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Modelling 3D Topographic Space Against Indoor Navigation Requirements

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Abstract Indoor navigation is growing rapidly with widespread developments in the collection and processing of sensor information for localisation and in routing algorithms calculating optimal indoor routes. However there is a general lack of understanding about the requirements for topographic space information to be used in indoor navigation applications and thus the suitability of existing information sources. This work presents a structured process for the identification of topographic space information starting with use cases that support the complete capture of requirements, thus allowing existing models to be evaluated against these requirements and conceptual semantic and constraint models developed. A proposal is put forward for the implementation of topographic space semantic and constraints models as a CityGML Application Domain Extension (ADE) that will be integrated into the Multilayered Space-Event Model (MLSEM), a flexible framework supporting all indoor navigation tasks.

1 Introduction

The field of indoor navigation is now a major research topic with research taking place on the development of localisation sensors and techniques, routing algorithms and display and dissemination of navigation information to a user. Topographic Space is a fundamental part of indoor navigation, representing the interior environment of buildings and its semantic decomposition into building elements (e.g. rooms and storeys) for route planning and use in combination with additional sensor information. Indoor environments are increasingly being modelled in 3D using Industry Foundation Classes (IFC) and CityGML and therefore components of these indoor environments are inherently represented in 3D. When considering an Unmanned Aerial Vehicle (UAV) being routed through a large indoor airport terminal, we have a real-world navigation object (represented as a 3D

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geographic feature) interacting with real-world topographic space features (e.g. a door opening) that therefore must be described by geographic features with a 3D representation in Euclidean space (Nagel et al. 2010). A number of developing indoor navigation techniques are reliant upon a constant, rich 3D information model for building interiors, considered within the wider context of indoor. Currently topographic space information is frequently being provided by building models captured for the purposes of urban / building modelling. These current sources of information create a number of potential problems including incomplete/inconsistent topographic space features and incompatibility of all information sources required for tackling the complete set of indoor navigation tasks (localisation, route planning and route homing). As an example when considering the use case of routing a person from a start point to an end point within a single building during an emergency evacuation scenario, a number of requirements are created including the need to define that elevators are commonly out of use during this scenario. In existing building models (e.g. CityGML), all semantic features are not always captured and there is a general lack of support for defining complex navigation constraints (e.g. that an 'elevator' = 'inaccessible' if 'scenario' = 'emergency').

The lack of suitable information models is complicated by the lack of understanding of the use cases for topographic space information and the corresponding requirements. Therefore there is a need to improve the understanding of the semantics and constraints required for topographic space. Standardised building models are increasingly being used to provide the topographic space information, even though these models have not been developed considering this specific application. The evaluation of existing building models will provide us with a detailed understanding of the comparable suitability of building models and the developments required to fully meet these requirements. The problem is also complicated by topographic space information only being a sub-part of the information required for full indoor navigation. Therefore the integration of the extended building model within a flexible indoor navigation framework is required to ensure that the information provided works in combination with other information sources to fully support the requirements for all indoor navigation tasks. A Multilayered Space-Event Model (MLSEM) framework has been proposed in order to fully support all of the navigation tasks (as detailed in Nagel et al. 2010). Crucial aspects of this framework are the flexibility in integrating multiple space layers (topographic space, sensor space, and logical space), the clear separation of these space layers and the integration of user context information (e.g. modes of locomotion and user groups). This framework allows a range of different information sources to be used for space layers (see Fig. 1), including both CityGML and IFC for a topographic space layer. This model allows arbitrary space cells to be captured but however lacks the semantic information required for differing topographic space features. The MLSEM does not aim to provide this level of semantics, instead preferring that a suitable existing building model provide the required semantic information. Therefore future work will look at extending existing building models that can be integrated into the MLSEM for full indoor navigation support.

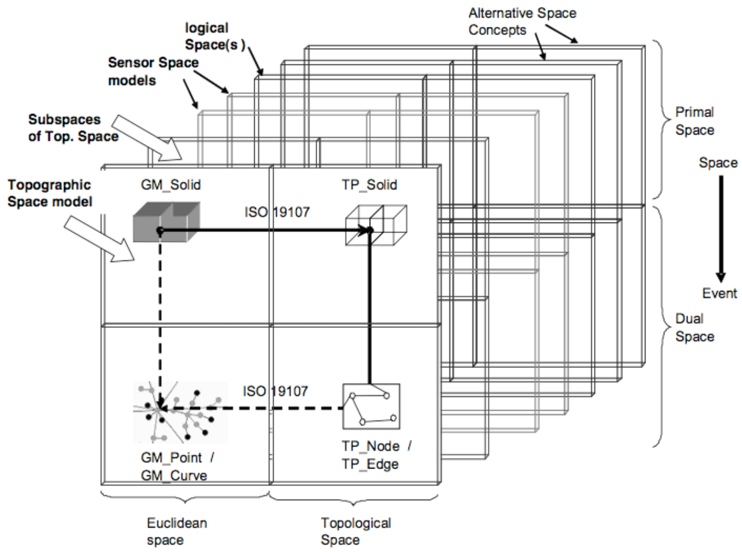

Fig. 1 Multilayered Space-Event Model combining differing space layers (topographic, sensor, logical space etc) (Nagel et al. (2010))

In Sect. 2 the use cases and corresponding requirements for modelling 3D topographic spaces are discussed in detail, as a prerequisite for the assessment of the suitability of related models. Existing topographic space semantic and constraint models are introduced and evaluated in Sect. 3. In Sect. 4 our conceptual approach for modelling semantic topographic space objects and constraints, with respect to the identified requirements is presented. Linked hierarchical conceptual models have been developed for semantic topographic space objects, including all relevant spaces and objects relevant for indoor routing and topographic space constraints, including all factors that can be used to define the level of navigability through/around indoor spaces and obstacles. In Sect. 5 we draw conclusions and give an outlook to future work including the implementation of the conceptual models for an existing building model.

