Building Information Modeling: BIM in Current and Future Practice
By Karen M. Kensek and Douglas Noble

CHAPTER 17

Communicating Semantics through Model Restructuring and Representation

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17.1 INTRODUCTION

> Design is intentional, purposive, goal-seeking, it decisively relies on reasoning. . . . "Reasoning" pertains to all those mental operations we are aware of, can even communicate to others. It consists of more or less orderly trains of thought, which include deliberating, pondering, arguing, occasional logical inferences.
>
> (Rittel 1987)

In the processes of designing and creating buildings, architects and other building professionals explore various configurations for a desired outcome of design, function, and performance. Designers reason about evolving designs through inferences and interpretation of explicit information, processed or gleaned, from drawings, physical and digital models, documents, diagrams, and mathematical models. Design intentions and decisions are communicated to the relevant professionals and stakeholders through a variety of representational medium. Inevitably, during this process, there is information exchange between one form to another such as from sketch to digital model or from one context to another such as from architectural model to energy model.

Commonly used software tools to assist in design essentially provide graphic visualization of geometry where lines, symbols, and annotations are interpreted as definitive objects with definitive meaning. Building information modeling (BIM) has emerged as a significant tool to represent the various building components as objects with semantics (Eastman et al. 2008). A building information model is a digital representation of the physical and functional characteristics of a design. "[It] serves as a shared knowledge resource for information about a [design] forming a reliable basis for decisions during its life cycle from inception onward" (Smith and Edgar 2008). Each proprietary software application specifies its own internal model to capture the relations and intended uses of the various types of data. In order to make these models accessible to applications outside of the proprietary BIM environment, data need to be extracted to nonproprietary applications. Inevitably, during this process there is information loss; on the positive side, the tradeoff is having platform independence. There are public data exchange formats that can be employed to implement tools that support reasoning and decision making. Of these, IFC (Industry Foundation Class) and CIS/2 (for steel) are currently the widely recognized data exchange standards (Eastman et al. 2008). IFC provides a suitable data structure based on concepts and relationships, which can offer a complete and uniform description of the project data, independent of project specifics or proprietary software (Stouffs and Krishnamurti 2001).

For purposes of reasoning about building-domain-related questions, one requires the semantic model encapsulated within the building information model. However, such semantics are hard to access, navigate, and manipulate. Three important issues arise: knowing the kind of data that must be extracted, how effectively the data can be augmented and/or restructured, and how effectively the data can be represented for a specific need. In order to leverage the power of BIM for reasoning and decision making, the inherent semantics of a multidimensional building product model need to be made explicit (Figure 17.1).

Two projects are described, which explore how BIM assists in reasoning and decisionmaking. Each project employs its own kind of "drawing board." One examines the provisions of building information models for analyzing spatial and network topologies through data extraction, data restructuring and representation; and the other explores capabilities for assessing designs for green certification through data extraction, data augmentation, and representation.

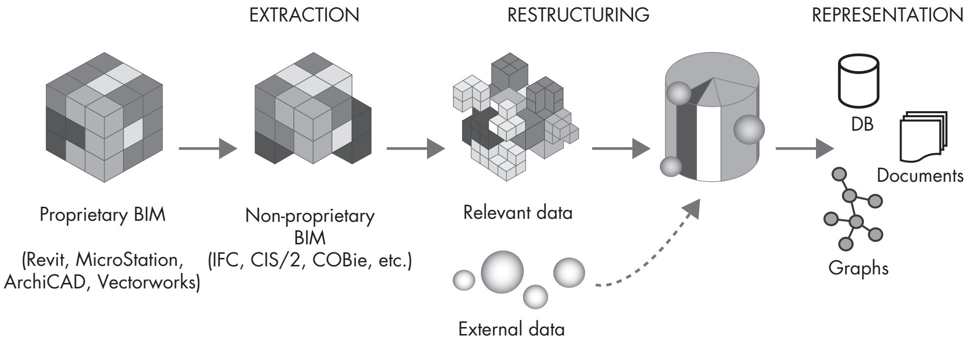

FIGURE 17.1 General process for using information from BIM for reasoning.

17.2 SPATIAL REASONING AND QUERYING

17.2.1 BIM as an Infrastructure for Spatial Reasoning

Understanding spatial relations of building components plays an important role in decision making during the design process of a building. Moreover, querying spatial relations in an existing design solution can facilitate evaluation of the design in terms of meeting specific criteria and requirements. These queries refer to spatial topology requirements. Common questions include:

- Is the bedroom adjacent to the bathroom?
- Are the electromechanical spaces separated from the user spaces?
- What is the shortest egress from this room to the exit?

