Modeling Spatial Compositions with Network-based Spaced Layouts

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ABSTRACT

A significant challenge in building information modeling (BIM) concerns support for modeling multiple views of buildings to meet diverse data needs of architectural, structural, or building services domains. The focus in this paper is on extending an existing schema for network-based space layouts with spatial composition modeling capabilities. The schema has been introduced in previous work to support modeling of multiple space views. Network-based space layouts are generated from space data that are created in BIM authoring systems. Selected, view-specific spatial relations between objects in a layout are modeled as a spatial relation network. An architectural designer may use graph algorithms to find the shortest path in the spatial relation network of a pedestrian circulation layout between a workplace and a building exit. Likewise, a lighting control system designer may query a spatial relation network of a lighting layout to determine luminaires that are near a workplace. Multi-view space models may be composed of layouts with view-specific spatial relation networks. However, spatial compositions are currently not modeled explicitly. The schema is therefore extended with topological spatial relations, which include containment, overlap, equality, touch, and disjoint relations. With these relations, it is feasible to relate objects in different layouts. They are derived from object geometries with clash classification functions that are provided by a commercial solid modeling engine. Examples from pedestrian circulation and lighting domains illustrate rich spatial composition of network-based space layouts and its benefits for building design.

INTRODUCTION

A significant challenge in building information modeling (BIM) concerns support for modeling multiple views of buildings to meet diverse data needs of

architectural, structural, and building services domains (see, for example, van Nederveen and Tolman 1992; Rosenman and Gero 1996). Hierarchical spatial composition is a widely used method to structure BIM data. For example, a building may be divided into sections, floors, zones, and rooms to facilitate locating spaces and other objects, e.g. 'The Help Desk is in the Study Area on the First Floor of the North Wing of the Library Building'. The focus in this paper is on extending an existing schema for network-based space layouts (Suter 2013) with spatial composition capabilities. A network-based space layout explicitly models spatial relations between whole spaces, subspaces (partial spaces) and space elements (such as windows, furnishing elements, or technical equipment elements) as a spatial relation network (Suter 2013). Building designers may analyze such a network with graph algorithms. For example, an architectural designer may determine the shortest path between a workplace and a building exit in a spatial relation network of a pedestrian circulation layout. Likewise, a lighting control system designer may query a spatial relation network of a lighting layout to determine luminaires that are near a workplace.

Multi-view space models may be composed of layouts with view-specific spatial relation networks. Layouts are generated from space data created by building designers in BIM authoring systems (Suter 2013). Coverage of view-specific spatial relations between objects is limited in typical space data. An example is the proximity relation between windows and luminaires, which is relevant for lighting control. Operations on network-based space layouts have been defined to generate and query multi-view space models (Suter 2011; Suter et al. 2012). An example is a selection operation which selects objects from a layout based on user-defined filters.

Extending spatial relation networks with additional spatial relations would make modeling and querying of rich spatial compositions of layouts feasible. In addition to the containment relation, which is relevant for hierarchical spatial composition, modeling of overlap, equality, and touch relations is desirable. Vertical circulation spaces, such as elevators and stair cases, often span multiple floors and hence these spaces may overlap. As a multi-view space model may use space data from multiple sources, multiple views of an object (e.g. a space or a door) with equal shape but different IDs are feasible. Finally, consider an office space that is contained in a thermal zone. Spaces on the perimeter of such a zone may require higher supply air rates than non-perimeter spaces to compensate for increased heat loss to adjacent zones or the exterior. If the office is on the perimeter of its thermal zone, then its volume would touch volumes of adjacent thermal zones or the exterior.

RELATED WORK

Spatial composition modeling is supported in existing space schemas (Björk 1992; Eastman and Siabiris 1995; Ekholm and Fridqvist 2000; BuildingSmart 2010). For example, Eastman and Siabiris (1995) use a generic object composition method to recursively decompose buildings into constituent spaces. Zamanian and Fenves (1992) introduce spatial composition operations to derive domain-specific spatial views of buildings.