2 Topographic Space Requirements for Indoor Navigation

2.1 Indoor Navigation Topographic Space Use Cases

In order to develop a customised building model suitable for use in indoor navigation, a structured set of use cases for indoor navigation is required. Those papers proposing models for indoor navigation space do not include use case analysis for the developed semantic models (Tsetsos et al. 2006, Meijers et al. 2005, Goetz and Zipf 2011 and Yang and Worboys 2011). Therefore a process needs to be developed to identify the uses of topographic space information and the resulting requirements. Only use cases within the scope of indoor routing are considered, with those use cases considering navigation guidance, visualisation of information etc. viewed as being outside the scope of this work. Requirements can then be drawn out from the identified use cases and test cases developed to ensure that a customized/extended building model is fit for use as the topographic space information model.

Planning a route to single/multiple destinations is one of the fundamental tasks of indoor routing. For this task, a user wants to calculate an optimal route to a single/multiple known destinations considering parameters including the mode of locomotion, current scenario (e.g. emergency evacuation), time of day and access permissions of the user. Therefore this task can be broken down into use cases (see Table 2) to abstract the detailed requirements for topographic space information model. In table 2, five core use cases (use cases 1 to 5) are introduced with use cases 6 to 8 relating to this core set.

	Use Case Title	Example Scenario	Navigation Constraints
1	Route a user **within a single room** in a building	Route Person A from Check-in desk 14 to Gate A2 in London Heathrow Airport, considering that the space can contain fixed (e.g. pillars), movable (e.g. furniture) and dynamic obstacles (e.g. crowds of people).	- Spatial extent of Space and Obstacles - Surface material of floor - Supporting weight of floor / furniture
2	Route a user **between separate rooms in a single storey**	Route Person A between Office 0.02 (Ground floor) and Office 0.12 (Ground floor) of a multi-storey Office building.	- Temporal, user specific, access type, directional, current state and spatial extent restrictions on door and window (to a lesser extent) spaces.

3	Route a user **between different storeys** within a building	Route Person A from the main entrance (ground level) to Platform 12 (2 storeys below ground level) of Berlin Main Train Station using Ramps, Stairs, Escalators and Lifts where appropriate.	- Space types (e.g. power assisted escalator, stairs etc.)
4	Route a user from **outside a building to inside a building** and from inside to outside a building.	Route Person A from Office 5.12 in the Main Building of the TU Berlin to Fire Evacuation point 4 (outside the building) during an emergency evacuation scenario.	- Type of door / window spaces (e.g. interior/exterior)
5	Route a user **between separate buildings** (e.g. from a start point in Building A to a destination in Building B).	Route a user from a parking space in a Car Park to Office 6.13 in a neighbouring office block, requiring a user to walk outside.	
6	Route a **user with specific requirements** (e.g. human on foot, human in a wheelchair, UAV, emergency services worker).	Route Person A travelling in a wheelchair from Departures Entrance 1 of Berlin Tegel Airport to check in desk B2.	- User groups / mode of locomotion
7	Route a user considering a **specific scenario** (e.g. emergency evacuation, rush hour journey etc).	Route Person A from Supermarket 1 to Men's Clothing Shop 2 within a large shopping centre, at a peak shopping time.	- Scenario type for routing - Persistency and current state of obstacles (e.g. walls, furniture)
8	Route a specific user within a building where **access to certain parts is controlled**.	Route Person A with limited security clearances, considering restricted access for specific person / directional access / temporal access constraints, between Room 1 and Room 10.	- User specific access permissions.

Table 2 Use cases for indoor navigation topographic space information with accompanying navigation constraints

2.2 Indoor Navigation Topographic Space Requirements

From the use cases, defined in section 2.1, an extensive list of requirements for topographic space information have been identified. The completeness of this list will be subject to further investigation along with the determination of dependencies between requirements. The indoor environment requirements identified are as follows:

- **Requirement 1:** An indoor environment model shall capture the general semantic information for a specific building and be represented by all spaces belonging to this indoor environment (relates to use cases 3, 4 and 5).
  Example Scenario: When route planning all space objects belonging to a specific building (e.g. a Hospital) will need to be able to be identified for use with routing algorithms.
- **Requirement 2:** All spaces belonging to an indoor environment shall be represented both semantically and geometrically, defining spatial properties of physical spaces (Use cases 6 and 1).
  Example Scenario: Indoor navigable spaces (e.g. rooms) must be semantically classified and have a geometry so that navigable space can be identified for different modes of locomotion (e.g. user in a wheelchair).
- **Requirement 3:** Spaces belonging to an indoor environment shall be categorised according to specific pre-defined space types (Use cases 2 and 3).
  Example Scenario: All space types will need to be broken down into predefined space types for the definition of common constraints (e.g. power-assisted movable doors).
- **Requirement 4:** All spaces belonging to an indoor environment shall be able to be decomposed into smaller space parts (Use cases 7 and 1).
  Example Scenario: A large indoor navigable space (e.g. an airport) will need to be subdivided into smaller space parts for the definition of start and end points for a route.
- **Requirement 5:** All spaces belonging to an indoor environment shall be able to be extended with additional semantic attributes (does not relate directly to any single use case).
  Example Scenario: Future requirements from routing algorithm developers could require that additional semantic attributes be represented (e.g. speed penalty traversing for dynamic obstacles).
- **Requirement 6:** Storeys within an indoor environment should be represented and associated to all spaces belonging to a specific storey within an indoor environment (relates to use cases 2 and 3).
  Example Scenario: When routing between Room A and Room B on different storeys, the storeys these rooms are located on are required to support the analysis of whether elevators can be used to travel between these 2 storeys.
- **Requirement 7:** An indoor environment model should be able to be seamlessly used with outdoor spatial information providing transport networks, navigable areas etc. (relates to use cases 4 and 5).
  Example Scenario: When routing a user from a space in Building A to a space in a separate Building B, outdoor information must be used together with the

indoor information to define outdoor navigable routes between the entrance/exits of these buildings.