Building information models offer a promising infrastructure for spatial reasoning. Beyond explicitly representing building components, their properties, and geometric characteristics, BIM additionally represents basic topological relationships among building components. However, current central model management servers, which mediate between user and BIM, are not based on certain spatial semantics of particular attributes and relationships, and therefore information stored in these models cannot be interpreted, adequately, to infer spatial relations.

BIM servers provide ways for the user to select, filter data, perform queries, and constraint checks and even implement custom queries by programming (Mazairac and Beetz 2012). Although it is possible to resolve certain spatial topology queries using these ways, nevertheless, implementing a more complete evaluation tool to compare existing designs against standard building criteria necessitates good working knowledge of the syntax and structure of the underlying building information model.

17.2.2 Extraction, Restructuring, Representation

The title of this section suggests the order in the sequence of evaluating a spatial topology query. For ease of explanation, however, this order is reversed, and representation is considered first. The choice of representation guides decisions relating to the structuring and data extraction steps. The representational needs for a given query imply a certain but appropriate data structure to maintain the extracted data and determine whether the data provided by the building information model suffices or needs to be augmented. Ideally, any tool for spatial reasoning and querying must support representational flexibility, which, in this context, implies models that are scalable and multimodal. A scalable representation model allows for moving effortlessly between scales of three-dimensional space, changing view and granularity. A multimodal representation model enables changing across different perspectives, namely the various spatial topology relationships that might be considered. In the context of BIM, scalability and multimodality are key properties if one considers the differing information and reasoning needs of the various project professionals and stakeholders.

Graph representations have proven to be convenient models of spatial configurations in architecture and other space planning domains (March and Steadman 1974, Hillier and Hanson 1984). A typical example is the graph theoretic application to the space layout problem, namely, generating a layout that meets certain adjacency requirements between activities (Liggett 2000). Nodes in these graphs typically represent spaces, and edges typically connect two nodes to represent spatial topology relationships among spaces. Certain graph models provide greater representational flexibility than others. For example, hierarchical hypergraphs form an infrastructure that may allow through the appropriate user interactions change in scale as well as the capability to extract subgraphs according to user defined levels of detail (Grabska et al. 2012).

The need to extract relevant data from industry foundation classes (IFC) instead of from a proprietary software application has been previously highlighted in the introduction. However, the IFC data structure does not provide an efficient infrastructure on which to base a graph representation. Therefore, the extracted data must be effectively structured *a posteriori* so as to provide the basis for a scalable and multimodal representation model.

Data structures to support graph representations are important. Choosing the appropriate data structure enables certain queries to be effectively answered. In certain cases a simpler representation may suffice. For example, to answer a shortest egress query, Dijkstra's shortest path algorithm (Dijkstra 1959) may be used. This can be implemented with an adjacency list, a data structure where each space-node in the graph references a list of the space-nodes it is connected to (Cormen et al. 1990). There are other design problem situations that require finer-grained layouts of architectural spaces to be queried. For example, to answer queries related to electrical circuitry infrastructure, a schema that represents adjacency among spaces and connectivity between the boundary elements of each space would be required. Such a schema could be implemented with a double-edge list (Berg et al. 2000), a data structure that enables the space boundaries of the spaces to be efficiently traversed in order, either clockwise or counterclockwise. There is usually a trade-off between the complexity of the data structure and the types of the queries that can be answered.

17.2.3 Spatial Topology Data Extraction from IFC

Spatial topology querying is considered in the context of a specific BIM format, namely, IFC, industry foundation classes. IFC is an object-oriented data structure to represent building models. Building components are members of classes; for example, these could be discrete objects such as walls, windows, or abstract objects such as project and process. An IFC model is a collection of such discrete and abstract building components and the relationships between them. Each IFC object has attributes that specify its semantics.

Objects in an IFC model are linked to each other through a complex network of relationships forming a tree hierarchy. An investigation of how IFC conceptualizes space, how it breaks space down into its basic entities, and how it defines relationships among those entities reveals the types of data that are useful for inferring spatial topology relations. Information is stored in the IFC structure either explicitly, available by accessing a simple property of an object, or implicitly requiring complex navigation of the underlying model (Mazairac and Beetz 2012). For instance, deriving networks of adjacency and connectivity relationships belongs to the second category and requires extraction of information involving a significant number of steps in navigating over the IFC tree structure.

