A FRAMEWORK FOR SEMANTIC ENRICHMENT OF IFC BUILDING MODELS

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ABSTRACT

Building information models provide semantically rich information with objects that explicitly represent 3D geometry and non-graphical properties. However, there are significant difficulties in exchanging information between domain-specific BIM tools. Exchange formats, such as the Industry Foundation Classes (IFC) Coordination View (CV), cannot represent all of the domain- and profession-specific information required by the different construction project stakeholders (and their diverse software tools). Similarly, building models compiled from laser scanning point clouds or other survey methods often contain the major building objects but lack the semantic richness of relationships and other concepts needed for a model to be useful for a range of engineering purposes. All these limit the ability of diverse systems to interoperate together. An automated or semi-automated approach is therefore needed for deriving a semantically useful building model file from the explicit and implicit information contained in an IFC building model. In this paper, we present such an approach for semantic enrichment of IFC building models exported according to the IFC CV version 2. The innovation of the approach is that it supplements the exchange model data with semantic constructs defined for the receiving application. This places the emphasis for data exchange on the receiving application by moving the onus from export to import. The approach is based on a taxonomy of semantic inference rules. A three-tier structure for the taxonomy is proposed in order to capture the domain information in a structured way. The paper outlines the approach and illustrates it with examples of exchanges from the precast concrete domain defined by the US National BIM Standard (NBIMS). The digital information content needed to support these exchanges is specified in Model View Definitions (MVDs). Intermediate results of a pilot technical implementation for the examples are presented and analyzed in the paper.

Keywords: Building Information Modeling (BIM); Architecture, Engineering and Construction (AEC); Industry Foundation Classes (IFC); Coordination View (CV); Semantic enrichment; Model View Definition (MVD)

1. INTRODUCTION

Building Information Modeling (BIM) refers to 3D object-oriented parametric digital representation of the physical and functional characteristics of a facility. BIM tools serving the Architecture, Engineering, and Construction (AEC) industry encompass various domains and have different internal data model representation to suit each domain. Neutral file formats such as DXF, IGES, and SAT were developed to facilitate file exchanges between one tool and another. However, the information content of these exchanges was limited to geometric entities only. An early approach was to make data exchanges possible by hard-coding interfaces between pairs of tools. This method is costly to implement and maintain on an individual system-to-system basis.

The Industry Foundation Classes (IFC) (Liebich, et al. 2006) schema is a neutral and open data exchange format for interoperability within the AEC industry. Although IFC is a rich product model schema, IFC implementations need clear guidance for specific data exchanges due to a lack of semantic rigidness in IFC CV 2 and inconsistencies in the assumptions different implementers of exchange functions make about how information should be expressed (Sacks, et al. July 2010). For any particular building information model exchange there needs to be semantic clarity to issues such as embedded and type-instance relations or topology.

Another interoperability problem for the use of BIM concerns data capture of existing buildings. 3D surfaces of constructed facilities generated from state-of-the-art surveying technologies, such as laser scanning (LIDAR) and photogrammetry, do not have any semantics corresponding to the building elements they contain nor any information pertaining to the relationships among the elements. They cannot provide as-built information such as material properties and structural health. As a result, creating a useful building information model of a constructed facility from scanned point clouds has to be done manually, which is costly and time consuming. Efforts are under way to develop systems that can at least derive the vector geometry of elements and express the data in IFC format (Brilakis, et al. November 2010).

Both of these problems lead to the deficient interoperability. A lack of the adequate interoperability between software applications is the limiting factor in achieving the full potential of BIM (Young, et al. 2009). Therefore, there is a need for an approach capable of deriving a semantically useful building model file from the explicit and tacit information contained in IFC building models exported from BIM tools or generated from scans. This paper presents an innovative approach for semantic enrichment of IFC building models exported according to the IFC CV 2 with semantic constructs defined for the receiving application. The approach is based on a three-tiered taxonomy of inference rules that can identify domain-specific semantic constructs and add them to the IFC files in a structured way according to the concept bindings defined in the domain's model view definition.

