A BIM-Oriented Model for Supporting Indoor Navigation Requirements

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Abstract

Existing indoor navigation approaches such as navigation based on 2D geometries and pre-defined routing remain insufficient for many applications such as emergency response, delivery, utility maintenance, facility management and so on. The insufficiencies caused by existing navigation approaches can be overcome by using the advanced geometric and semantic information included in intelligent building models.. In this paper, we present a novel Building Information Model (BIM) Oriented a model in order to support indoor navigation and orientation. This paper explains the BIM Oriented Modeling methodology used for the definition of a new indoor information model (BO-IDM) and describes the transfer of information from a standard BIM (IFC) into the BO-IDM. The results of the research indicate that the BO-IDM carries the potential of facilitating emergency response operations by, i.) overcoming the limitations of geospatial and city models regarding representation of semantic information required for better navigation and orientation and ii.) eliminating the non-geo-referenced structure and complex geometries of BIMs.

Research Highlights

- A novel (BIM Oriented) approach to Indoor Data Model Development is introduced.
- A new indoor model (BO-IDM), with the focus of facilitating indoor navigation and orientation is developed, implemented in geospatial environment and populated as a result of information transformation from a BIM.
- The impact of different geometric representations (in geo-referenced building models) to the accuracy in transformation of geometries is investigated by using the developed model as the test case.

Keywords: BIM, Indoor Navigation, Data Model, 3D GIS, Building

1. Introduction

As city models used in practice focus on representing the outdoor environment and building facades, the information provision by them related to indoors still remains limited. Therefore, many actors of the indoor navigation process use their own information sources, such as emergency responders who maintain their own 2D maps (called ‘access maps’) to determine the location of entrances in public buildings (Diehl et al., 2006, Scholten et al., 2008, Snoeren et al., 2007 and van Oosterom and Zlatanova, 2008). However, current studies on user requirements points towards an increased interest in 3D indoor information for navigation (Lee, 2009, Lee and Zlatanova, 2008 and Zlatanova, 2008). Thill, Dao, and Zhou (2011) states that the ability to understand complex spatial and functional relationship in the contemporary 3D city is enhanced by a 3D representation of the indoor and outdoor infrastructure on which people plan and realize their travel activities. In recent years, research has been reported on the development of 3D models that can represent floor and apartment structure (including rooms, floors, doors and windows) and the use of them in analysis related to disasters, evacuation and navigation (i.e. Kwan & Lee, 2005; CityGML (OGC, 2008), Isikdag et al., 2008, Lee and Zlatanova, 2008, Lee, 2009, Kemec et al., 2009 and Kim and Jun, 2009). However, the major barrier preventing the use of these models in real life has been the lack of models providing ‘appropriate and applicable’ representations of building geometry and detailed semantics of indoors. The models developed are either too complex to query, not geo-referenced, defined with complex geometric representations (i.e. CSG) or do not provide sufficient level of semantic information for supporting indoor navigation.

Recent research denotes Building Information Models (BIMs) and CityGML as valuable information sources for facilitating indoor navigation. A BIM is a digital representation of all the physical and functional characteristics of a building through its entire life cycle (Isıkdag et al., 2007 and NBIMS, 2006). The 3D City Modeling Standard CityGML and its Level of Detail (LOD) 4 offers possibilities to represent interiors of buildings with their geometry, semantics, topology and appearance (OGC, 2008). Research has been already reported on using this model to derive information appropriate for navigation (Becker, Nagel, & Kolbe, 2009). These models have been considered in the development of the novel model presented in this paper. This paper presents a new indoor modeling methodology and a novel model BO-IDM, developed with the focus of facilitating indoor navigation and orientation. The model utilizes ISO 19107 compliant data types and is populated as a result of information transformation from an IFC BIM. The paper is organized as follows. Next section establishes conceptual requirements for indoor navigation. Section 3 elaborates on the information representation in building models, and their role of being information sources for indoor navigation. Section 4 presents the details of the new model (BO-IDM) that focuses on supporting indoor navigation requirements. Section 5 illustrates the applicability of the new model using a specific platform (i.e. ArcGIS) and discusses the results of the interoperability validation exercise completed using this novel model. Section 6 concludes by outlining the advantages of using the model in support of indoor navigation and overviews the future developments..

2. Conceptual Requirements for Indoor Navigation

Semantically rich 3D models can provide critical information for navigation that cannot be found in traditional 2D representations. Many authors have already investigated information models that can be of interest for indoor navigation (i.e. Brown et al., 2012, Diehl et al., 2006, Hijazi et al., 2011, Isikdag, 2006, Isikdag et al., 2008, Yuan and Zizhang, 2008 and Zlatanova, 2008). Based on these investigations, the 'Çonceptual Requirements for a Building Model for Supporting and Facilitating Intelligent 3D Indoor Navigation' appeared as:Semantic information, i.e. a clear definition (and naming) of building storeyse, elements, spaces, as their usage would support better orientation and guidance.

1. Semantic information, i.e. a clear definition (and naming) of building storeys, elements, spaces, as their usage would support better orientation and guidance.
2. Properties of each building element (e.g. material of the walls, opening directions of the doors, doors used as exits) to support routing and better orientation/guidance during navigation.
3. Functional states of the building elements and moveable objects (e.g. door can be 'open' or 'closed', a furniture can be acting as an obstacle) and temporal changes in the building (such as areas that can be inaccessible for a time period) to reflect the temporal states for facilitating the real time navigation guidance.
4. Information on structural elements for the 3rd dimension (including vertical elements such as columns, walls, stairs) to support navigation to targets hidden in vertical dimension (such as pipes and cables) which are not present on a 2D map.
5. Spatial Relationships between the elements (e.g. a wall can be a container of openings, a column can be connected to a wall, two floors can be connected with a stairs, etc.) to facilitate the derivation of the navigation network.

Building elements and spaces defined with 3D interoperable geometric representations, such as defined in ISO 19107 (OGC, 2001) to facilitate the seamless exchange/sharing of geometric information between various applications and indoor and indoor/outdoor navigation.
Semantic information, property information, spatial relationships, geometric information can be acquired from building representations in BIMs or City Models. The model presented in this paper acquires this information from BIMs, the following section elaborates on this decision.

3. Information models for indoor navigation

Indoor navigation requires the use of a number of interrelated building representations. Meijers et al., 2005 and Becker et al., 2009 based on Lee, 2004 and Lee and Zlatanova, 2008 propose that primal and dual models of buildings can be constructed for various conceptual/physical spaces. Primal models include a geometric representation in 3D Euclidean Space and a topology representation for expressing the relationships between building elements. Dual(s) of these models are a network (metric graph) for representing the physical connectivity and a graph (logical graph) for denoting abstract connectivity in a building.

In addition to the mentioned geometric and topologic representations, a semantic representation completes the three pillars of information representation for models that are supporting indoor navigation. In the current work, a distinction is made between Semantic, Euclidian and Topological information spaces, and Primal and Dual Model Layers (Fig. 1). The Semantic, Euclidian and Topological representations are used in building models and building representations in city level, as pairs or triples of these representations are found in tightly coupled form in BIMs and 3D City Models. In other words, the models in the primal layer, i.e. CAD, BIMs, CityGML (OGC, 2008), BISDM (BISDM, 2009) may contain geometric representation only, both semantic and geometric representation, or semantic, geometric and topologic representations. The representations in the primal layer are mainly utilized for information provision, retrieval and visualization purposes. The geometric networks and graphs in the dual layer are usually derived from the primal representations (based on Poincare Duality or using techniques such as Skeletonization) and used to compute the required (i.e. shortest, fastest) navigation path. For example, Thill et al. (2011) recently demonstrated path finding and facility location planning cases using a network model (3DCityNet) which is developed based on a (primal) 3D geometric representation. In addition to these, the semantic dual (ontology model) can be used for reasoning about the building.