The key elements in inferring adjacency and connectivity relations within the context of a BIM are the concepts of bounded space and shared element. Space is defined as "an area or volume bounded actually or theoretically" (buildingSMART 2013). IFC grounds the definition of space on the property of it being bounded by enclosing elements. It objectifies this relationship of the space to its physical or virtual boundaries (referred to as IfcRelSpaceBoundary) by the BoundedBy attribute in the IfcSpace entity. Each physical space boundary references the building element that physically separates the space under consideration from its adjacent spaces. On the other hand, if the space boundary is deemed virtual, it either references a virtual element or none at all.

It is important to note that although an IfcRelSpaceBoundary expresses a unique relationship between an element and the space it bounds, each element is allowed to define many such relationships, and each space is allowed to be defined by many such relationships (buildingSMART 2013). This observation leads to the concept of a shared element, which is the basis for deriving adjacency and connectivity relations. If a building element, either vertical or horizontal, is referenced by more than one space (in other words, it is shared by more than one space), these spaces may be respectively vertically or horizontally adjacent. If, additionally, the building element contains an opening intended for access, these spaces will also be connected.

The concept of shared elements has been adapted by researchers; for instance, implementing shortest path queries on the connectivity network of a floor plan from IFC models (Taneja et al. 2011), and for deriving topological relationships directly from the 3D geometry of spaces based on the Poincare duality (Lee and Kwan 2005). The latter example is instructive; according to the Poincare duality principle, the common 2D face shared by two adjacent solid objects can be transformed into an edge linking two vertices in the dual space of the graph. Thus, the edges of the dual graph represent adjacency and connectivity relationships that may correspond to doors, windows, or walls between rooms in primal space.

17.2.4 Prototype for Spatial Topology Queries

A prototype application that generates and displays graphs representing adjacency, connectivity, composition and containment was developed (Figure 17.2). The prototype has been implemented in Java and has been successfully tested with IFC models of three different building types.

The source application, ideally, is a commercial BIM software (for example, Revit, ArchiCAD, or VectorWorks) that provides options for exporting a model to IFC. The prototype parses the IFC model, determines the building decomposition into floor levels and spaces, and extracts the relevant spatial topology information. The relevant data referring to adjacency and connectivity has been described in the previous section. Once the data are extracted and restructured the spatial topology graphs are generated. The prototype's user interface lets the user select between the available graph representations. The user can navigate over the building composition tree provided by the user interface, select a floor level

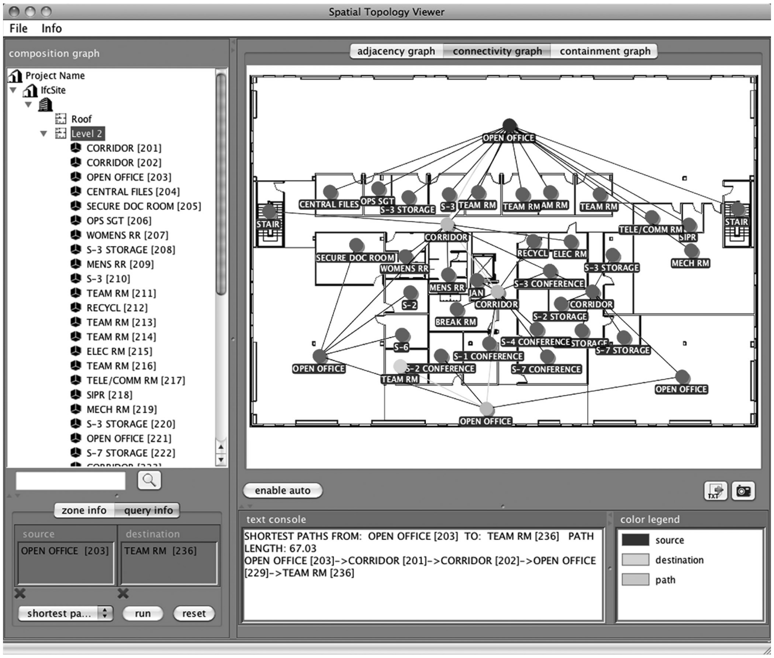

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FIGURE 17.2 Spatial topology prototype.

or a specific space, and have the respective graph displayed. By further interacting with the graph nodes a subgraph can be extracted. Additionally, the prototype allows querying the generated graphs by applying a series of graph theory algorithms, namely, all paths and shortest paths among sets of user selected spaces, connected components, and spanning trees (Cormen et al. 1990).

