	■ □	■ □ ●			The material volume of 'drop heads,' insignificant compared to the added labor to form such details. Estimators diligently account for such additional costs.
Exterior column	■ □		●		Exterior columns are much more difficult to build; everything has to be plumb, perfectly plumb/ perfect, and the slab has to match up with the next floor.
Interior column		■ □	●		Conceivably, an exterior column might cost more when it is intended to be finished differently than an interior column of like dimension/shape. Actually, depending upon the detailing at perimeter edges of floor/roof slabs, layout precision for an exterior column might require a bit more time than does an interior column.
Off-grid vs. on-grid columns		□ ■	□ ○	○ ●	Avoiding costly mistakes requires a more precise layout for off-grid columns than do on-grid columns – layout might not cost significantly more, but mitigating higher risk makes it a key concern.
Spacing of columns:					Estimator relatively less concerned than practitioner(s) assuring accurate layout of work.
Spacing of columns in the X-direction		□	■ ○ ●		
Spacing of columns in the Y-direction		□	■ ○ ●		
Maximum spacing of columns	□	○	■ ●		
Minimum spacing of columns		■	□ ○ ●		Conceivably, slab forming systems may be impacted if columns are too closely spaced.

Design Conditions	Relevance/Importance				Experts' Comment, if any
	Significant	Moderate	Little	Irrelevant	
Centre-to-center spacing between columns		■ □	○ ●		ditto
Clear spacing between columns		■ □	■ ○ ●		ditto
Alignment of columns:					Alignment of columns is a significant issue. If columns are on-line and consistent, I can use my fly forms.
Horizontal alignment of columns	■	■ □ ○	●		
Vertical alignment of columns	■ □ ○		●		
Design uniformity (or consistency):					Repetition enhances constructability, reducing risks of costly layout errors when "everything" is the same. Repetition enhances work efficiency.
Uniform size/shape of columns in a floor	■ □ ○	●			Changing column size will not save money.
Uniform size/shape of columns from floor to floor	■ □ ○	●			
Uniformity in the location of columns from floor to floor	■ □ ○	■	●		
Uniform spacing of columns in a floor	□	■ ○	● ■		
Uniform spacing of columns from floor to floor	□	■ ○	●		

■ Project Manager; □ Formwork Manager; ○ Site Superintendent; ● Chief Estimator

Table 6 presents design conditions related to the feature "column" and their relevance to construction practitioners. For the site superintendent, spacing of columns is more of an engineering issue. However, on some jobs, he said that he tends to question what will work and what will not, in order to ensure that the design is structurally safe, even though this issue is more a designer's responsibility. The site superintendent further explained that he provides feedback to the architect and to the design engineer and even consults with rebar trades to ensure they are confident with respect to columns spacing. The formwork expert noted that the bigger the span, the easier the job, notwithstanding the fact that one needs to consider the dead load of the building. "*If every grid bay is the same, it is far easier to build. Obviously you want to maximize the spacing, but that is more (in the domain) of engineering,*" he said.

While many column-related design conditions listed in Table 6 are generally relevant to practitioners, formwork and site personnel, however, are more concerned with the consistency of design. For example, the formwork expert said:

> *"I don't care much whether columns are on grid or off-grid. What is really important is that grids remain consistent. If you can get the grid line to stay the same or add up to the same value all the time, it is easier for the trades to build and easier to design scaffolding for suspended slabs, because it is always the same load. When grids are consistent, you can move fly tables from one area to the next one, because that table is the same. In other words, if you keep the building consistent, the costs drop. Same thing applies to floor height; if the columns are changing all the time, you have to adjust their heights because it can't be too high; when you go to pour the concrete, you've got to be able to see inside the column to get it to the perfect elevation. If you get the same floor every time, you don't have to change formwork. If you're changing formwork, it costs money. The more consistent the design is, the cheaper it is to build. If you've got a building that goes around a circle or oval, and you want to do the glazing and do the concrete, how long do you think the guys would take to put the slab edging? Of course, it takes way longer. Change in column sizes costs money. You've got to design the load for every one of these redesigned columns; you got rebar issues. For every floor, the detailer has to change the detailing. For every different size of column, I have to build different column forms. I have to pay someone to change the forms or build the form. Contractors also like aesthetically pleasing buildings. If there are changes in size/shape of columns, to save or reduce concrete volume, and the volume is not that much, that is not worth it."*

The relevance of grid lines to construction was somewhat ambiguous. The site superintendent explained that he is not overly concerned about grid lines and off-grid versus on-grid columns. However, he indicated that he measures off-sets distances, and considers offsetting columns. Similarly, a related issue raised by the formwork expert relates to the placement of columns. This expert is always keen to know whether columns are located right on the slab edge or projecting past the slab edge. "*Practically speaking, formwork practitioners like to see the columns inside of the building (from slab edge) by about 30 cm. That is a safe design,*" he remarked.