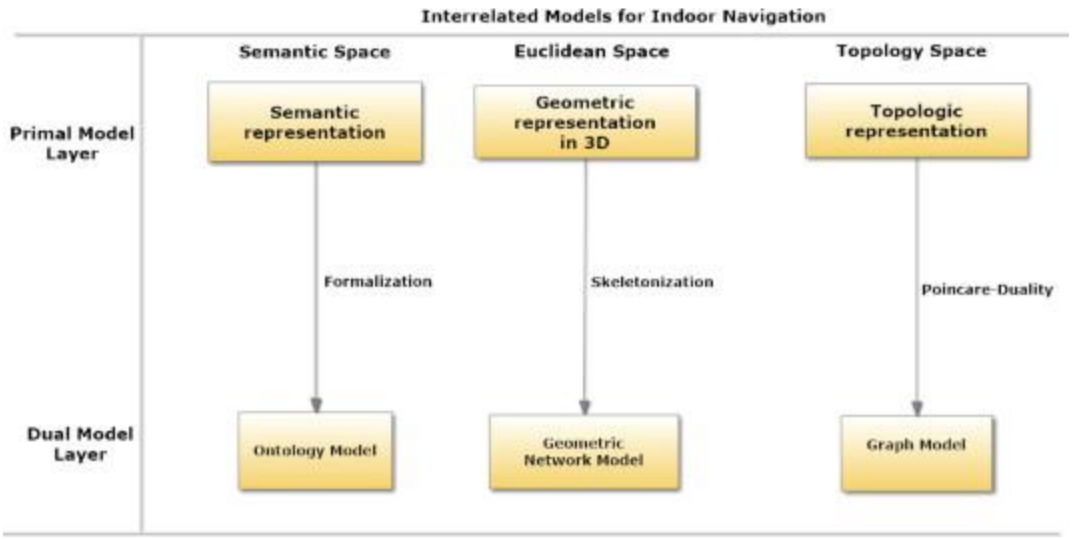

Figure 1. Interrelated Models required for Indoor Navigation

A range of different design and real-world representations in the primal layer can be used to acquire geometric and semantic building information. A BIM can be considered as a design phase representation, while building representations in digital city models (i.e. CityGML) can be classified within the real-world representations. Various comparative studies regarding these design and real-world representations, starting by comparing early CAD and GIS models, have been completed through the years (Cowen, 1988, Kolbe and Plümer, 2004, Logan and Bryant, 1987, Sun et al., 2002 and van Oosterom et al., 2006). Fundamental similarities and differences related to indoor navigation aspects are provided in Table 1.

Table-1: Fundamental Similarities/Differences between Design Phase/Real World Models

Design Phase Representations	Real-World Representations
Similarities	
Object Oriented Paradigm is used in modeling.	
Semantic information regarding building elements exists and is represented in object attributes.	
Spatial hierarchy between building elements is preserved.	
Indoor-outdoor navigation related differences	
Generally one building is represented in a single model.	Multiple buildings (and other real world features) are represented in a single model.
Models are defined in a local coordinate system.	Models are defined in an absolute (geodetic) coordinate system
Differences related to model structure	
Extended Geometrical Representations (BRep, CSG, Sweeping, CSG + Sweeping) exist. Brep is usually not preferred.	Boundary Representation (Brep) is preferred. Representation of objects as Simple Features is possible.
The objects of the model are defined focusing on the construction/maintenance of the building.	The objects of the model are defined focusing on the occupancy and use of the building.

BIMs contain advanced geometric and semantic representation of the building elements and they are considered as the most valuable source for representing and managing building information through the lifecycle of a building (Eastman, Teicholz, Sacks, & Liston, 2008). As indicated in Nagel, Stadler, and Kolbe (2009), BIMs follow a generative modeling approach and focus on the built environment. Therefore, BIMs are typically composed of volumetric and parametric primitives. BIMs such as IFC (ISO PAS 16739, 2005) also contain advanced semantics. Movable/immovable building elements and spaces are defined with detailed semantic and geometric decompositions and they have many attributes that cannot be found in any other models (such as City GML) or other building representations. Thus (i) the advanced geometric and semantic representation in BIMs and (ii) the instant availability of 3D information has been the motivation for transforming the information in BIMs into the CityGML representations (Kolbe, 2009). Additionally, each building element in BIM has detailed property sets which contain detailed information about that element. For example in the IFC model, DoorWindowGlazingType property set of Window class contains a rich set of attributes to denote Glass Layers, Glass Thickness, Glass Color, Thermal Transmittance, and if the glazing IsTempered, IsLaminated and so on. Furthermore BIMs represent a large set of utility elements embedded or located inside the building (in 3D) with detailed semantics (i.e. detailed information on properties and functions of the elements), which can also be within the focus of indoor navigation for facility management or building maintenance operations (Hijazi et al., 2011). In contrast, CityGML does not provide so many details. Similar level of detail in terms of semantic representation can only be achieved through two CityGML mechanisms, i.e. Application Domain Extensions (ADEs) or Generic Objects. For example, BIM ADE provides classes to represent the information acquired from BIMs (van Berlo & de Laat, 2011). Detailed 3D geometric and semantic representations of large set of objects for utility elements including Electrical Junction Box, Humidifier, Cable Carrier is strongly-typed in BIMs. In contrast, the CityGML model provides a generic class (IntBuildingInstallation) to define the semantics of several immovable indoor and utility elements. CityGML also provides a Utility

Network ADE (Becker, Nagel, & Kolbe T. H., 2011) but with less object types (and decomposition compared to BIMs). Thus, most detailed semantic representation of building elements can be found in BIMs. Unlike CityGML, BIMs neither make use of generic objects/attributes, nor model extensions are required to represent advanced semantics. Furthermore, as the BIMs are designed, developed/maintained with the collaborative effort of designers, constructors and the facility owners/managers, the information regarding building elements is always accurate and up-to-date. When BIMs are used as a source model, information for supporting indoor navigation can be obtained instantly from them by querying the readily available information. In contrast, CityGML needs to be extended with extra objects or detailed semantic information, which may become complex effort if different indoor navigation aspects are considered. Based on this analysis, BIMs appear as the superior resources of semantic and geometric information and therefore BIMs was used as basis for developing a new model that would support indoor navigation.

4. The BIM Oriented Indoor Data Model (BO-IDM)

As the BIMs might be very complex, a new BIM Oriented information model was envisaged with a less complex structure. Additionally, the model needs to compliant with ISO 19107 standard to allow for integrated indoor/outdoor navigation. For example, Figure 2 depicts the result of a BIM based egress route analysis. The blue line(s) illustrated over the slabs point out the shortest path(s) from each room to the fire exit. This result can point out a certain door as an exit point of the route. In fact, the fire in focus might have been started in a risky neighbourhood near that indicated exit. In this situation, the endpoint of the egress route would be wrong as it is generated without taking the fire risk of the outdoor environment into account. Thus, the use of isolated BIMs and stand-alone BIM based analysis tools would not the produce required functionality for supporting indoor navigation.