Tier 1 contains domain-specific inference rules that relate domain-specific concepts, universal concepts and relationships. Tier 2 provides a set of domain-specific and universal concepts, properties and relationships as well as geometry and spatial operators that are used to compile the tier 1 rules. Tier 3 provides technical implementation of the intermediate level rules. The approach is illustrated with examples of information exchanges specified in Model View Definitions (MVDs) for the precast concrete domain, defined by the US National Precast BIM Standard (Precast Concrete BIM Standard Documents: Volume I. Model View Definitions n.d.).

2. LITERATURE OVERVIEW

2.1 Industry Foundation Classes and National BIM Standard

The Industry Foundation Classes (IFC) schema is widely recognized as the common data exchange format for interoperability within the AEC industry (Eastman, et al. 2008). It is a rich product model schema, but it is highly redundant and lacks formal logic rigidness. Thus, data exchanges selecting from the redundant data representations have had unacceptable problems of mismatch. This has posed a barrier to the advance of BIM (Eastman, Jeong, et al. Jan/Feb 2010), (Olofsson, Eastman and Lee 2008). These inconsistencies have led to the conclusion that domain specific MVDs are needed to define precisely how building model exchanges should be expressed using IFC (Final and Hietanen 2006). In 2010, buildingSMART developed the new IFC Certification 2.0 procedure for the IFC 2X3 Coordination View (CV) Version 2, which is an MVD intended to promote consistent and reliable implementations of the IFC specification by many software vendors across multiple software platforms.

The National BIM Standard™ initiative (NBIMS 2007) proposes facilitating information exchanges through MVDs (Hietanen and Final 2007). A model view is a subset of the IFC schema that satisfies the requirements for a particular industry model exchange. This NBIMS methodology defines the appropriate information entities from the IFC schema for a particular use-case. Studies on data exchanges, by reducing or simplifying the information, show that without well-defined exchange model views, the current approaches are vulnerable to errors, omissions, contradictions and misrepresentation (Bazjanac and Kiviniemi 2007). The results of the exchange scenarios between BIM applications have been shown to contain information loss or distortions (Palzar and Turk 2008).

Most of these problems can be related to the lack of semantic uniformity in the way BIM tools map their internal objects to and from IFC entities and properties. Performance studies of BIM data bases, to create partial models and run queries, show a strong need for both identifying model views for specific exchanges, as well as for specifying the exchange protocols in a stricter manner (Nour 2009), (Eastman, Jeong, et al. Jan/Feb 2010). A need for a more formal definition of IFC concepts is analyzed in (Venugopal, et al. 2010). All in all, a layer of specificity for selecting and specifying information entities, their attributes and rules over the top of the IFC schema needs to be provided for effective exchanges. This layer is a subset of the IFC schema and when used for a particular exchange it is called a model view. A more generic definition of an MVD is a subset of a building product model schema that provides a critical representation of the information concepts needed for a particular information exchange in AEC workflow (Eastman, Panushev, et al. 2011). The information concepts are shared through an open website, IFC Solution Factory (See 2010), and serve as MVD specifications.

2.2 Related research

The importance of generating useful IFC building models, which suit domain specific applications or data exchange requirements, has been recognized in different researches (Beetz, van Leeuwen and de Vries 2009) (Wiese, Katranuchkov and Schere 2003). Different approaches exist for extracting information on a certain view or deriving a subset of all entities out of an original building model. The Coordination View 2 of buildingSMART International (buildingSMART International n.d.), graph query method on the IFC ontology which filters out geometry and topology information (Beetz, van Leeuwen and de Vries 2009), Generalized Model Subset Definition schema proposed in (Wiese, Katranuchkov and Schere 2003), no-schema extraction algorithm for IFC instance models (Won, Lee and Cho 2013) are good examples of creating partial IFC models. There are also server-based approaches for creating partial building models. However, the expressive power of the query languages provided by product model servers such as Jotne EDMServer (Jotne EPM Technology n.d.) or EuroStep Model Server (Eurostep n.d.) is limited: they are unable to interpret explicit and implicit information contained in building models because they are not familiar with the spatial semantics of particular attributes and relationships. All in all, these approaches keep original building model objects unchanged. However, in real information exchanges between BIM tools building entities and/or semantic constructs might need to be modified and/or to be added to a model to suit data exchange requirements. One such example is described in (Zang and Issa 2011). The following section introduces the approach for creating semantically enriched IFC building models.