The Industry Foundation Classes (IFC) provide several methods to model spatial compositions. Buildings, floors, and spaces are examples of *IfcSpatialStructureElement*s (BuildingSmart 2010). Each parent node in an *IfcSpatialStructureElement* hierarchy aggregates a set of child nodes using *IfcRelAggregates*. Building elements may be attached to a hierarchy using the *IfcRelContainedInSpatialStructure* relation. The number of aggregation hierarchy levels is project-specific. Alternatively, *IfcSpatialZone* structures may be defined that do not need to be entirely hierarchical, that is, *IfcSpatialZone*s may overlap. However, overlap relations are not modeled explicitly. This method is more flexible and motivated by modeling needs of building services. *IfcZone*s are groupings of *IfcSpace*s or other *IfcZone*s. An *IfcZone* may be associated with an *IfcSpatialStructureElement* but does not have a shape. *IfcSpatialStructureElement* and *IfcZone* classes are included in the IFC Coordination View, which is a partial IFC schema for architectural, mechanical, and structural design coordination (BuildingSmart 2013).

In order to address limitations in existing BIMs regarding rich spatial relations between objects, Borrmann and Rank (2009) propose a spatial query language that derives implicit topological spatial relations between given object pairs. A point-set topology representation scheme is used to model bodies, surfaces, lines, and points in 3D space. Relations are derived by evaluating the 9-intersection model (Egenhofer and Franzosa 1991). Bhatt et al. (2012) use description logic and qualitative and quantitative spatial logics to develop an ontology for the architectural design domain. Spaces are modeled as regions in this ontology. Topological spatial relations between spaces are defined based on Region Connection Calculus (Randell et al. 1992).

EXTENSION OF THE SPACE LAYOUT SCHEMA

A UML diagram of the space layout schema extended for spatial composition modeling is shown in 0. Existing spatial relations, which are shaded in the figure, include *is adjacent to* relations between, respectively, whole spaces (*A_WS*) and

subspaces (*A_SS*), and the *is near* (*N_SE*) relation between space elements, that is, between walls, windows, furnishing or technical equipment elements. These relations are specific to related objects. There are additional object-specific relations in a layout's spatial relation network which are not included in the figure to minimize visual clutter.

Topological spatial relations (*SR_LE*) are added to the schema. They are modeled as optional spatial relations between layout elements and include *contains (C_LE)*, *overlaps (O_LE)*, *touches (T_LE)*, *equals (E_LE)*, and *disjoint (D_LE)* relations. This ensures flexibility in modeling spatial compositions. For example, the

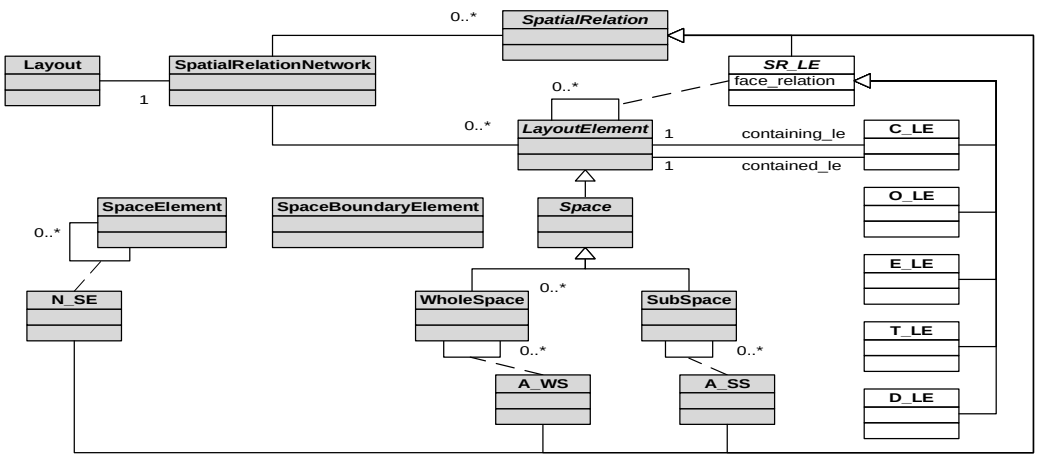
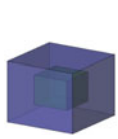
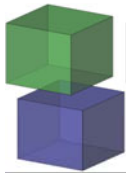
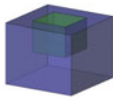
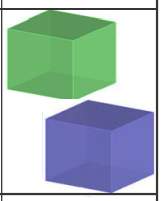


Figure 1. Layout schema extended with topological spatial relation (*SR_LE*) classes: *C*: *contains*, *O*: *overlaps*, *E*: *equals*, *T*: *touches*, *D*: *is disjoint from*. Existing *SpatialRelation* classes (examples): *A*: *is adjacent to*, *N*: *is near*.

Table 1. Definition of topological spatial relations based on *BODY* clash classification in the Acis solid modeler (Spatial 2011b).