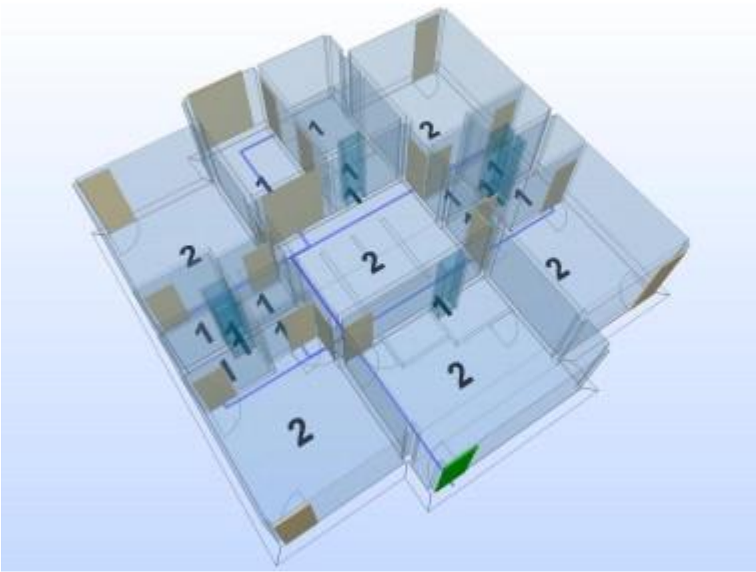

Figure 2 Egress paths calculated by Solibri Model Checker by using a BIM

4.1. Model Development

The BIM Oriented Modeling approach has its roots in Isikdag (2006), a research conducted with the aim of investigating the transfer of BIMs into the geospatial environment. In order to fulfill the 6 conceptual requirements mentioned earlier, a BIM Oriented Model should address seven technical requirements, four of which concentrate on preserving BIM properties and the remaining three focus on adaptation of BIM to the geoinformation domain. These BIM Oriented Modeling technical requirements are as follows:

1. Preserve the object semantics of the BIM. The differences in meaning of the objects in source and target models can lead to ambiguities in automatic transfer of information from a source to the target model, which should be prevented. For example, an IfcSpace class in an IFC BIM can represent a closed volume and the target model can have a Room class which represents a room with 2D geometry. In this case, it would be extremely difficult to find which closed space in the source building model matches to which room of the target model when the semantics of the source model is different. To prevent this semantic preservation principle is introduced.
2. Eliminate BIM classes representing void elements (i.e. holes in the slabs, walls). BIMs have classes that represent the empty spaces (voids) inside the building elements. If there is a building element that fills that void (i.e. window, door, etc.) this can be represented instead of the 'void class'. It should be noted that, the geometry (of the hole) represented by the void class (in the source model) should be taken into account and be transformed to the target model. The only difference will be that the hole geometry in the target model would not be semantically referred/called as 'void'.
3. Preserve the spatial relationships in the object model of the BIM. The relationships preserved in the new model would make it possible to query the building elements as if the model is a BIM. For example, it would be easy to acquire which 3D wall contains which windows and so forth.
4. Eliminate the separate spatial relationship classes defined in BIM and implement these relationships in the schema of the target model (in form of object relations). This would make the target model more compact, and easy to discover and query.
5. Convert 3D BIM geometries into the target domain. This ensures that the building element geometries of the new model can be easily recognized and visualized by the applications in the new domain.
6. Implement only the attributes that are necessary for the target domain and ensure that the model will be less cumbersome.
7. Introduce a geographic/geodetic coordinate system. This would prevent the model becoming an isolated island of information in the geoinformation domain.

In the development of the new model, IFC was selected a source BIM standard, as it is the mainstream schema standard of Building Information Modeling (i.e. ISO PAS 16739, 2005). As mentioned in IFC2x3 Online Documentation (2009), the key building elements (of interest for indoor navigation) are Beams (IfcBeam), Columns (IfcColumn), Walls (IfcWall), Slabs (IfcSlab), and Stairs (IfcStair). In IFC, a building is composed of storeys, a storey can contain several different building elements (beams, slabs, walls, etc.). Some building elements (i.e. walls, slabs) may contain openings (i.e. voids/holes) and these voids/holes may contain other building elements (doors, windows) which are located in them. The spaces in the IFC model are contained within, a building, storey or another space, and the spaces are the containers of movable elements. The geometric representations of elements are mostly in CSG/Sweeping, and rarely in BRep (i.e. the representation type changes depending on the requirements and software used in generating the model). The spatial relations between the building elements are preserved within the models' spatial structure, in the form of spatial hierarchies, which are established with the help of (spatial) relationship classes. These spatial hierarchies are expressed by 'relationship classes and attributes'. Attributes such as, 'ProvidesBoundaries', 'ConnectedFrom', and 'ContainedInStructure' can point other objects and relationship classes, to represent the hierarchies.

4.2. Model's Schema and Classes

The newly developed model BO-IDM has a schema similar to IFC, but some classes are eliminated based on requirements presented in the previous section. The model keeps the buildings elements as defined in IFC, but uses ISO 19107 compliant the geometries.

BO-IDM represents the building with 18 classes (Fig. 3). The class details of the BO-IDM are as follows;