3. APPROACH OVERVIEW

The semantics of a building object are composed of its form, function and behavior (Lee, Sacks and Eastman 2006). These are manifested by its shape (3D geometry), material and mechanical properties, its functional classification, its topological and aggregation relationships with other objects, and the domain context. The relative locations of objects to one another are key determinants for their functional classification and for determining their topological and aggregation relationships. This section outlines a three-tier structure that supports operationalization of these relationships for the purpose of semantic enrichment. It introduces universal and domain-specific concepts and spatial relationships among model objects.

3.1 Tier 1

This level consists of a set of inference rules that can be processed in an inference engine in order to infer new facts about a model and thus enrich its semantic content. The inference rules relate the instances of any given building model using concepts, properties and relationships defined in Tier 2. An example of a set of tier 1 rules is provided in section 4 below.

3.2 Tier 2

This level defines concepts, properties, and relationships, as well as geometry and spatial operators that can be used to derive additional properties. All of these are used to compile the tier 1 rules. Concepts, properties, and relationships are either universal or domain-specific. The former are universal within the universe of discourse, which in this context is the broad AEC domain as defined by the IFC Coordination View 2.0. The latter are defined by MVDs, such as the precast concrete (PCI) MVD. Operators are mostly universal, but they can also be domain specific. In some cases, domain-specific operators may specialize universal operators.

3.2.1 Concepts

- *Building elements*: These are the basic physical parts of buildings that are defined either in the IFC CV 2.0 or in the domain-specific MVD.
- *Objectified relationships*: A precast connection is an example of a domain-specific objectified relationship. The relationship object may or may not have a specific geometry, and it will usually have relationships with the objects it relates and may represent an assembly of its parts (such as steel plate embeds in a precast connection). These are defined in domain-specific MVDs.

3.2.2 Properties and Relationships

- *Function:* The function of a building element is defined by its classification (e.g. *IfcBeam*). The classification in any given exported IFC file is often unreliable, because the BIM tool's export may not match the intended classification. For example, a steel bearing plate may be exported as an *IfcBeam* if the tool's internal representation does not model plates. In some cases, users may have used massing tools to generate geometry, which are then generic objects with no specifically declared function.
- *Geometry:* Each entity has a geometric representation, which can be attribute driven (parametric, usually with swept solid geometry), boundary representation (B-rep) or constructive solid (CSG) geometry. Entity properties and their values are also provided in the IFC files.
- *Cross-section* is a property of objects that is available only for geometry modeled as swept solids.
- *Material.*
- *Identity.*
- *Aggregation relationships* relate the parts of assemblies. The relationships are defined in the relevant model view. For example, hollow-core planks are parts of a precast slab.

3.2.3 Geometry Operators

- *Centroid* operators determine whether the centroid is inside or outside a shape. This is useful for classifying shapes.
- *Face* operators derive parts of the external envelope of objects. For example, the *vertical_narrow_face()* of a wall is an operator that returns a particular face of an object based on its geometry, proportion and orientation.
- *Volume* operators derive a volume of space that is occupied by an object or a set of objects (such as a bounding box) or that results from the relative locations of two or more objects. For example, the volume between two objects is derived by the *proximate_volume()* operator.
- *Orientation* in a coordinate system XYZ. Three orientation operators determine whether the axis of an object or the plane of a face is vertical, horizontal or inclined.
- *Proportion* as a shape characteristic. Building objects are commonly perceived as: *1D (*one dimension is much larger than the other two, e.g. beams and columns); *2D* – one dimension is much smaller than the other two (e.g. walls and slabs); or *3D* – all dimensions are relatively of the same size (such as pad foundations).

3.2.4 Spatial topology operators

These operators test the relative locations of the objects they receive as arguments and return true or false.