The indoor space requirements identified are as follows:

- **Requirement 8:** Storage of semantic information for the function, usage and occupants of an indoor space (relates to use case 2).
  Example Scenario: When planning a route it is important that the usage of a room is known, so that a user is not navigated through meeting rooms when unoccupied rooms are available instead.
- **Requirement 9:** Specialised types of indoor space shall be used to differentiate levels of connectivity of indoor spaces (relates to use cases 2 and 3). This information could be derived but is required for the categorisation of connected spaces.
  Example Scenario: When planning a route between two rooms, only the spaces that connect together multiple spaces must be considered when creating a route between a start and an end position.
- **Requirement 10:** Specialised types of connecting space with specific semantics shall be used for vertical (e.g. staircase) and horizontal (e.g. corridor) and fixed (e.g. ramp), assisted (e.g. escalator) and transfer (e.g. elevator) connecting spaces (relates to use cases 3 and 5).
  Example Scenario: A vertical staircase space requires different specialist attributes for the spatial properties of the stairs, number of flights of stairs and the staircase types, to determine if this space is navigable for a wheelchair user in an emergency scenario.

The transfer space requirements identified are as follows:

- **Requirement 11:** Transfer spaces (e.g. a door opening space between two rooms) shall be separated into both physical (e.g. door or window opening spaces) and virtual opening spaces (e.g. airport security gate) for which specialist attributes can be defined (relates to use cases 2 and 4).
  Example Scenario: Virtual opening spaces are required when no physical boundaries exist between two indoor spaces or indoor and outdoor spaces. A virtual opening could define the potential access points into an indoor environment.

The indoor obstacle space requirements identified are as follows:

- **Requirement 12:** Indoor obstacle spaces should be semantically categorised as fixed (e.g. pillar), movable (e.g. small table) and dynamic (e.g. fire) obstacle spaces, with physical attributes representing the spatial extent, supporting weight, persistency, current state and scenario type (relates to use cases 6, 7 and 1).
  Example Scenario: Persistency of obstacle spaces is required, as certain types of wall (a fixed obstacle space) could be removed in an emergency evacuation scenario, if required.

- **Requirement 13:** Fixed position obstacle spaces will have the surface material and specialist semantics defined for interior and external walls, floors, ceilings, stairs, ramps and general fittings (e.g. light fittings) (relates to use case 1), allowing constraints to be defined for these features.
  Example Scenario: The surface material of a floor surface is required to determine the suitability of a floor surface for use by a wheelchair user.
- **Requirement 14:** Movable obstacle spaces will have semantics including physical weight and specialist semantics defined for windows, doors, furniture, construction work etc (relates to use cases 6, 7 and 1) allowing constraints to be defined for moving this obstacle space.
  Example Scenario: A movable furniture obstacle requires physical weight and other attributes to determine the movability of this obstacle by different user groups.
- **Requirement 15:** Door and window (movable obstacle spaces) should have specialist semantics allowing constraints to be defined according to the type, opening mechanism, sub-parts, directionality of opening, current state, accessibility (users with access, times of access, access type and direction) and usability in scenarios (relates to use cases 6, 7 and 2).
  Example Scenario: A movable door obstacle must be able to capture the users that have access permissions for opening a door in a specific direction.

3 Related Models

Indoor navigation requires a detailed topographic space model including both semantics and constraints, to meet the requirements specified in section 2.3. In the following section, we will examine the existing building models, semantic topographic space models and constraint models against these requirements.

3.1 Semantic 3D Building Models

We will focus on the international standards CityGML and IFC only. These semantic building models have the potential to provide part or all of the topographic space information required for indoor navigation through semantic enrichment. Only semantic models are considered as the requirements have defined that a detailed set of semantics are required for topographic space. 3D graphics formats will only be considered in comparison to these semantic building models.

3.1.1 CityGML

CityGML is an Open Geospatial Consortium (OGC) standard based on GML3. This multi-purpose information model is used for describing geometric, topologic and semantic aspects of city models in a 3-dimensional way (Kolbe et al. 2005). The building model is the most detailed thematic concept of CityGML and supports 4 levels of detail (LOD). A LOD4 building model provides the semantics and geometry for the interior of a building (see Fig. 3).

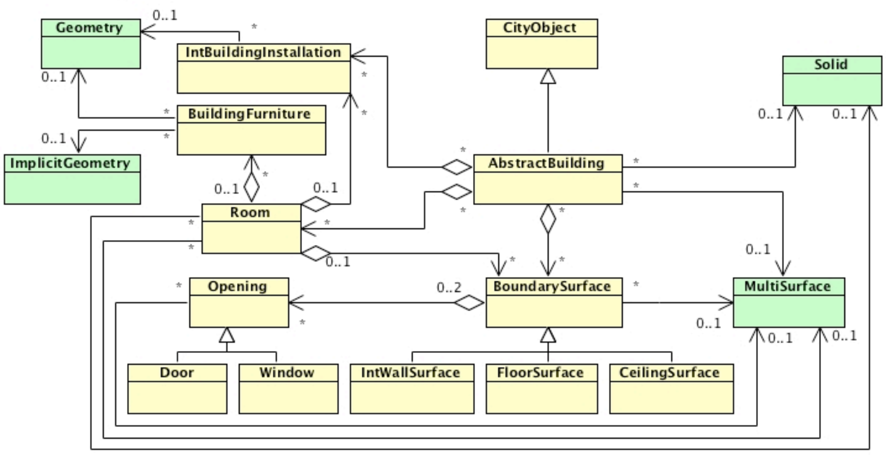

Fig. 3 Simplified CityGML LOD4 building model

The semantic and constraint features of a CityGML building model include an *AbstractBuilding*, with each building being able to be composed of Rooms and *IntBuildingInstallations* (requirement 1). Indoor spaces (*Rooms*) and transition spaces (*Openings*) can be fully semantically and geometrically represented in CityGML. All required obstacles can only be partially represented by *Building-Furniture*, *IntBuildingInstallation* and indirectly from *BoundarySurfaces* (requirement 2). CityGML does not provide a specific concept for the representation of storeys, as is implemented for IFC. A storey can though be represented as an explicit aggregation of all building features on a certain height level using CityGMLs notion of *CityObjectGroups* (Groeger et al. 2008). This *CityObjectGroups* may also have a defined geometry. However if building features are associated to a specific storey, this may require the vertical fragmentation of these features, one part per storey (Groeger et al. 2008). CityGML also supports the use of a world coordinate system, allowing outdoor and indoor spatial information to be used seamlessly together to route a user outdoors between buildings (requirement 7).