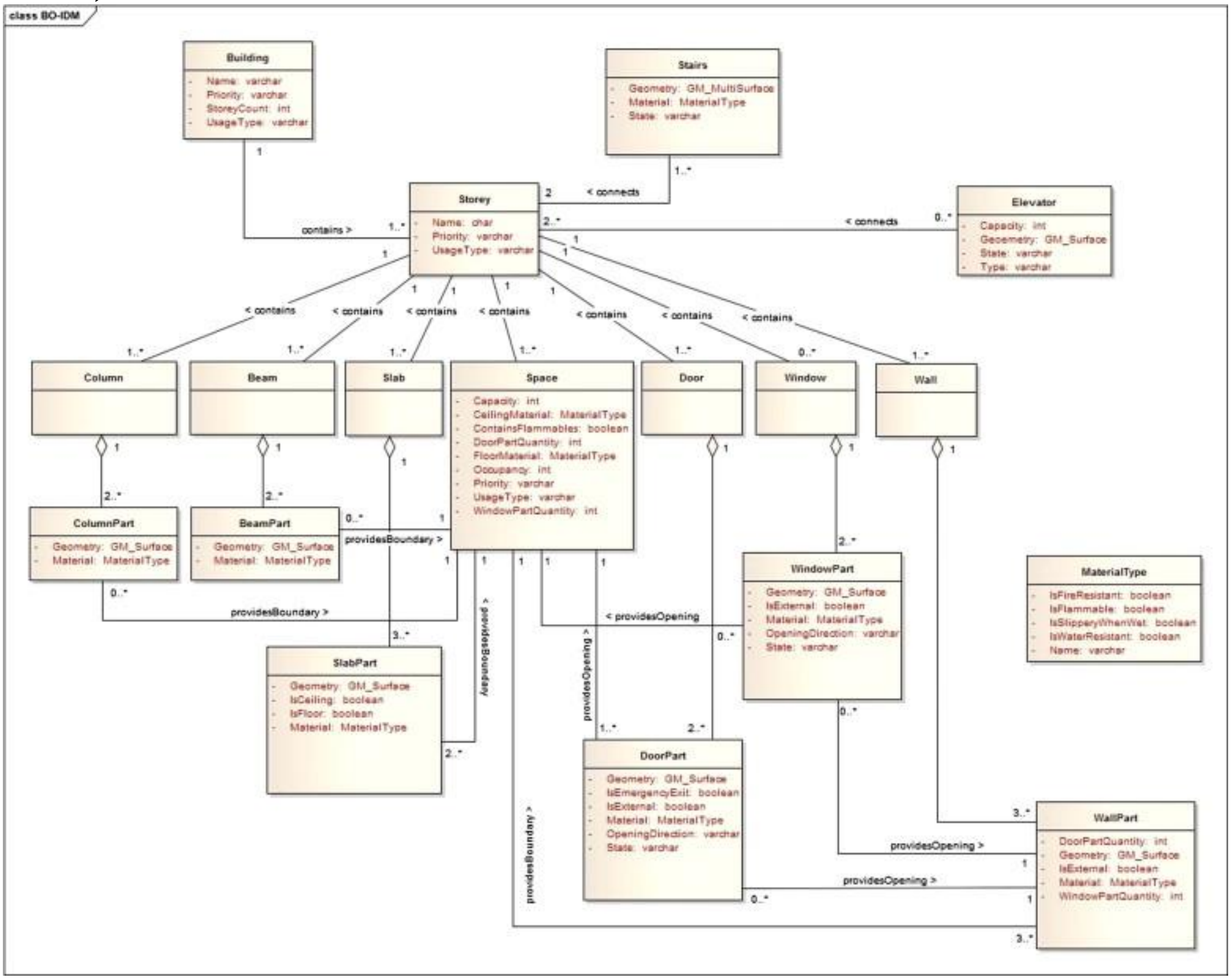

Figure 3. BO-IDM Object Model

4.2.1. Building

The class at the top of the spatial hierarchy in BO-IDM is *Building*. Each *Building* would have a Name in the BO-IDM. The Priority attribute indicates the level of priority in an emergency response operation or for a process in LBSs. The Building might be of high priority for emergency evacuation or for a delivery operation. The StoreyCount attribute provides the number of floors in that building, while the Usage Type attribute represents the usage type of a building such as being a School, Hospital, Concert Hall, and so on. A *Building* can have many *Storey(s)*.

4.2.2. Storey

The second entity in the hierarchy is the *Storey*, which contains Column*(s)*, *Beam(s)*, *Space(s)*, *Wall(s)*, *Slab(s)*, *Door(s)*, *Stairs*, *Elevator(s) and Window(s)*. The Priority attribute indicates that the floor might be of high or low priority for navigation or emergency response. The *Storey* class has a UsageType attribute to represent the usage type of a floor, i.e. a floor can be used as a warehouse, storage area and so on. A *Storey* can be connected to another *Storey* by *Stairs* or *Elevator(s).*

4.2.3. Stairs

A *Stairs* object can be used to represent the connection of a floor to the ground floor or two floors to each other. Moreover the State of the *Stairs* can be Blocked, In Operation, etc.

4.2.4. Elevator

An *Elevator* can be used to connect many floors. More than one *Elevator* can be used to connect a floor to another. The *Elevator* class has Type attribute to provide a generic type for the elevator such as Passenger Lift, Safety Lift, Luggage Lift, and so on. The Capacity attribute defines the capacity of the elevator based on its type, for example it can be the maximum number of persons or luggage that the elevator can carry. The State attribute indicates that the elevator can be In Operation, Not Operating, etc.

4.3. Space

Spaces in the model are virtual (non-existing) elements used to represent the closed volumes. Space also refers to a room in the Storey. Although both in BO-IDM and IFC spaces refer to closed volumes, there is a difference between the space interpretation of IFC and BO-IDM. In IFC an IfcSpace is an area or volume that provide for certain functions within a building. An IfcSpace may span over several connected spaces, and can contain other spaces. In BO-IDM, unlike IFC, the Space does not span over or contain other spaces. In BO-IDM, a Space is a closed volume that is bounded by other building elements. The geometry of the Space can be derived from its boundary elements. This representation paradigm is very similar to the Room Class in CityGML. A Space is used for representing volumes used for living or work (i.e. room, corridor) and is therefore the possible navigable space (as in Becker et al., 2009). The UsageType and Priority attributes of *Space* represents the similar concepts as described in Building and Storey. The Capacity attribute refers to the maximum number of people that a *Space* can accommodate, while the Occupancy attribute refers to the number of people that are currently in that *Space*. The DoorPartQuantity and WindowPartQuantity attributes are used to provide information regarding the number of door and window parts (panels) that are connected to that *Space*. The FloorMaterial and CeilingMaterial of the *Space* can be represented with the *MaterialTypes* provided in the model. If a *Space* contains flammable materials this is indicated with the ContainsFlammables attribute.

4.4. Parts concept

The representation of the building elements other than *Space* is further broken down to *Parts* in the model (Figure 4). For example in BO-IDM a Wall or a Slab is still a 3D object (composed of parts), which can contain the cabling and pipes that are passing inside itself. Based on adjacency and connectivity relationships between *Parts*, *Spaces* and building elements (i.e. *Walls* and *Slabs*), utilities such as HVAC systems can be indicated in the navigation graphs. A single *Part* element may refer to a side or a face, multiple sides or faces of a building element or a single panel of a door and window. The implementation of the parts concept fulfills, (i) the 1st technical requirement as the semantics of BIM is preserved (e.g. a Wall is still a 3D object in BO-IDM), (ii) the 5th technical requirement as the geometric representations provided within parts concept is ISO 19107 compliant and (ii) the 7th technical requirement by implementing geographical coordinate system in model representation by using parts.

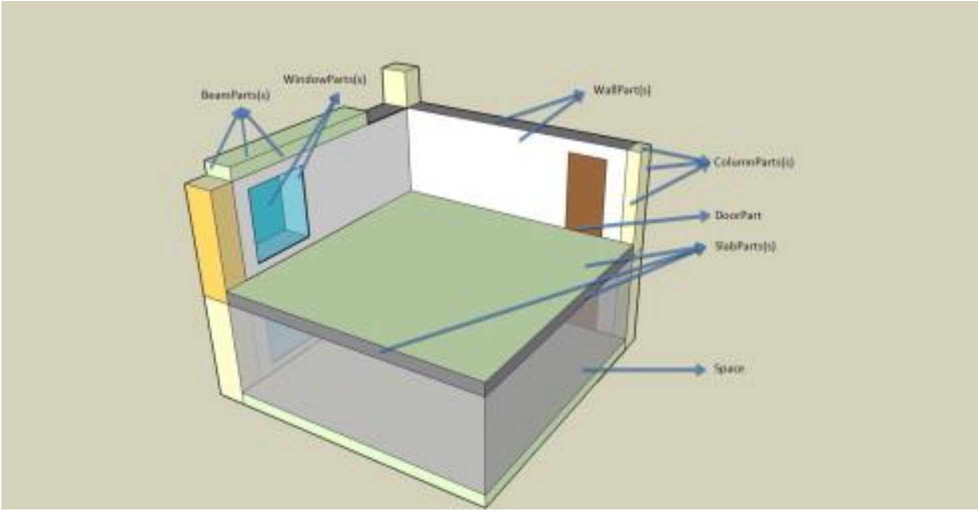

Figure 4: Context of parts representation.