- *Adjacent* – two objects *A* and *B* are adjacent if they have a common face or if one of each of their faces is less than some given tolerance distance from the other.
- *Contact* – a special case of adjacency where the objects must be in contact, i.e. the tolerance distance is zero.
- *Contained* – one object is completely contained within another spatial object.

- *Overlapping* – two objects have an overlapping volume (the rest of their volumes are separate).

The spatial topology operators are needed because explicit topological relationships among entities in an IFC model, if represented at all, are potentially misleading and do not necessarily reflect the topology of building elements because they are dependent on the way that people model. For example, a file with *IfcColumn* entities on the first and fifth floors that are related to the third *IfcBuildingStorey* will pass CV 2.0 certification. In many cases, the relationships between building storey and object are not *1-to-many*, but *many-to-many*; a precast column can often span more than one storey. For this reason, the IFC object relationship tree of a model is not a reliable source for inferring spatial or functional relationships and attributes. Assemblies, where they exist in the IFC relationships tree, can be useful, mostly for reinforcing (rebar meshes and cages). As a result, determining spatial relationships, whatever they are, is the starting point for semantic enrichment of an IFC model.

3.3 Tier 3

Tier 3 provides technical implementation of the Tier 2 concepts, properties and relationships. Many of the operators can be implemented using the tools provided by spatial query languages and function libraries. For example, a spatial extension of Oracle 9i (Oracle n.d.), which is a sophisticated widespread commercial database system, provides operators, for example, for selecting geometries within a given distance, nearest neighbor geometries, or geometries with topological relationships. 3D ACIS Modeler (Spatial n.d.), owned by Spatial Corp., is another is example of geometric modeling tool that provides a rich set of geometric operations.

4. ILLUSTRATION

The proposed approach is illustrated with an example of information exchanges specified in Model View Definitions (MVDs) for the precast concrete domain which are defined by the US National BIM Standard. When a precast building model is exported according to the IFC CV 2 from a BIM modeling tool, precast elements and steel hardware are explicitly represented in the IFC model in one or another way. However, semantic constructs such as constructs for precast connections and joints are not represented at all in the IFC model. PCI domain experts' knowledge defines connections and joints as extremely important issues for this domain. Therefore, corresponding semantic constructs should be inferred from explicit and implicit information contained in the IFC model and added to it. In PCI MVDs precast joints and connections described by their attributes, locations, elements and type assignments. The spatial and material properties are used in the proposed taxonomy for differentiating between main building elements such as beams, columns, walls, slabs and secondary building elements such as steel reinforcing and connecting hardware. A simple model (Fig. 1) was created in Tekla Structures 19 (Tekla Corporation n.d.) and exported into IFC files compliant with IFC CV 2.

Precast Joint

In the example shown in Figure 1, there are two wall panels and a sealing strip between them. In the IFC model the wall panels are represented by *IfcWallStandardCase* entities and the sealing strip is represented by *IfcColumn* entity. This is a typical IFC export representation, derived from a popular commercial BIM tool. In the exported file there is no semantic construct to represent the precast joint. However, the IFC binding for concept of precast joints, as defined in the PCI MVD, calls for use of *IfcFastener* and *IfcRelConnectsWithRealizingElements* instances, as shown in Fig 2. Therefore, the joint must be inferred from and added to the IFC file.

Original IFC file content:

#60=IFCWALLSTANDARDCASE('1HTI_90000Zp4pDZOsCpWq',#5,
'PANEL','200*3000','200*3000',#33,#59,
'ID51752f89-0000-008f-3133-363636333834');

#116=IFCWALLSTANDARDCASE('1HTI_90000Yp4pDZOsCpWq',#5
,'PANEL','200*3000','200*3000',#104,#115,
'ID51752f89-0000-008b-3133-363636333834');

#164=IFCCOLUMN('1HTI_90000XZ4pDZOsCpWq',#5,'Sealing
Strip','FLT10*100','FLT10*100',#153,#163,
'ID51752f89-0000-0086-3133-363636333834');