Room features contain attributes allowing the function and usage of these indoor spaces to be defined (requirement 8). CityGML does not include predefined connected room types, however through the aggregation associations between a *Room* and *BoundarySurface* and *BoundarySurface* and *Opening*, some information on the connectivity of indoor spaces can be derived (requirements 9 and 10).

For transition spaces, CityGML defines *Openings* (windows and doors) in the *BoundarySurfaces* and can create virtual openings through the use of *ClosureSurfaces* (requirement 11).

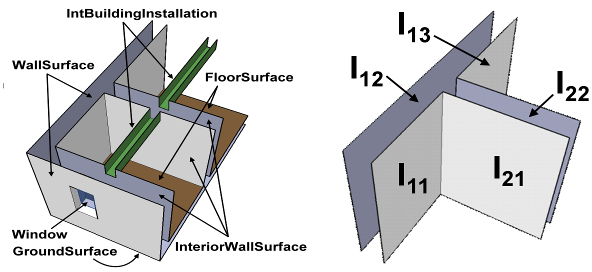

Fig. 4 CityGML model of a building storey (left) and *BoundarySurfaces* for Rooms (right) (Nagel et al. (2009))

CityGML has limited support for fixed and movable obstacle spaces and no support for dynamic obstacles (requirement 12). Complete fixed indoor obstacle spaces (e.g. walls) are indirectly partly represented in CityGML by *BoundarySurfaces*, which capture only the visible surfaces of a room, see Fig. 4. Therefore indoor obstacle space can be derived as being the Space of a building minus the indoor spaces (e.g. rooms). As a result of this wall, ceiling and floor spaces have no semantics and are unable to be decomposed into sub-parts (requirement 4). The movable components of a window or door are not modelled separately to the opening in CityGML and lack detailed semantic information. The limited semantic information for doors and windows and the lack of support for constraints prevents navigation constraints on topographic features (e.g. wheelchair only being able to traverse through a power assisted door) from being defined, as needed for requirements 12, 13, 14 and 15.

3.1.2 IFC

The term Building Information Modeling (BIM) describes the process of generating and managing building data (Ashcraft 2007), using 3D modeling approaches. A commonly used format for BIM is the IFC, describing a neutral and open specification, registered as ISO 16739 (IAI 2008). IFC defines an entity-relationship model providing an abstract and conceptual representation of data, consisting of around 900 entity classes organized into an object-oriented hierarchy (Goetz and Zipf 2010). IFC provides detailed semantics for constructive building elements, including beams and walls (Fig. 5).

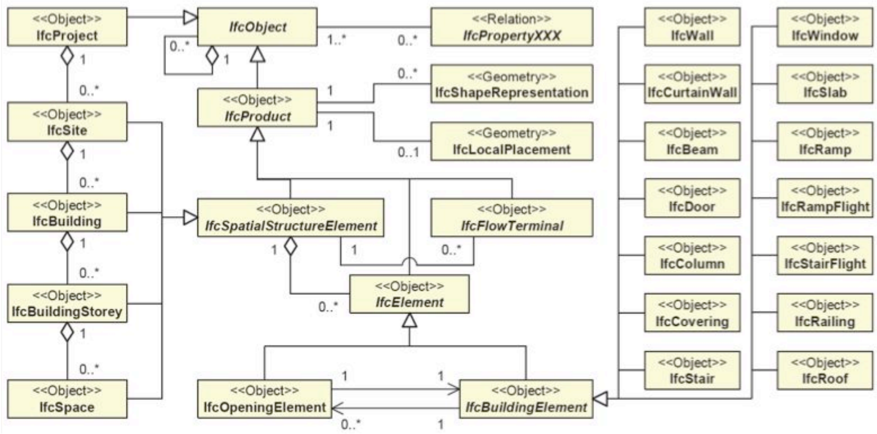

Fig. 5 Subset of IFC classes relevant topographic space information (Benner et al. 2005)

The semantic features of an IFC building model include an *IfcBuilding* that should have one or more *IfcBuildingStorey* (requirement 6), with each *IfcBuildingStorey* having zero or more *IfcSpaces* related to it (requirement 1). All indoor spaces (*IFCSpaces*), obstacles (*IfcBuildingElement* and *IfcFurnishingElement)* and transition spaces (*IfcOpeningElement*) are represented in IFC semantically and allowing multiple geometric representations (requirement 2 and 3). IFC supports complex space groups, spaces and partial spaces (requirement 4). IFC models are not normally used to model complete urban environments, but workarounds exist to support the modelling of sets of buildings within a real world coordinate system (requirement 7).

IfcSpaceType allows the function of specific spaces to be defined (requirement 8). IFC building models have limited support for connected indoor spaces, with IFC entities and relation classes (*IfcRelConnects*) defining general applicable object types for the connectivity relationship (IAI, 2008) that can express some information on the connectivity between spaces (requirements 9 and 10).

For transition spaces IFC supports the capture and representation of openings (window and door) and can indirectly create virtual openings through the utilization of *IfcVirtualElement* (requirement 11).

IFC has no support for dynamic obstacles (requirement 12). Detailed semantics are provided for fixed obstacles (*IfcBuildingElements*) and furniture (movable) obstacles (as specified in *IfcFurnitureType* for furniture elements) however other movable obstacles (e.g. construction work and indoor vehicles) are not supported (requirements 13 and 14). *IfcDoor* and *IfcWindow* provide detailed semantics including the opening direction, operation type (e.g. double swing) and operation type, hinge location and construction material. IFC does lack support for complex topographic space constraints (requirements 12, 13, 14 and 15).