In the IFC model, a wall is geometrically represented by a solid, i.e. in form of a 3D solid object that separates two spaces. In contrast, in CityGML a wall is represented with two different wall surfaces such as Interior Wall Surface/Wall Surface or Interior Wall Surface/Interior Wall Surface. Each of these wall surfaces forms boundary of one space. As a unique wall is actually represented by two distinct Wall Surface classes in City GML, the semantic representation of a solid wall (as found in the IFC model) is not present. In contrast, in BO-IDM, the wall will be represented as a collection of ‘parts’ which form the solid 3D wall object. This approach facilitates queries related to whole or a ‘part’ of a specific wall and provides links (adjacency and connectivity) between rooms.

4.4.1. Beam and column

Beams and Columns are concrete building elements, used to represent the load-bearing components of the structure. They are composed of their *Parts* objects. *BeamPart* and *ColumnPart* classes are important structural elements, because they may appear as obstacles in the passageways, corridors and even within the rooms. Existence of a column can narrow a corridor, or beams usually appear as obstacles at the roof floors, basements and sub-basements, as in these floors the height of the ceilings would be lower than usual. Each *Beam/Column Part* can have its own material. The model assumes that there will not be any utility components (to be navigated to) inside these elements.

4.4.2. Wall

Walls are concrete building elements used to represent the vertical subdivision between rooms, and rooms/outside. In the model they are composed of *WallParts*. In BO-IDM the assumption has been made that a wall would consist of at least 3 parts, one representing the front side, one representing the back side and the third would represent all other sides. In essence, the wall can also contain more than 3 parts, i.e. 3 is the minimum number of parts that it can contain. Each *WallPart* can have a different material which can be represented with one of the *MaterialType(s).* A part of the wall can contain a number of door or window panes/shutters (defined with *WindowPart* and *DoorPart* classes), the number of these panes or shutters is stored within the WindowPartQuantity and DoorPartQuantity attributes. The *WallPart* can be at the building façade or not, and this is distinguished by the IsExternal attribute. A *Space* class would require a minimum of 3 *WallPart* (s) to be associated with it, in order to represent a closed volume together with 2 *SlabPart* (s). The connectivity relationships defined in the BO-IDM such as this one (as associations to *Space*), can be populated based on information derived from IFC, as these connectivity's are represented in IFC model by using relationship classes such as *IfcRelSpaceBoundary.* Other relationships such as the one between a wall and a window can be established based on relationship attributes in IFC.

4.4.3. Slab

The *Slab* is a concrete horizontal building element, which indicates the floor subdivision. *SlabPart* class represents a part of a slab. Similar to a wall, a slab would also consist of at least 3 parts, one representing the up, another representing the down side and the third part can represent all other sides of the slab. In fact, the slab also can contain more than 3 parts. Each SlabPart can have a different material which is represented with one of the MaterialType*(s).* The part of the slab in the model might be representing a ceiling or a floor, and these are identified with IsFloor and IsCeiling attributes. A minimum of 2 *SlabPart* (s) need to be associated with the *Space* class to represent the floor and the ceiling of that *Space*.

4.4.4. Window

The *Window* class represents all the parts of a window (i.e. as the window casing/panes/shutters), where a window consists of at least 2 parts (i.e. representing a casing and a pane, a pane and a shutter, multiple glazings, etc.). The use of more than 2 parts is also possible. The OpeningDirection attribute would indicate the opening direction of the window pane/glazing/shutter (when applicable), such as left, right, bottom, top, sliding, left 45°. Each *WindowPart* can have a different material. The attributes to form the *WindowPart* objects can be derived from Pset_DoorWindowGlazingType property set of the IFC model, as this property set indicates several detailed semantic attributes such as, if a window has double or triple glazing, thickness of each layer, an indication of whether the glass includes a contained wire mesh to prevent break-in or not, and total solar heat transmittance that passes the glazing at normal incidence. Thus, for example if the window in the IFC model would have 3 glazing(s) the number of WindowParts in BO-IDM would be minimum 3 for that window. The materials of multiple glazings of the same window are considered as the same and are given within a common property set by the IFC model. This information can be assigned to different *WindowParts* in BO-IDM. The State attribute refers to the current state of the part or window panel, which might be open, closed, blocked, etc. The *WindowPart(s)* that are on the building façade are distinguished by IsExternal attribute.

4.4.5. Door

The *Door* class represents the parts of a single door (or each one of the double doors fixed/contained at the same location), where a door consists of at least 2 parts. Each of these 2 parts can represent a door panel/a casing, two panels, etc. 3 parts can be used to represent 2 panels and a casing. The Opening Direction, Material, State and IsExternal attributes have similar meanings as the *WindowPart*. A *DoorPart* can act as an emergency exit, and this is represented by IsEmergencyExit attribute.

4.4.6. MaterialType

The *MaterialType* class has attributes for perceiving whether the material is flammable, fire resistant, water resistant and becomes slippery when it is wet. These attributes would help in providing information especially to emergency responders mainly in a fire or a flood response situation.

BO-IDM provides more detailed semantic and geometric decomposition of the building compared to LOD 4 of City GML. For instance, a *Storey* class exists in BO-IDM, which cannot be found in CityGML LOD 4 or BIM ADE for City GML. In BO-IDM information related to the material of the objects (or object parts) would be preserved as strongly typed (i.e. with a defined Material Type), thus material related queries (i.e. which floor material is not appropriate for wheelchairs? – Brown et al., 2012) can also be responded for every building element without the need of generic attributes. BO-IDM provides a full 3D geometric and semantic representation of building stairs with a *Stairs* object, thus this eliminates the need for the use of enumerated StairType definitions (as found in BIM ADE for City GML).The elevators of the building are also represented with strongly-typed (object) definitions by BO-IDM. This helps in supporting vertical navigation through elevators, for example when elevators are not in operation the users can be directed to stairs. In summary, when compared with CityGML alternatives, the utilization/implementation of BO-IDM can bring distinctive advantages in support of indoor navigation. The benefits of BO-IDM has been realized by fulfilling the requirements specified in Section 4.1.

5. Model implementation

The model is tested with an emergency response scenario for the Greater Municipality of Istanbul. As emergency response operations are usually managed using a GIS within the Greater Municipality of Istanbul, the transfer of building information into a geoinformation model was the main requirement. The requirements gathered indicated that the BO-IDM conceptual model needs to be implemented for ESRI ptaform, i.e. using ArcGIS geometries and Geodatabase. Only the *Parts* classes of BO-IDM (*WallPart*, *SlabPart*, *BeamPart*, *ColumnPart*, *DoorPart*, *WindowPart*) and *MaterialType* are implemented to validate both geometry and semantic representations. As most of the other classes (with the exception of *Stairs*, *Elevator* and *Space*) only represent attributes and functional information, they are left out of the scope of the preliminary implementation exercise. GM_SurfacePatch and GM_Polygon data types are used to construct the GM_Surface(s) defined in the model. As mentioned in ISO 19107 the 'Segmentation' association relates a GM_Surface to a set of GM_SurfacePatch (es)/GM_Polygon (s) that shall be joined together to form a GM_Surface. In the ESRI Shapefile implementation, *ColumnPart*, *BeamPart*, *DoorPart*, *WindowPart* objects are represented with polygons which consist of a single ring. *WallPart* and *SlabPart* objects are represented with Polygons, which consist of multiple rings. The PolygonZ data type is used to populate the model geometries in the Shapefile implementation. On the other hand, in the ESRI Geodatabase implementation, all classes of the model are represented as the GM_SurfacePatch (composed of polygons). Multipatch data type is used in populating the objects in Geodatabase implementation. Table 2 provides a summary of the BO-IDM implementation, in terms of geometry and set of attributes used in the physical implementation, indicating the ISO 19107 equivalent of geometry types used in each different implementation.