Semantic Enrichment:

#420=IFCRELCONNECTSWITHREALIZINGELEMENTS(
'1HTI_90000Zp5pDZOsCpWq',#5, 'J-1', ‘Logical Joint',#,
#60,**#116**,(**#315**), 'Precast Joint')

#315=IFCFASTENER('1HTI_90000Zp6tDZOsCpWq',#5, 'Vertical
Precast Wall Panelto Wall PanelJoint Type 1', 'Precast
Joint',#153,#163,$,)

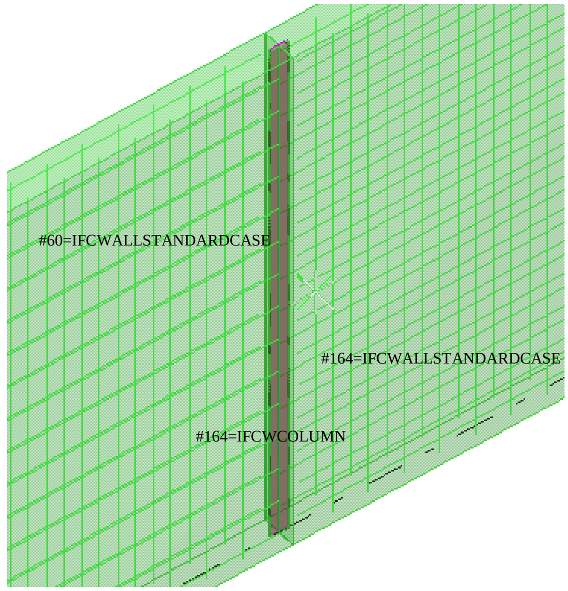

Figure 1: Joint location along vertical axis between precast wall panels.

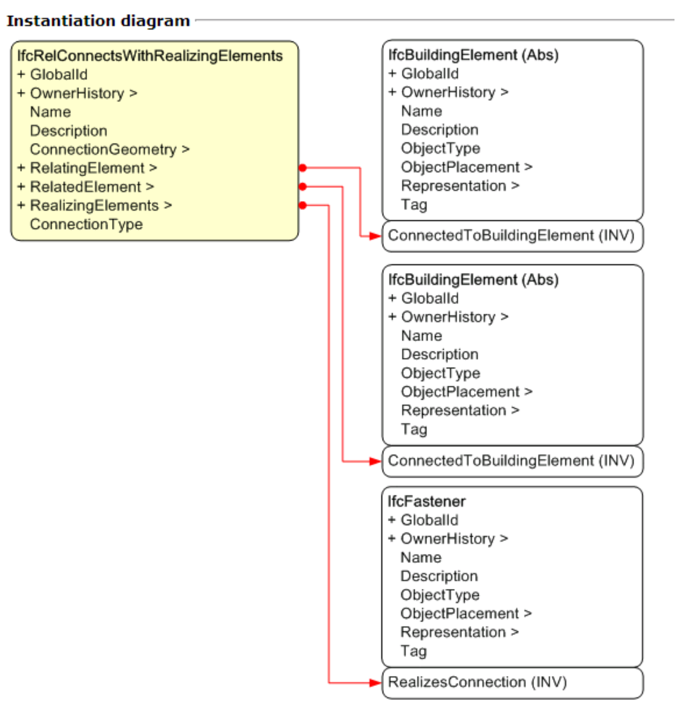

Figure 2: PCI-147: Instantiation diagram for precast joint element assignment.