3.1.3 Summary

CityGML, IFC and 3D graphics formats (e.g. kml, collada, X3D etc) were quantitatively evaluated against the requirements specified in section 2.2 (table 6), based upon the knowledge of and experience gained from working with these models/formats.

Requirement No.	CityGML	IFC	3D Graphics Formats
Indoor Environment			
1	++	++	•
2	+	++	•
3	+	+	•
4	+	++	•
5	++	++	•
6	++	++	•
7	++	++	•
Indoor Space			
8	++	++	•
9	•	•	•
10	•	•	•
Transfer Space			
11	++	+	•
Indoor Obstacle Space			
12	+	+	•
13	+	++	•
14	+	+	•
15	•	+	•

Table 6 Evaluation of CityGML, IFC and 3D graphics formats against topographic space requirements (++ requirement fully met, + requirement partially met, and dot requirement not met).

CityGML and IFC are both versatile data model that aim at spatio-semantic coherent models but also allow the representation of 3D models at various degrees of geometric and semantic complexity (Stadler and Kolbe (2007)). In this evaluation full spatio-semantic coherent IFC and CityGML building models are used. Table 6 clearly shows that an IFC building model fulfils slightly more of the overall requirements than CityGML. The minimal support for fixed obstacles (e.g. walls) in CityGML can be summarised as being a highly significant differences between these building models. 3D graphics formats are included in this evaluation to show that visualisation models are not sufficient as they lack semantics.

3.2 Semantic Indoor Navigation Topographic Space Models

Semantic models and ontologies are increasingly being developed for indoor navigation topographic space. An Indoor Navigation Ontology (INO) is included in the OntoNav framework, to describe the basic spatial and structural concepts of indoor environments (Tsetsos et al. 2006). INO introduces concepts that are relevant for indoor navigation (excluding guidance) including: Space (e.g. Building, Room, Floor etc.); Path_Element (e.g. Corridor_Segment, Escalator, and Door); and Obstacle (e.g. table and closed elevator). The Path_Element concept models the physical or conceptual elements of a navigation path. Passage, a type of Path_Element, is any spatial element that is part of a path and has specific accessibility properties (requirement 9). These are separated into: Horizontal (e.g. connecting corridors); Vertical (e.g. ramp); and Motor passages (requirement 10). This semantic model does not discuss the requirement for the decomposition of spaces into smaller parts (requirement 4) or the semantics and constraints for indoor obstacles including doors and windows (requirements 12, 13, 14 and 15).

Meijers et al. (2005) present a semantic model of interior spaces for facilitating the calculation of evacuation routes. This semantic model has a building composed of an aggregation of complexes of sections (e.g. a storey) or of sections (requirements 1 and 6). Three types of sections exist: end (with only one entrance/exit); connector (with more than one entrance/exit) and non-accessible (no entrance/exit) sections (requirements 9 and 10). These sections are geometrically defined by 3D polygons normally representing walls and are classified according to persistence (potential for temporary removal), existence (real and virtual walls), access granting (non-granting, limited and granting access) and types of passing (uni and bi-directional), partly fulfilling requirements 13 and 15.

In Goetz and Zipf (2011) a 3D Building Ontology (3DBO) is introduced for indoor environments, intended for use with OpenStreetMap (OSM). In this ontology the 3D Building representation is defined as having a distinct number of levels (requirement 6), with each level having BuildingParts for spatial elements belonging to a distinct level (requirement 2 and 3). These BuildingParts are categorised as rooms, halls, corridors, vertical passages and horizontal passages (requirement 8, 9 and 10). BuildingParts can also be fixed and movable obstacles and have both windows and doors, partly fulfilling requirements 11 and 12. This model does not consider how building parts can be decomposed into sub-parts and additional constraints added to fixed and movable obstacles (requirements 13, 14 and 15).

Yang and Worboys (2011) have started work on developing ontologies for a navigation model in a unified indoor and outdoor space. Four levels of ontologies are developed: upper (general event, object, state, setting concepts); domain (structure of spaces); navigation task (concepts for navigation guidance); and application (e.g. for indoor navigation of pedestrian). The domain ontologies include a structure ontology for indoor spaces. In this ontology the highest-level features modelled are: Surface (e.g. floor); Portal (e.g. window or entrance); ControlDevice (e.g. key or lock); Container (e.g. elevator or room); Obstacle (e.g. wall or internal door). This ontology captures indoor spaces as rooms and passages, transition spaces as doorways and window spaces and obstacles as fixed and movable barriers. In this model there is no support for complex constraints (e.g. persistency of wall obstacles in an emergency scenario).

To summarise, the existing semantic models for indoor navigation topographic space align much more closely with the requirements than the building models evaluated as they were developed for these specific tasks. The modelling and method for integrating navigation constraints in a semantic model was generally lacking in the semantic models evaluated.

3.3 Constraint Models

The analysis of the requirements for topographic space information showed that there is a need to be able to add both simple and combined constraints to topographic space entities (requirements 12, 13, 14 and 15). A simple constraint expresses a single condition / restriction for a single topographic space element, whilst a combined constraint expresses multiple constraints on a single feature or single/multiple constraints on a series of features. An example of a simple constraint is the users with access permissions for a specific door.

The ISO Geographic Data File (GDF) standard (ISO/TC211 2004) uses constraints when modelling features relevant for outdoor routing. This method and structure used for defining constraints in GDF can be evaluated and considered for use in modelling constraints of topographic space information. A combined navigation constraint for Prohibited Manoeuvres has been implemented as a GDF Relationship, defining a manoeuvre that is physically possible but prohibited legally. This GDF Relationship is specified for at least 2 road elements, a junction and a traffic sign feature. A similar principal may be able to be applied for uni-directional access through a door space (requirement 15).

In the OntoNav system, user context is modelled using a developed User Navigation Ontology (UNO) (Tsetsos et al. 2006). This ontology contains user classes and elements of user context. Only physical navigation rules, applied to discard any paths that are not physically accessible to a user, are within the scope of this work. This ontology links to the OntoNav INO model, fulfilling requirements 12, 13, 14 and 15. An example of a possible rule is for excluding Stairways for wheelchair users (requirement 2).