Table 2. Summary of the BO-IDM Implementation

Class	Attributes	Data Types for Geometric Representation	
		ESRI Shapefile	ESRI Geodatabase
WallPart	Storey_ID Wall_ID Material	PolygonZ GM_Polygon (1..*: GM_Ring)	Multipatch 1..1: GM_SurfacePatch
SlabPart	Storey_ID		Multipatch

	Slab_ID	PolygonZ GM_Polygon (1..*: GM_Ring)	1..1: GM_SurfacePatch
BeamPart	Storey_ID Beam_ID	PolygonZ GM_Polygon (1..1: GM_Ring)	Multipatch 1..1: GM_SurfacePatch
DoorPart	Storey_ID WallPart_ID Door_ID OpeningDirection	PolygonZ GM_Polygon (1..1: GM_Ring)	Multipatch 1..1: GM_SurfacePatch
WindowPart	Storey_ID WallPart_ID Window_ID OpeningDirection	PolygonZ GM_Polygon (1..1: GM_Ring)	Multipatch 1..1: GM_SurfacePatch
ColumnPart	Storey_ID Column_ID	PolygonZ GM_Polygon (1..1: GM_Ring)	Multipatch 1..1: GM_SurfacePatch

As mentioned previously, in the IFC model the building elements are represented with CSG, Sweeping and rarely by BRep, thus the main effort in the model population (i.e. instance generation) process was on transforming CSG and Sweeping representations of IFC BIM into geometric representations in BO-IDM. The transformations included extrusion operations (when an objects' geometry is defined by Sweeping representation) and Clipping operations (with half spaces, when an objects' geometry is defined by a CSG representation). The critical geometrical operation in this case was the clipping, as acquiring the object coordinates as result of the extrusion of a plane was a straightforward task.

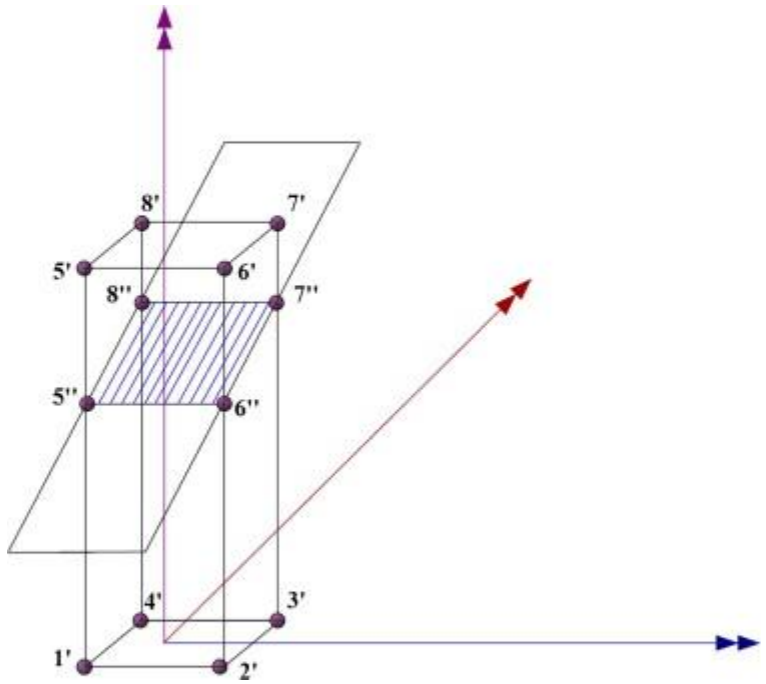

Figure 5: The Single Clipping Operation for a Column

The algorithm used in the clipping operation was based on set operations and constructing the geometry by using intersection of planes. A single clipping operation is illustrated in Figure 5, where the hatched polygon is derived out of the rectangular prism (bounding box) representation of the column. Once the BO-IDM geometries were constructed from the Sweeping and CSG representations of the IFC, they were then translated into the corresponding projected coordinate system used by BO-IDM. In the case of the current study, the coordinate system was UTM and height values were stored separately (as *Z* values). The information regarding the properties and functions of building elements such as the materials of the walls or opening directions of the windows were later transferred from the attributes in the IFC entities to the entities of BO-IDM. In the final stage, the transformed information was tested in terms of accuracy and reliability of geometric and semantics transferred from the IFC. The representations illustrated in Figure 6 are showing the BO-IDM visualization of two different buildings within a GIS software, which were transformed from IFC models.

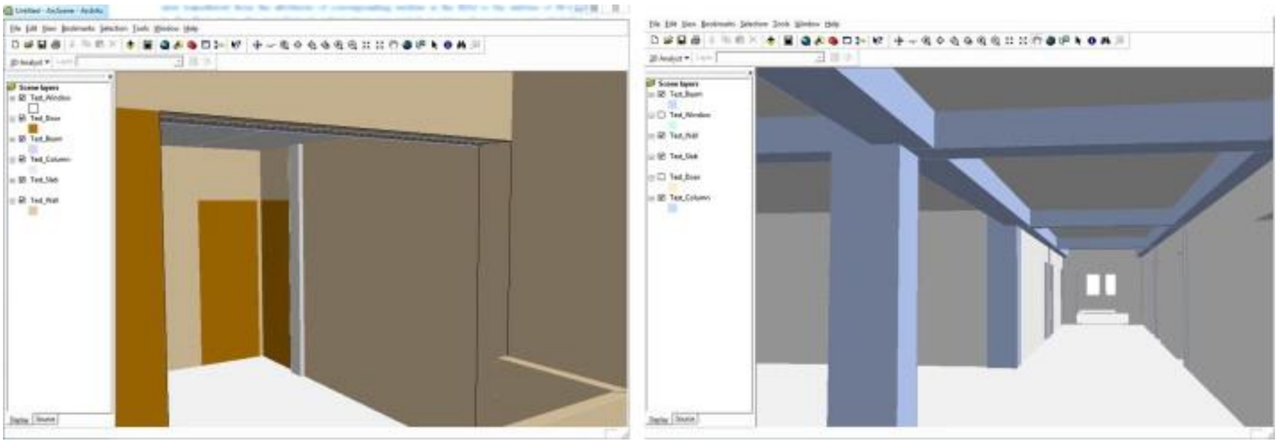

Figure 6: Visual representation of BO-IDM within a GIS environment.

As indicated in Table 2, in the ESRI Shapefile implementation each of the *ColumnPart*, *BeamPart*, *DoorPart*, *WindowPart*, *WallPart* and *SlabPart* classes was represented with a separate Shapefile, where each database table contains the set of attributes provided in Table 2. The physical implementation of the geometric representation (ISO 19107 GM_Polygon) was accomplished by using Single Ring (1..1: GM_Ring) and Multi Ring (1..*: GM_Ring) Polygon data types in ESRI Shapefiles. In the ESRI Geodatabase implementation, each of the *ColumnPart*, *BeamPart*, *DoorPart*, *WindowPart*, *WallPart* and *SlabPart* classes was represented within a Geodatabase Feature Class table. Each table in the Geodatabase contained the geometry and set of attributes provided in Table 2. The implementation of geometric representation was realized with the use of Multipatch (1..1:GM_SurfacePatch) data type in ESRI Geodatabase. Figure 7 presents a screenshot, showing a part of the ESRI Geodatabase table of the *WallPart* entity.

	shape	OBJECTID	MATERIAL	WALLID	STOREYID
	Long binary data	994	Masonry Block	67	3
	Long binary data	995	Masonry Block	68	3
	Long binary data	996	Masonry Block	68	3
	Long binary data	997	Masonry Block	68	3

Figure 7: ESRI Geodatabase table illustrating the attributes of *WallPart* classes.