The set of tier 1 rules needed to infer the joint can be written in pseudo-code as follows:

```
1   IF A is a precast_wall_panel                          : domain-specific object concept
2       AND B is a precast_wall_panel                     :    "        "        "   "
3       AND A.vertical_narrow_face is adjacent_to (2 in.) : universal spatial relationship
4           B.vertical_narrow_face                        :    "        "        "
5       AND E is a IfcBuildingElement  (any subtype of it) : universal AEC object concept
6       AND E is in contact_with A                        : universal spatial relationship operator
7       AND E is in contact_with B                        :    "        "        "        "
8       AND E is contained_in the proximate_volume(A, B)  :    "        "        "        "
9   THEN G is a precast_joint                             : domain-specific objectified relationship concept
10          E is a precast_joint_filler                   :    "        "    object concept
11          G joins A                                     : domain-specific relationship concept
12          G joins B                                     : "       "          "         "
```

In this example, all of the domain specific concepts are defined in the PCI MVD (Precast Concrete BIM Standard Documents: Volume I. Model View Definitions n.d.), and all of the universal AEC object concepts are IFC CV 2.0 concepts. Some of the clauses would themselves be derived using tier 1 rule processing. The classification of object A as a *'precast_wall_panel'* in line 1, for example, would be derived using a tier 1 rule that would consider the IFC functional classification, shape, proportions, material and domain-specific typical dimensions of the object (such as those shown in Appendix 1, which lists typical dimensions and proportions for precast concrete pieces). The *vertical_narrow_face* operator in lines 3 and 4 finds the vertical faces of the object with the smallest area. It is implemented as a specialization of a *vertical_face* operator. The *adjacent_to* checks whether the shortest distance between either of the two narrow faces of A are closer than some parameter distance from either of the two narrow faces of B. The in *contact_with* relationship in lines 6 and 7 returns true if the distance between the two objects is zero. The *proximate_volume* in line 8 is a spatial query operator that is defined as shown in Figure 3. The statements in lines 9-12 implement the semantic enrichment itself. The *precast_joint* of line 9 is a domain-specific objectified relationship, defined in the PCI MVD. It is represented by an *IfcRelConnectsWithRealizingElements* entity that relates two precast pieces, each represented by a subtype entity of *IfcBuildingElement.* The *precast_joint_filler* is generated in line 10: it is a domain specific object concept represented by an instance of *IfcFastener*. Lines 11 and 12 apply the relationship between the precast joint and the filler. Thus, as the example has shown, applying tier 1 inference rules for the precast joint to the example, the missing semantic constructs can be inferred and added to the IFC model. Incorrect instances, such as the *IcfColumn* instance, are replaced with the correct ones (in this case an *IfcFastener* entity) and missing instances are added (*IfcRelconnectsWithrealizingElements* and *IfcFastener*).

5. CONCLUSION AND FUTURE WORK

Creating a semantically useful IFC building model which is suitable for a range of engineering purposes is a key issue in improving collaboration between different construction project stakeholders. The proposed three-tier taxonomy of semantic inference rules supplements the IFC CV2 model with domain-specific semantic constructs, which are inferred from the explicit and implicit information contained in the model. The paper has presented the example of rigorously defined Tier 1 and Tier 2 inference rules which relate the instances of the IFC CV 2 model using universal, PCI MVDs concepts, properties, relationships and update the model accordingly. However, the proposed approach has limitations. It requires that IFC building models must be exported according to the IFC CV version 2. This limits the approach to certified building information modeling tools only. Although many industry and research groups are developing model views for varying aspects of the AEC information exchanges, such as PCI MVDs, only a few MVDs have been defined thus far. Tier 3 rules require technical implementation and the semantically enriched IFC CV 2 model must be checked against targeted MVDs.

Further development of the proposed taxonomy is under way and examples that are more complex will be elaborated. Packages for reading and editing native IFC format files, such as the OpenIFCTools API (Open IFC Tools n.d.), existing spatial query languages and function libraries will be adopted for practical implementation of the Tier 3 rules.

1. Given two adjacent spatial objects A and B, for each face perpendicular to a main axis of each object extend the volume of the object in the direction of the main axis by a distance *d* to create $B^{extended}$.

2. C = A $B^{extended}$.
3. Find the face of C closest to B.

4. Extend C back to B by projecting the face found in the previous step along the extension axis from step 1 for the distance *d*, creating extended $C^{extended}$.