17.3 REASONING FOR GREEN CERTIFICATION

> No single computer application can support all of the tasks associated with building design.
>
> (Eastman et al. 2008)

In light of this claim each type of specialty has to be supported and augmented by its own application. In addition to supporting geometry and material specification, additional applications are required for structural and energy analyses, fabrication, and facilities management among others. These added applications obtain data from a basic building information model, then restructured or processed within an augmented data structure in order to address functions necessary for reasoning and decision making. Here, BIM is examined in the context of green certifiability through the lenses of data requirement and extraction, suitable data structures for augmentation, and tools and processes.

A building typically achieves a green certification when it fulfills requirements set by a rating standard. Green or sustainable building rating systems are defined as "tools that examine the performance or expected performance of a 'whole building' and translate that examination into an overall assessment that allows for comparison against other buildings" (Fowler and Rauch 2006). In the process of assessing a project for green certification, design teams are exposed to different types of information (codified as drawings, product models, standards, etc.) and have to use a combination of tools to come to a conclusion using knowledge related to green assessments. Some common requirements are:

- Is the building X percent more water efficient than the benchmark?
- Is the building X percent more energy efficient than the benchmark?

These performance requirements are specified in the building rating standards. BIM-based environments can assist in decision making to comply with sustainable rating standards, in particular, during the early stages of design (Biswas et al. 2013).

17.3.1 Aggregation, Augmentation, Representation

As in the case of querying spatial topology, knowledge necessary to support sustainability could be used efficiently, provided the relevant data can be identified, extracted, aggregated, and restructured, which in this context is for the purpose of checking of certification requirements. Data are aggregated from a combination of sources such as performance data, sunlight, and rainfall (in general, external data), and internal data from BIM, essentially, geometry, pertinent attributes and other BIM-dependent data (Figure 17.3). This data must be stored in a suitable data structure so as to lend the information to checking outcomes according to green assessment criteria.

In practice, no single specification standard provides support for sustainability assessment, nor do these completely suffice as a data structure. In examining building representation models, Huang (2011) concludes:

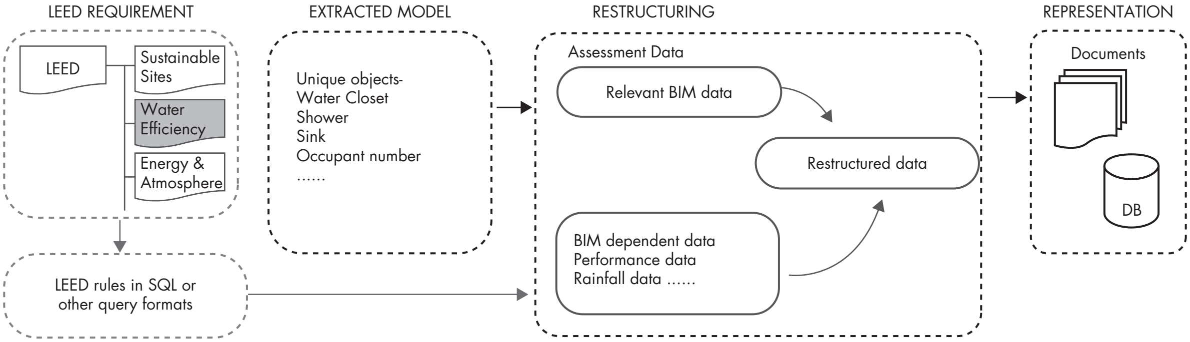

FIGURE 17.3 Data extraction, structuring, and representation for green certification.

> There are significant differences between the IFC and gbXML schemas, including comprehensiveness, efficiency, robustness, redundancies, and portability. . . . Both formats are not yet able to represent all information across all building performance domains (p. 6).

In order to use design information and integrate sustainability related information requirement, a number of information exchange formats were explored. COBie (Construction Operations Building Information Exchange) was seen as a suitable candidate for a lightweight building information model, which is derivable from an IFC model. A COBie model saves building owners and occupants from having to rekey information multiple times throughout the life cycle of a project (East 2013). The objective behind the development of COBie is not to specify an alternative model for information for building management, but rather to provide a standard format for common information. COBie was adopted as the data structure because its format offers a structure that could be easily used, extended, and augmented to drive sustainability assessments.