	BODY **clash classification**					
	contains	abuts	contains abuts	coincident	interlock	none
Examples						
E_{LE}				x		
C_{LE}	x		x			
O_{LE}					x	
T_{LE}		x				
D_{LE}						x

containment relation between whole spaces and subspaces in a layout may be modeled as well as the containment relation between whole spaces in different layouts.

Relations are derived from layout element volumes. These are modeled with objects of type *BODY*, which is a solid Brep data type in the Acis solid modeler (Spatial 2011a). Relations are mutually exclusive and exhaustive. That is, exactly one of the modeled spatial relations applies to any given *BODY* pair. Relations are defined in Table 1 in terms of *BODY* clash classifications in the Acis modeler (Spatial 2011b). The modeler's clash classification functions cover more granular base relations. Thus, for example, a body *A contains* another body *B* if clash classification returns either *contains = true* or *contains abuts = true*. In the latter case, there is at least one face in *B* that touches a face in *A*. A *face_relation* attribute in the *SR_LE* class provides additional details regarding spatial relations among selected face pairs. In case of the *contains* relation, possible values for *face_relation* are either *none* or *coincident_inside*. In the latter case, there is at least one pair of faces in bodies *A* and *B* with coincident regions and face normals pointing in the same direction (Spatial 2011b). Similarly, face clash classification is useful to distinguish variations of the *touches* relation, including vertex-vertex, edge-edge, and face-face touch cases.

EXAMPLES

Two examples demonstrate the spatial composition of network-based space layouts based on topological spatial relations in the extended layout schema. In both examples, relations between whole spaces are modeled explicitly. The first example features a set of space layouts that model part of a building's pedestrian circulation spaces (Figure 1). Layouts include *Building*, *Floor*, *Vertical space*, and *Room* layouts. Rooms are contained in floors, which in turn are contained in a building. Alternatively, rooms are composed into vertical spaces. The stair case separates a North wing from a South wing. All these spaces are contained in the building. Spaces in floor and vertical circulation layouts overlap. The spatial relation network may be queried to retrieve symbolic location data in the form of paths that users of a building directory could relate to intuitively. For example, the network may be traversed along paths (*'Library'*, *'Ground Floor'*, *'North Wing'*, *'Main Building'*) or (*'Library'*, *'North Wing'*, *'Ground Floor'*, *'Main Building'*) to derive the symbolic location of the library. The *overlaps* edge relating whole spaces in floor and vertical space layouts is traversed in both paths, thereby enriching retrieved location data.

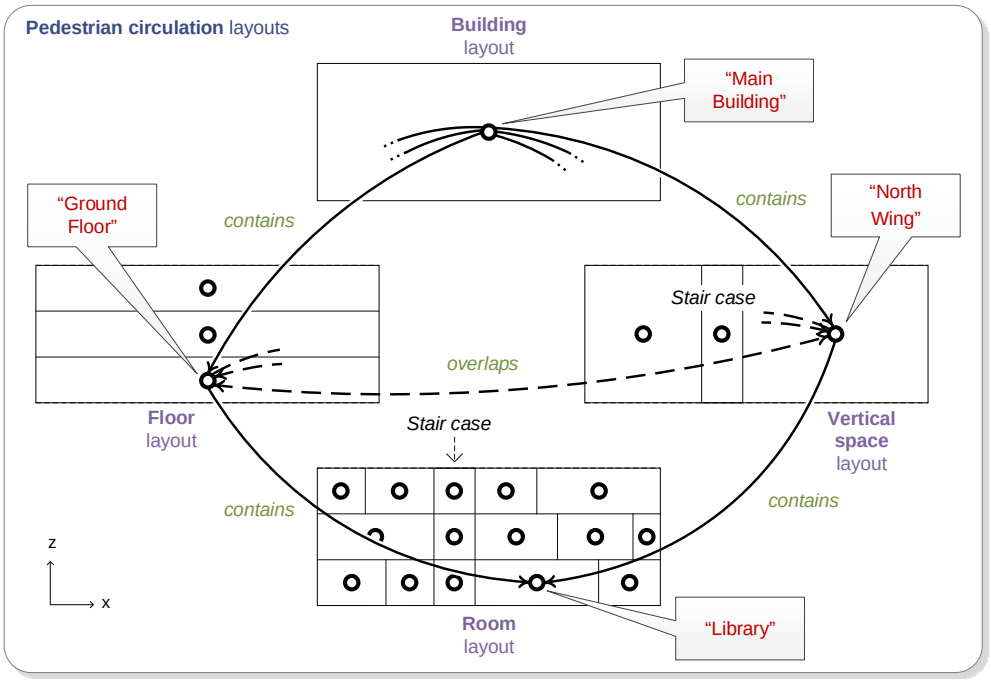


Figure 1. Spatial composition of pedestrian circulation layouts (elevation view). Sample spatial relation edges are shown only.