The Multipatches were stored as Binary Large Objects (BLOBs) in the Geodatabase in a field named *'shape'*. The '*OBJECTID*' attribute is a surrogate key automatically generated by ESRI Geodatabase for each object stored in the database (i.e. *WallPart*). As assigned in the BO-IDM object model, the material of the Wall Part is stored within the '*MATERIAL*' attribute (which refers to one of the *MaterialType* (s) defined earlier), the unique id of each wall is stored in the '*WALLID*' attribute. As illustrated, some *WallPart* objects contain the same '*WALLID*' as they are representing the parts of the same wall (i.e. Wall #68). The Storey_ID's of the *WallPart*(s) are stored in the '*STOREYID*' attribute (i.e. all *WallParts* shown are residing in the 3rd storey of the building).

5.1. Example queries

The model allows a large number of space related and semantic queries in support of indoor navigation. Some examples of these queries that can be responded and their SQL counterparts are provided below (n and m are given id's of the elements, from stands for fragile material).

• To find a wall that separates two room spaces we can use the query below.
• Provide the distinct Wall ID of the Wall Parts that separates Space (n) and Space (m)?
• SELECT DISTINCT WALLID FROM WALL_PART WHERE SPACEID = n AND WALLID IN (SELECT WALLID FROM WALL_PART WHERE SPACEID = m).
• In order to learn which parts of the Wall (n) have flammable coverings we can use the query below.
• Provide the materials of the Wall Parts of a specific Wall?
• SELECT MATERIAL FROM WALL_PART WHERE WALL_ID = n.
• In order to explore which parts of Slab (n) are the floor and ceiling we can use the query below.
• Provide the values of IsCeiling or IsFloor fields of a specific Slab?
• SELECT ISCEILING, ISFLOOR FROM SLAB_PART WHERE SLAB_ID = n.
• To understand which parts of Slab (n) contain material that will become slippery when wet, we can make use of this query.
• Provide the material(s) of Slab Parts of the specified Slab?
• SELECT MATERIAL FROM SLAB_PART WHERE SLAB_ID = n.
• To identify the emergency exits located in rooms where the wall material is fire resistant we can use the query below.
• Provide the value(s) of IsEmergencyExit field of the DoorPart, of which its Space is connected to the walls that's material is fire resistant?
• SELECT ISEMERGENCYEXIT FROM DOOR_PART WHERE SPACE_ID=(SELECT SPACE_ID FROM WALL_PART WHERE MATERIAL = frm)
• In order to explore the number of windows for the rooms in which the occupancy is over 20 we can use the query below.
• Provide the value(s) of WindowPartQuantity field of Space entity, where the value of Occupancy field is greater than 20?
• SELECT WINDOWPARTQUANTITY FROM SPACE WHERE OCCUPANCY > 20

Table 3 summarizes the key points of the BO-IDM implementation in comparison with the conceptual requirements for supporting indoor navigation (i.e. mentioned in Section 2) and BIM Oriented Modeling principles.

Table-3: Model Requirements vs. BO-IDM definition

Requirements for a Building Model supporting Indoor Navigation	BIM Oriented Modeling Principle	BO-IDM Implementation	Fulfills the requirement
1. Semantic information, i.e. a clear definition (and naming) of building storeys, elements, spaces, their usage.	1,6	Preserves the object semantics of the BIM. Only attributes that are necessary for the new model domain were implemented.	√
2. Properties of building elements	6	Properties about material of walls, opening directions, etc. exist in the model.	√
3. Functional states of the building elements and moveable objects and	6	Preserves information about 'opening direction', and represents the state of the elements such as	√

temporal changes in the building		doors and windows.	
4. Information on structural elements for the 3rd dimension	5	BO-IDM represents the building elements with 3D geometries	√
5. Spatial Relationships between the building elements	2,3,4	BO-IDM preserves the spatial relationships between non-void building elements of the BIM, while keeping the geometry of voids and eliminating the unrequired classes in the BIM	√
6. 3D building elements and spaces defined with interoperable geometric representations	5,7	Uses geometric representations and coordinate system compatible with the new model domain.	√

The BO-IDM implementation was successfully validated with the tests performed for the Greater Municipality of Istanbul. A series of the spatial and semantic queries (some of which are provided here) were successfully completed during the validation tests. The results have demonstrated that information transformed from BIMs and represented with a BIM Oriented Model (BO-IDM) would support the conceptual requirements of indoor navigation by provision of 3D geometric representation of indoor environment enriched with detailed semantics.

5.2. Interoperability validation

As mentioned in Section 2 the 6th conceptual requirement for indoor models specifies that within the models 3D building elements and spaces need to be defined with interoperable geometric representations, in order to facilitate the seamless exchange/sharing of geometric information between various applications. In order to validate the fulfillment of this requirement, the final phase of the implementation was devoted to testing;

1. How successfully the geometric information contained in the BO-IDM can be translated and transferred into other geoinformation models?
2. The impact of the different geometric representations (implemented in BO-IDM) to a successful translation and transformation of geometric information.

The tests involved transformations from two (Shapefile and Geodatabase) implementations of BO-IDM to CityGML, BISDM, GML and KML. The transformations were performed with Safe Software's "*FME Universal Translator 2010*" (Safe Software, 2010). The choice of FME Universal Translator as the test software was based on FME's wide recognition in the industry regarding geoinformation model translation and transformation, as well as its availability for research. Model transformation from the three representations:

• Polygons consisting of a single ring → GM_Polygon (1..1: GM_Ring).
• Polygons consisting of multiple rings → GM_Polygon (1..1: GM_Ring).
• Surface Patches→ 1..1: GM_SurfacePatch.

into GML, CityGML, KML and BISDM had been tested during the exercise. The results are provided in Figure 8.