The superintendent on the EDC project mentioned that column height (some columns on this project were constructed as per specifications, all the way from the foundation to the second floor, without obstruction), and change in column height from floor to floor, as the most relevant of the design conditions. While the experts considered the size/dimension and shape of columns as very or moderately important, it was specifically the change in size, shape, and location of columns that was the more important issue for the project manager, site superintendent and formwork expert, than it was for the estimator. Existence of some project-specific design conditions, such as column drop panels, column mats, and off-grid columns, were particularly relevant to the formwork expert for the Discovery Place project. The formwork expert on this project was also concerned about the spacing of façade columns, as well as the maximum spacing of columns. There were changes in height, size, shape and location of the columns from floor to floor. Due to such variations, the horizontal and vertical alignment of the columns was a significant issue on the Discovery Place project. On the EDC project, however, the alignment of columns was not challenging for the site superintendent since there were only two types of column size, of rectangular shape, and with uniform locations.

The detailed interviews with the construction experts provided evidence that the knowledge formalized in this research is representative of reality in terms of representing design conditions that are relevant to construction. The interviews with the domain experts showed that the knowledge elicited/acquired and represented has a varying degree of relevance/importance (from significant to moderate, to little). The degree of relevance/importance however also varies from one CM function to another (i.e. can vary from one discipline/profession to other discipline/profession) and from one project to another. The experts have generally highlighted the fact that a number of situation-specific or contextual variables or conditions interplay on what design conditions are important in a particular design, and when and how they impact construction. They also highlighted the challenges they face in their role. This underlined the need for acquiring and representing rich knowledge in support of different CM functions and FM tasks. Furthermore, it is not just the presence or absence of specific design conditions or features but the consistency of their presence or occurrences and the degree of variation or uniformity, both within a floor (horizontally) and from floor to floor (vertically) of a building, which is more of a concern to most practitioners.

7.2 Retrospective Analysis

The research used retrospective analysis to demonstrate the soundness (realism) of the system as well as the completeness and appeal of the knowledge specifications and reasoning approach in relation to the state-of-the-art tools, Solibri Model Checker and Navisworks. For each feature type, a list of spatial and non-spatial queries was compiled based on a thorough review of literature and the detailed interviews with the construction experts. The compiled sets of queries represent generally useful and desirable information for different construction domains and functions such as construction planning, concrete construction, interior construction, MEP coordination, cost estimating, constructability analysis and were treated as a "gold standard".

In comparing systems against such a gold standard, two metrics are commonly used to determine the value of the system: "precision" and "recall". In this case, precision measures how many queries within a system are correct, while recall measures the fractions of correct answers from the gold standard that are returned by a given system. Because the different systems are made for very different purposes, we did not measure precision (e.g., it makes little sense to penalize the results of Navisworks for including all clashes based on the geometry of the building components because Navisworks has the ability to work with all the key 3D design file formats, but Navisworks does not have the functionality to leverage semantically rich BIM data in more meaningful ways). Instead, the evaluation was focused on the measure of recall which was sub-divided into three categories; "full," "partial," and "none" to provide a more precise and unequivocal evaluation process. Table 7 shows the recall results for querying different spatial and non-spatial design conditions. The results suggest that the formalized knowledge base and the query-based approach that operates on this knowledge provide richer representation and/or querying of construction-specific information compared to the state-of-the-art tools. The full analysis results including the descriptive and interpretative analysis of the results for querying spatial and non-spatial queries are provided elsewhere (Nepal, 2011). Descriptive and interpretative analyses were used to further demonstrate the usability and realism or practicability of the research through richer and flexible representation and querying of design conditions that are relevant to practitioners (Nepal, 2011).