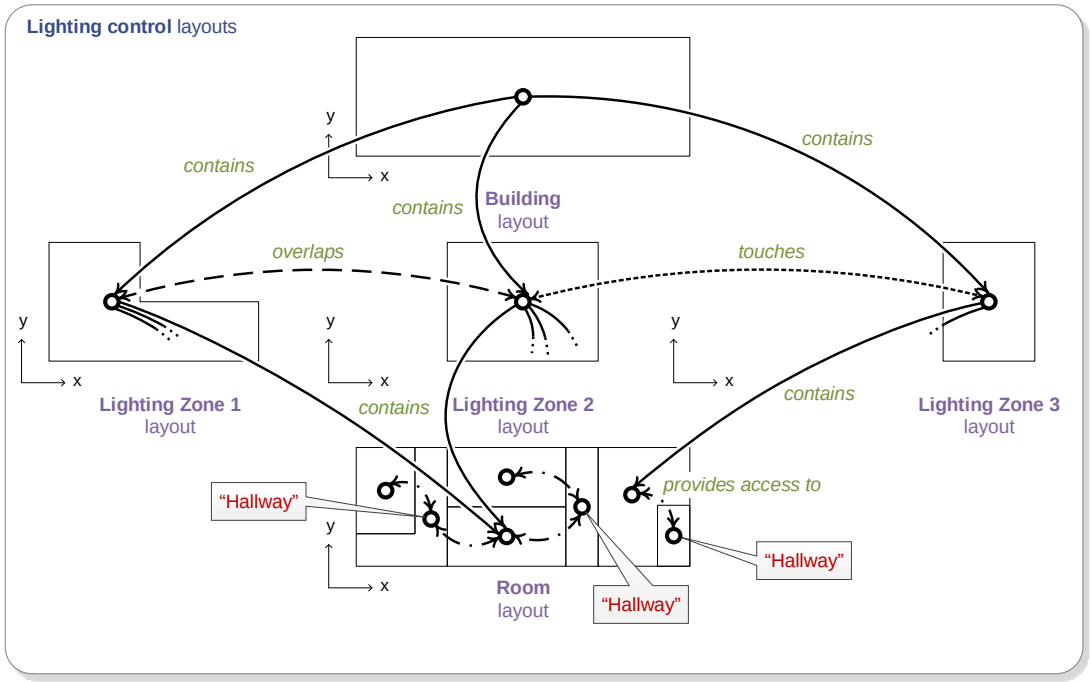


Figure 2. Spatial composition of lighting control layouts (plan view). Sample spatial relation edges are shown only.

The second example features a set of space layouts that model a part of another building's lighting control spaces (Table 1). Layouts include *Building*, *Lighting zone*, and *Room* layouts. Each hallway in the *Room* layout is composed into a lighting zone together with the rooms that it provides access to. This results in three lighting zones, of which one pair overlaps and another pair touches. Overlapping zones are due to a room that is accessible from two hallways. Lighting zones are modeled as separate layouts as overlapping whole spaces may not be modeled in the same layout. The lighting zones are further composed into the *Building* layout.

The resulting spatial relation network may be used to assign lighting controllers to lighting zones. For example, at night a controller may illuminate a hallway when at least one room that is accessed from the hallway is occupied. As whole spaces in *Lighting Zone 1* and *Lighting Zone 2* layouts overlap, controllers for these zones may need to coordinate control actions with each other.

CONCLUSION

Network-based space layouts are fine-grained space models that are generated from space data created in BIM authoring systems. In this paper, an existing schema for network-based space layouts with topological spatial relations has been extended to support spatial composition modeling. In addition to implementing the derivation of these spatial relations using solid Brep data structures and clash classification functions in the Acis solid modeler, future work should address the need for spatial composition operations. Spatial composition modeling is a repetitive and error-prone task if done manually, and visual inspection of three-dimensional models is challenging. Spatial composition operations would complement existing layout aggregation and decomposition operations (Suter 2011).

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