5. Proximate volume
D = $C^{extended}$ – A – B

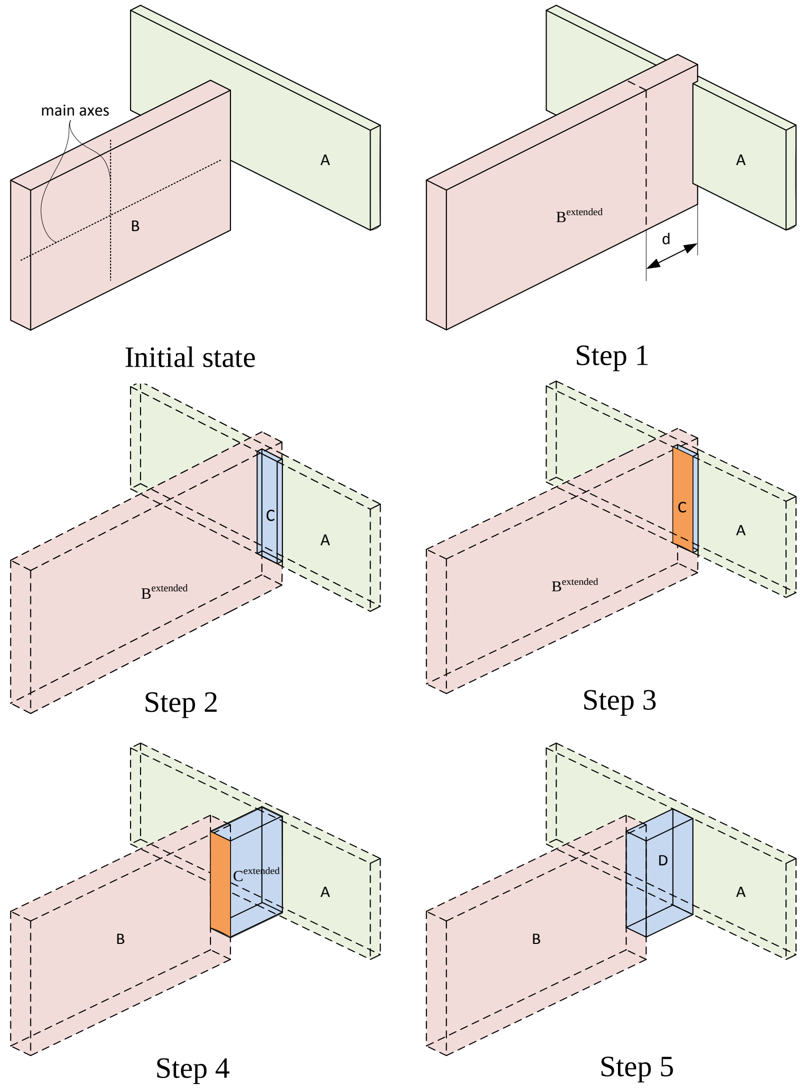

Figure 3: Algorithm for deriving the proximate volume between two spatial objects. The algorithm is run on each of the spatial objects.

APPENDIX 1

PCI typical components, shapes and span-to-depths ratios (PCI n.d.).

Component	Shape	Size		
		Depth	Width	Span-to-depth ratio
Beams	Rectangular, Inverted Tee, L	16 to 40 in.	12 to 20 in.	10 to 20
Columns (multilevel)	Square or rectangular	from 12 by 12 in. To 24 by 48 in.		
Double Tees		8, 10, 12, and 15 ft.	24, 26, 28, 30, 32, and 34 ft.	25 to 35 / Roofs 35 to 40
Hollow-core slabs		2, 4, 8, 10, and 12 in.	6, 8, 10, 12, 15, and 16 in.	30 to 40 / Roofs 40 to 50
Insulated walls sandwich panels		8 to 50 ft.	4 to 15 ft.	Thickness : 5 to 12 in.
Shear walls		8 to 16 in.	15 to 30 ft.	Thickness : 8 to 16 in.
Solid slabs		8 to 30 ft.	4 to 12 ft.	Thickness : 4 to 12 in.
Spandrels		25 to 60 ft.	5 to 8 ft.	Thickness : 4 to 12 in.
Wall panels		10 to 50 ft.	4 to 15 ft.	Thickness : 4 to 12 in.

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