Stoffel et al. (2007) developed a semantic spatial model for pedestrian indoor navigation and introduced the concept of annotating nodes and region graphs with further attributes (e.g. list of key-value-pairs) to provide further context information. Modelling of Boolean constraints is introduced for doors and windows, which can be locked or require access authorisation, have temporal opening times, and used only in an emergency scenario (all constraints fitting to requirement 15).

To summarise, limited work has been undertaken on understanding the constraints needed for topographic space, hierarchically modelling these conceptual constraints and implementing a method for all navigation constraints to be defined for semantic entities (IAI 2008; Groeger et al. 2008; Yang and Worboys 2011; and Meijers et al. 2005).

4 Indoor Navigation Topographic Space Model

Existing models have been shown to be lacking semantic and constraint entities (Sect. 3). Initial work has started on the conceptual modelling of the topographic space features and constraints needed to fully meet the requirements, defined in Sect. 2.2. These conceptual models would support the customisation/extension of existing building models. In order to introduce the semantic and constraint concepts an example environment, Berlin main train station, is used (see Fig. 7)

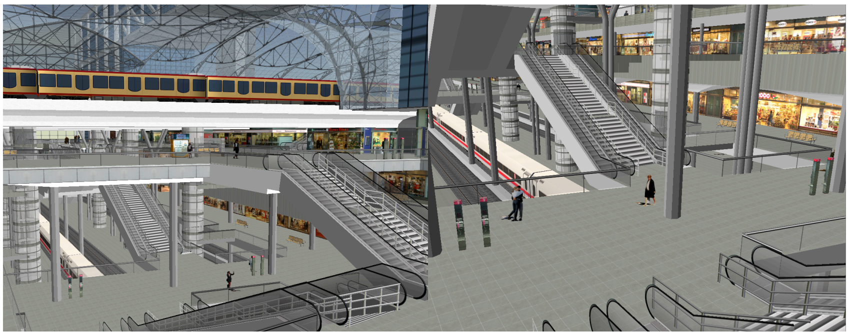

Fig. 7 Visualisation of CityGML LOD4 building model for Berlin main train station

4.1 Conceptual Semantic Indoor Navigation Topographic Space Model

We define an indoor environment as an abstraction of the collection of all real-world topographic objects being relevant indoor environment components. The conceptual modelling of an indoor environment and its components complies with ISO 19109 and the General Feature Model (GFM) concept, with featureType, Constraint and geometry stereotypes used.

The basic unit for modelling topographic space (*IndoorNavigationTopographicSpaceObject*) is an abstract concept mapping topographic space features to the GFM feature types. All *IndoorNavigationTopographicSpaceObjects* are aggregated together as a collection of units (*IndoorNavigationTopographicSpac-*

eModel), see Fig. 8. All abstracted topographic space components (e.g. train station platform spaces, staircases and doors) can be aggregated to an *IndoorEnvironment* (requirement 1). This central feature is an extension of the Building feature used in other semantic models (Meijers et al. 2005; Tsetsos et al. 2006; Yang and Worboys 2011; Goetz and Zipf 2011; IAI 2008; and Groeger et al. 2008), to include additional environments (e.g. underground transport systems). An *IndoorEnvironment* is composed of multiple *SpaceUnits*, with these hierarchically categorised and able to be decomposed into sub-space parts (requirement 2 and 4).

Existing building and semantic models use various approaches for modelling a *Storey* feature, including the aggregation of an indoor environment into storeys (with a geometry) and storeys aggregated into spaces (IAI 2008; Meijers et al. 2008; and Goetz and Zipf 2011) and the approach discussed for CityGML (see Sect. 3.1.1) whereby a CityObjectsGroup could be used to associate all CityObjects belonging to a storey (with or without an individual geometry). The defining of the geometry of a *Storey* requires that all indoor spaces are aggregated to a single storey. This requirement results in this approach not being considered at this point in time, with a *Storey* currently represented as a collection of indoor *SpaceUnits* (requirement 6).

One of the types of *SpaceUnit* belonging to an indoor environment is *IndoorSpace* and is defined as a volume of space that has the potential to be navigated through by a user. *IndoorSpace* and sub-space parts are able to have geocoded addresses, function and usage attributes stored, supporting the search for spaces and routing considering the semantics of *IndoorSpaces* (requirements 7 and 8). *IndoorSpace* is categorised into both *EndSpaces* and *Passages*. This categorisation uses the concept of end and connector space as introduced by Meijers et al. (2008) (requirement 9), see Fig. 9. An *EndSpace* is a unit of bounded indoor space that only has a single entrance/exit. A connector space (*Passage*) has multiple entrance/exits and thus is connecting together multiple indoor spaces (e.g. corridor). Similar categorisations are used in existing semantic models (Tsetsos et al. 2006; Yang and Worboys 2011; and Goetz and Zipf 2011), with spaces and passages being separated. The classification of a corridor space varies within semantic models, with a corridor either considered a space (Tsetsos et al. 2006; and Goetz and Zipf 2011) or a Passage (Meijers et al. 2005); Yang and Worboys 2011). The use of the connector space concept in this semantic model results in a corridor or connected room (to 2 or more indoor spaces) being defined as a passage. A *Passage* is categorized by the direction of passage, with both *HorizontalPassage* (e.g. corridor, moving sidewalk) and *VerticalPassage* (e.g. staircase and elevator) being defined (requirement 10). This same categorisation is adopted in existing semantic models (Tsetsos et al. 2006; and Goetz and Zipf 2011). For both