TABLE 7: Summary of the recall results for querying different spatial and non-spatial design conditions of features

Feature	Relevant No. of Design Conditions Treated	State-of-the-Art Tools						Our Approach					
		Full Support		Partial Support		No Support		Full Support		Partial Support		No Support	
		Count	Percent (%)	Count	Percent (%)	Count	Percent (%)	Count	Percent (%)	Count	Percent (%)	Count	Percent (%)
Components in general	22	4	18	6	27	12	55	4	18	8	36	10	45
Wall	29	8	28	4	14	17	59	15	52	4	14	10	34
Column	20	2	10	0	0	18	90	8	40	5	25	7	35
Component intersection	22	2	9	4	18	16	73	13	59	1	5	8	36
Opening	15	5	33	4	27	6	40	9	60	3	20	3	20
Penetration	12	2	17	0	0	10	83	8	67	1	8	3	25

It should be noted that inputs from the construction experts were incorporated for knowledge acquisition and in the subsequent representation and validation of the knowledge. The proposed and/or created solutions were evaluated retrospectively in relation to four case study projects and in comparison with the state-of-the-art tools, Navisworks and Solibri Model Checker. The interviewed practitioners did not evaluate the developed solution or system as such but provided expert opinions on the relevance of formalized concepts to experts and their domains and rationale/s for "why", "when" and "how" different building component-specific design conditions impact construction.

8. CONCLUSIONS

The construction of a building or facility relies on the accuracy and completeness of design information for the application of appropriate construction methods, tools and processes. Effective utilization and organization of construction knowledge helps to provide a better understanding of construction and FM requirements during design development. It also enables better, more explicit articulation of the design information to constructors and facilities managers for improving design constructability, and the operation and maintenance of constructed facilities. With the increased use of BIM and the subsequent increase in the volume of digital information, the availability of desirable information at defined levels of specificity, is of utmost importance to seasoned construction and FM practitioners.

This research investigated how explicit specification of design-relevant construction knowledge would provide better support for accessing BIM. The research identified a subset of design conditions obtained from the synthesis of the literature and acquired through different knowledge acquisition techniques. It formalized the identified knowledge in the form of ontology and query specifications to enrich BIM with construction-relevant information. This research used interviews with domain (construction) experts to validate the knowledge base. Interviews with domain experts are powerful mechanisms both for acquiring the knowledge and validating the knowledge base, particularly for "what," "when" and "why" types of factual and conceptual knowledge and "how to" types of procedural knowledge. This research mostly identified "what" type of knowledge and to a lesser extent "why" and "when" aspects as an explanation to "what" design conditions. Further research in the elicitation of procedural knowledge on the design conditions identified in this research will provide a richer knowledge base for embedding problem solving reasoning structures, such as advanced rule based systems in BIM, and for providing better explanation and justification facilities of query results.

Retrospective analysis of several design conditions demonstrated the soundness (realism), completeness, and appeal of the knowledge base and query-based reasoning approach in relation to the state-of-the-art tools, Solibri Model Checker and Navisworks. The knowledge engineering process and the methods applied to acquire, represent and/or specify knowledge can be useful for the AEC/FM industry in leveraging BIM in support of a number of knowledge intensive tasks. Some of the key practical outcomes which can be realized as benefits from this approach are summarized as follows:

1. Quick identification of cost-incurring features of a design to support cost estimating.
2. Improvement in the consistency and accuracy of information extracted from digital models (BIM).
3. Identification of constructability issues prior to construction and provision of constructability feedback to designers and owners.
4. Improvement of construction efficiency and productivity through improvements in the speed and ease of obtaining construction information.
5. Support for decision-making tasks related to purchasing and methods selection.
6. Provision of information in a form that helps practitioners to manage the construction process and coordinate trades.
7. Provision of informed decisions and reduction in errors during the layout and installation of components.

Construction works are project-based, temporary and interdisciplinary in nature, with complex networks of project organizations and stakeholders. There are inherent challenges in acquiring and/or formalizing construction knowledge to leverage BIM in construction. Oftentimes, the very nature of the industry necessitates the need to incorporate multiple (or mixed) methods and sound methodological principles at each stage of research, including the knowledge acquisition and formalization phase (Abowitz & Toole, 2010). Such multiple methodologies are useful, not just for understanding the problem and phenomenon but also for generating qualitative and quantitative information. They also provide contextualized information to aid comprehension of phenomena (Leicht et al., 2010). The use of multiple methods, which included observational studies, case studies, state-of-the art reviews of BIM technologies, interviews of domain experts and were adopted in the different stages of this research proved very useful for knowledge acquisition and specification.

While a range of design conditions at the component level were captured, the acquired knowledge was, by no means, exhaustive. The research didn't capture detailed or low level of design conditions (e.g., joints, tolerances) as well as very high, system level design conditions (e.g., uniformity of floor-to-floor layout). Further studies are needed therefore, to extend the breadth and depth of this research in order to uncover the design conditions not captured in this research as well as more comprehensive validation of the acquired and/or formalized knowledge including the user studies for evaluating the usefulness of query-based approaches of information extraction/retrieval to different CM domains.

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