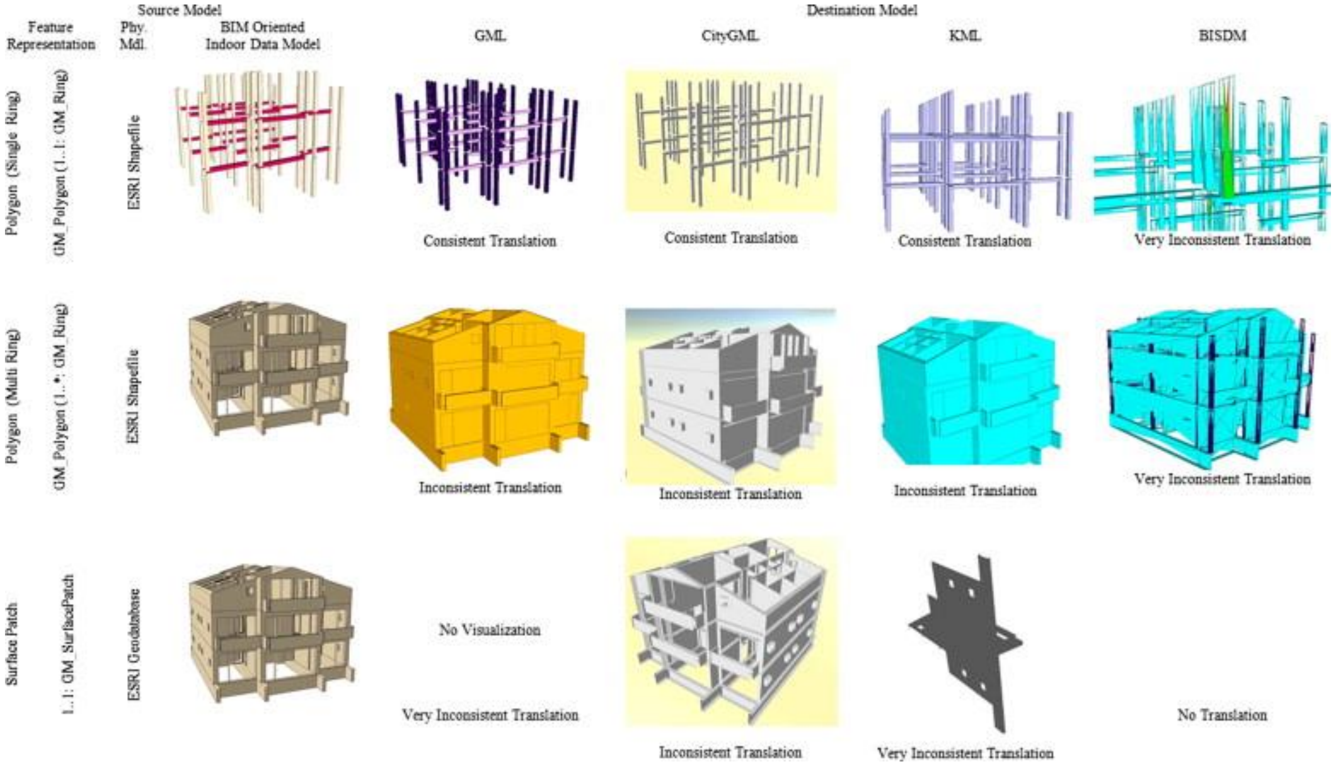

Figure 7: Summary of Model Transformation Tests

The results of the of the geometric transformation tests points out the following findings:

1. BO-IDM facilitates straightforward data conversion to other spatial file formats, but the results are dependent on the data types used for representing geometries.
2. The use of simple geometric objects (i.e. polygons consisting of single ring) make the automatic geometric transformation operation and the resulting models more consistent with the source building model.
3. Representations with multi-ring polygons create some problems, and most geometric transformation errors is related to improper representation of inner rings (as filled polygons).
4. The surface patch representations cause many errors in the model transformation process, and the transformed models appear very inconsistent with the source model in terms of model geometry.

The geometric transformation between geoinformation models appeared as more reliable and coherent when the single polygons are used. As the representation becomes more complex (i.e. from polygons to surface patches) the transformation may become less reliable or inconsistent. Inconsistencies in validation tests might also be caused as a result of using vendor specific data types in the implementation or using a single test tool for the transformation of information between BO-IDM and other models. Although the BO-IDM representations are ISO 19107 compliant, the implementation formats were vendor specific (as a result of user requirements in the implementation tests). It should also be noted that these transformations are completed with a single software (i.e. FME). Other conversion programs may reveal different results. The developers of FME were informed of the performed tests and obtained results.

6. Conclusions

Indoor Navigation requires the use of a number of interrelated models of buildings for the calculation of navigation paths, visualization of the navigation, and for assisting the actors in the navigation process. The motivation behind the work presented was to facilitate intelligent indoor navigation by providing detailed semantic information along with 3D geometries. Based on the analysis, BIMs appear as the most detailed resources of semantic information, and they were used as basis for developing a novel (BIM Oriented) model BO-IDM to support indoor navigation requirements. BO-IDM contains geometric representations compliant with ISO 19107. Extra objects and attributes were added to the object definitions in the BIM when defining the objects of BO-IDM. In addition, BO-IDM preserves the object hierarchy between the building elements of the BIM. A specific scenario related to the information requirements in emergency response operations helped in the physical implementation of the model. The use of BO-IDM in representing buildings brings the following advantages:

1. BO-IDM is a '*semantics-focused*' primal model that preserves key properties of BIMs for supporting indoor navigation. The semantic information provided by the model also includes the functional characteristics (e.g. usage type of a room) and states of the building elements. The property set of BO-IDM objects is appropriate for indoor representation and thus the model would support provision of highly detailed semantic information related to indoor navigation.
2. Structural elements such as beams, columns, slabs and walls are represented with 3D geometries in BO-IDM and thus, information related to the utilities that are located inside building elements (i.e. pipes, cabinets) can be quickly integrated with the model.
3. The georeferenced geometries of BO-IDM are compliant with object representations of ISO 19107 hence the model can be, recognized by geoinformation analysis and processing applications, easily mapped to CityGML, and used as a substitute (an alternative) of LOD 4 representation of CityGML in supporting indoor navigation.
4. Adjacency graphs can be derived based on the relations between Space/WallPart/SlabPart and that would facilitate navigation to the utilities embedded inside Walls and Slabs. In addition, the relations between Space/DoorPart/WindowPart would facilitate the generation of connectivity graphs which would support navigation inside the building

The advantages of using BO-IDM instead of BIMs in support of indoor navigation are as follows:

1. In parallel with the 1st conceptual requirement both BIMs and BO-IDM contain semantic information. BIMs in use (i.e. IFC/CIS2) are complicated models and the connectivity/containment type of relationships between building elements are implicit in BIMs. In addition, as a result of complex schema structure of the BIMs, queries to reach the semantic information regarding an element become more and more difficult when the object tree of the model grows. BO-IDM contains semantics focused on indoor navigation represented with a simple schema structure. Connectivity/containment type of relationships between building elements are explicit, i.e. easy to reach and query in BO-IDM.
2. The 2nd conceptual requirement addresses that properties of the building elements in support of indoor navigation need to be represented with the model. BO-IDM provided additional attributes such as State, IsFireResistant, IsSlipperyWhenWet, etc., to support the indoor navigation requirements.
3. In addition to the semantics represented in BIMs, BO-IDM is capable of representing the functional states of the building elements, i.e. information related to event based state

changes (i.e. being open or closed for doors/windows) are represented in BO-IDM. This representation supports the 3rd conceptual requirement.

4. The 5th conceptual requirement indicates that spatial relationships need to be represented in a way that would facilitate the derivation of the connectivity graphs and network models. The complex structure of BIMs which makes it difficult to derive such graphs. In contrast, the objects, attributes and mainly the relationships between objects defined in the BO-IDM simplifies the generation of the graph and network models.
5.

BO-IDM is a primal representation of the building. The algorithms in the current implementation of the model check the geometric validity of objects i.e. if surfaces are formed with closed polygons (exterior and interior rings, there is no overlap between surfaces, etc.). Thus a valid topology can be derived from the current implementation of the model (with minimal effort) and the dual graph model would then be generated based on Poincare-Duality. The network representations can also be derived from the model, based on connectivity relationships and using techniques such as Skeletonization. In order to obtain the semantic only representation, future research will focus on transforming the UML representation of BO-IDM to OWL. Tools such as explained in Leinhos (2006) would facilitate this process. This representation would help in reasoning without the need of geometric component of the model. Future work will also concentrate on the testing and improvement of transformation algorithms developed for BIM to BO-IDM information transformation. Enriching BO-IDM with more objects for representing utility elements to respond to utility related queries is also in the focus of future research. Finally, future research will also focus on implementing the model into other DBMS or GML, which will contribute to the overcoming the inconsistencies in transformation of information from BO-IDM into other data formats.

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