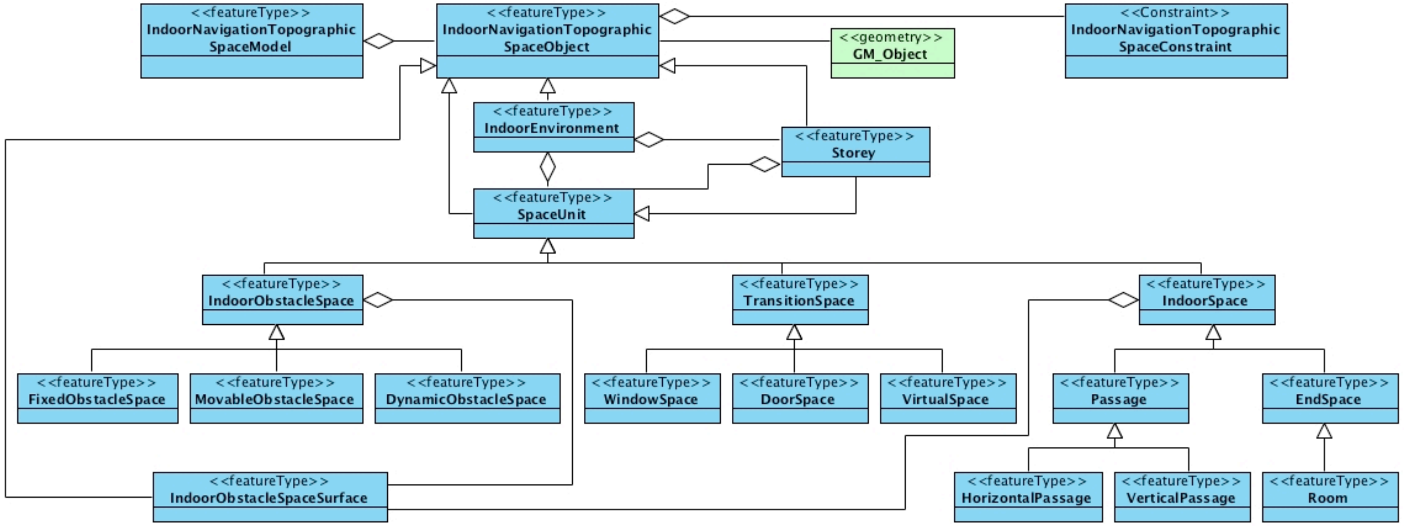

Fig. 8 Conceptual semantic indoor navigation topographic space model

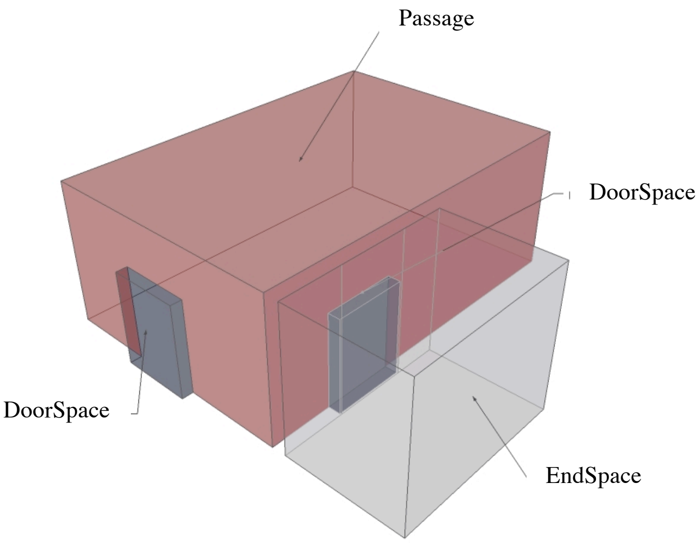

Fig. 9 Specialised types of *IndoorSpace*: EndSpace (grey) with one *DoorSpace*; and *Passage* (red) with multiple *DoorSpaces*

HorizontalPassges and *VerticalPassages* further specialist space objects can be categorised and defined according to whether these passages are *Fixed* (e.g. staircase), *Assisted* (e.g. escalator) or *TransferSpace* (e.g. elevator), requirement 10.

An indoor obstacle (*IndoorObstacleSpace*) is any object that can restrict the movement of a user. Within Berlin's main train station obstacles will include *FixedObstcacleSpace* (e.g. unmovable pillar in the centre of a room or an interior wall), *MovableObstacleSpace* (e.g. furniture or construction work) and *DynamicObstacleSpace* (e.g. fire or crowd of persons), requirement 12. This categorisation fits in closely with existing semantic models (Yang and Worboys 2011; and Goetz and Zipf 2011), with *DynamicObstacleSpace* extending the categories defined in these models. There is a need for the surface materials of some *FixedObstcacleSpaces* to be defined (e.g. surface material of a floor object is important for wheelchair users). *Therefore IndoorObstacleSpaceSurfaces* may be aggregated to *IndoorObstacleSpaces*.

A *TransitionSpace* is an opening space providing passage between *IndoorSpaces*. Similar concepts are termed Portal (Yang and Worboys 2011) and Polygon (Meijers et al. 2005) but represented significantly differently in other existing semantic models (Tsetsos et al. 2006; and Goetz and Zipf 2011). *TransitionSpace* has 3 subclasses: *WindowSpace*; *DoorSpace*; and *VirtualSpace* (requirement 11). Window and door transition spaces can be related to a window or door movable obstacle, which represents the actual door or window entity.

4.2 Conceptual Constraints Model

Initial work on the modelling of topographic space constraints follows on from the modelling of topographic space semantics. Topographic space constraints are linked to the topographic space semantic model through the relation of *IndoorNavigationTopographicSpaceConstraints* to *IndoorNavigationTopographicSpaceObject*, shown in Fig. 9. When considering topographic space constraints, the basic unit is *IndoorNavigationTopographicSpaceConstraint*, an abstract concept mapping topographic space constraints to the GFM feature types. Single *IndoorNavigationTopographicSpaceConstraints* can be aggregated together as a collection of units for a more complex constraint (*CombinedIndoorNavigationTopographicSpaceConstraint*), see Fig. 10.