17.3.2 Prototype for Green Certification

Following this approach a prototype application was developed using COBie as the extendible data format (Figure 17.4). The source application ideally is a commercial BIM software that provides options for exporting a model to IFC. The IFC model is then converted to a COBie model via data exchange software provided by BimServices (Nisbet and East, 2013). For the prototype, LEED (Leadership in Energy and Environmental Design) is chosen as the exemplar sustainable building rating system. LEED requirements are represented as a set of executable rules and stored in an augmented COBie database, COBie+. Evaluation rules are taken as input, and these are interpreted for assessment against building data held in the COBie+ model. Storing rules in the augmented COBie+

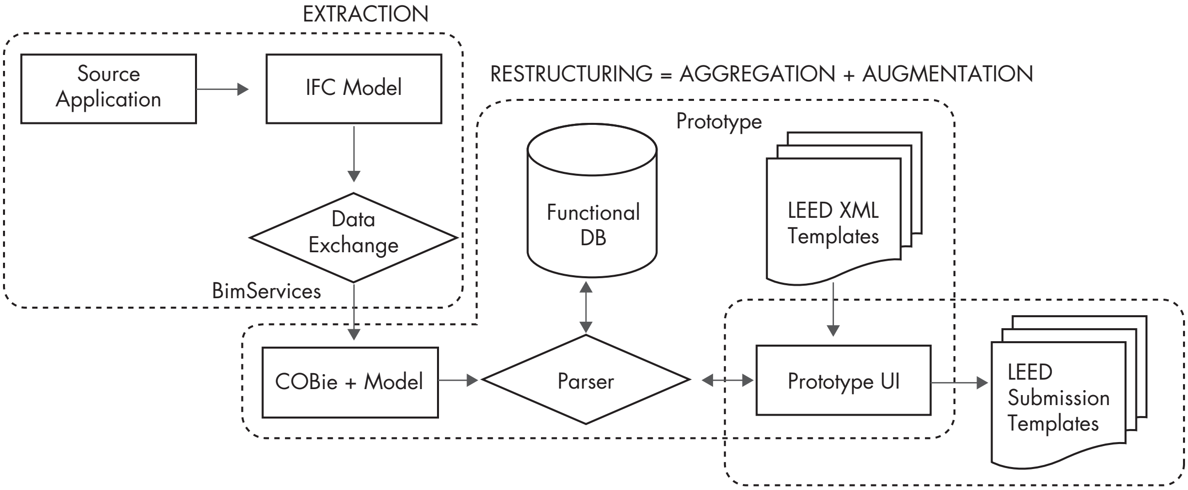

FIGURE 17.4 Data extraction, restructuring, and representation using the prototype.

model allows the application to more readily accommodate future rating requirement updates. It enables multidisciplinary cooperation from sustainable assessment rule mapping to corresponding building data (and vice versa). The prototype generates LEED submittal documents in HTML format, containing the aggregated results. The prototype exemplifies a process where design information can be aggregated, structured, and represented to support the certification of designs according to a green rating standard.

17.4 CONCLUSION

Assumptions, factors, and processes, which are required of a building information model to provide reasoning support, have been explored in the context of two projects: spatial topology querying and green certification. BIM is a rich repository of data that can support exchange between applications and databases. However, understanding the semantics and data structures imposed by industry standards for data exchange is key in developing tools for specific needs. This understanding enables one both to navigate a given building model and to identify data availability. A general process of data extraction from proprietary to nonproprietary BIM, extraction of relevant chunks of data and/or data augmentation, and restructuring and representation in addressing domain specific queries are necessary. These steps are integral for implementing tools that are flexible and adaptable for the differing and changing needs of the different stakeholders and professionals in the industry.

Perhaps, the single most important lesson learned from the two projects on spatial topology querying and green certification is that building information model–based processes need to be more knowledge intensive; this responsibility has been previously placed upon the construction industry (Wetherill et al. 2007). This challenge of making specific project knowledge available to interested parties for purposes of reasoning in a systematic and reusable way may be resolved by developing ontologies, each essentially an “explicit specification of a conceptualization” (Gruber 1995). To this extent, such ontologies become the next relevant step in refining building information models and their relationship to domain specific applications.

DISCUSSION QUESTIONS

1. How can building information models become shared knowledge resources to support decision making about a project?
2. What are the most vital components of a BIM for communication? Which of these are useful in understanding and explaining problems and solutions?
3. How can conceptualization be used in analyzing BIM domain knowledge, in making explicit domain assumptions, and enabling reuse of domain knowledge?

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