From the requirements for topographic space information for indoor navigation, different categories of constraints can be identified: *AccessConstraint*; *PhysicalConstraint*; *ScenarioConstraint*; and *SpaceConstraint*, shown in Fig. 10. *AccessConstraints* allow the access properties for Door and Window *TransitionSpace* objects to be defined, requirement 15. A sub-type of *AccessConstraints* is *Users,* supporting the provision of access permissions for individual/groups of users. The second sub-type is *Temporal*, allowing the definition of one-off or repetitive times where access through a door is permitted. *AccessType* supports the definition of whether access is possible, partially (in one direction) or not possible. *Direction* of access can be combined with other constraints to allow a specific user group to be allowed to have access to pass in one direction through a door.

PhysicalConstraints support the determination of the physical usability of spaces and obstacles, requirements 2, 12, 13 and 14. The sub-types of *PhysicalConstraints* include: *Spatial*; *Weight*; *State*; *Persistency*; and *SurfaceMaterial*. *Spatial* constraints allow the minimum required *IndoorSpace* to be defined for a particular mode of locomotion. For example a wheelchair can only pass through a door space where the width is greater than approximately 83cm. *Weight* constraints include both the physical weight (e.g. of a movable piece of furniture) and the supporting weight of a fixed *IndoorObstacleSpace* (e.g. floors). *Persistency* reflects the possibility of an obstacle being removed if required, including the removal of a thin glass interior wall during an emergency evacuation scenario. *State* defines whether a fixed or movable indoor obstacle is currently open or closed (e.g. a window being open). Specific *SurfaceMaterials* cannot easily be traversed by certain modes of locomotion, including wheelchairs and blind persons, and therefore the surface material needs specifying.

A scenario type can be specified using the *ScenarioConstraint* and is designed for use in combination with other constraints to form a *CombinedTopographicSpaceConstraint*. An example of this could be access through a door only being available for all users when an evacuation scenario occurs, requirements 12 and 15.

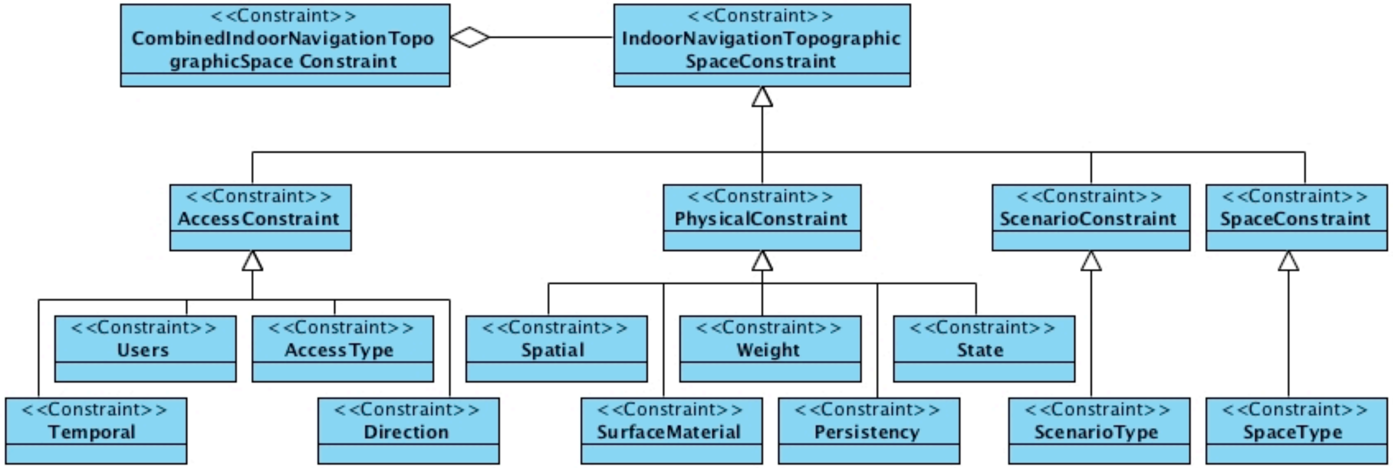

Fig. 10 Conceptual model of indoor navigation topographic space constraints

SpaceTypes of topographic space objects can be used to differentiate between single objects, requirements 3, 8, 9 and 15. An example is an electric powered elevator type of elevator being inaccessible to all users in an emergency evacuation scenario.

The hierarchical conceptual constraint model could be used to create single or combined constraints for single or a series of semantic topographic space entities. An example could be a combined constraint limiting the passage through a door space. This constraint would need to be created for an ordered series of semantic entities (*IndoorSpace*, *DoorSpace* and *IndoorSpace*). The complex constraint could include *Temporal* access restrictions (e.g. only accessible between 08.00 and 16.00), *Users* access (e.g. only employees), *Directional* access restriction (e.g. navigation constraint is unidirectional from start space to end space) and *ScenarioType* (e.g. only in heightened security scenario). Only when all components of this complex constraint are fulfilled, is this door space passable. Additional constraints can also be created for the same series of semantic entities but with a difference in the properties of the constraint elements (e.g. for a emergency scenario).

6 Conclusions and Outlook

In this paper we have presented a structured process for defining topographic space requirements, the evaluation of existing topographic space models and conceptual semantic topographic space and constraints models. Further work is though required to analyse the completeness and dependencies between the defined requirements. The approach explained for deriving conceptual features from a requirement capture driven by use cases, does not only allow the derivation of the required conceptual data model entities and their relations, but also supports the identification of requirements and thus use cases for specific entities in the conceptual models. This enables us to answer questions like if we do not have this type of information in our dataset / building model, which requirements and ultimately which use cases cannot be realised.

In section 2, a detailed set of semantic and constraint requirements were identified from use cases for the task of planning a route to single/multiple destinations, supporting the review of existing models. The evaluation of existing semantic and constraint models for topographic space (Sect. 3) showed that none of the models are sufficient to meet all the requirements identified, with a general lack of support for the modelling of constraints. Whilst topographic space semantic models have been implemented (Sect. 3.2), building data is normally acquired in accordance with a standardised building information model (section 3.1). Therefore the development of a customised/extended building model from a developed conceptual semantic and constraint model is required in order to avoid duplicating existing standards for the capture of interior environments. The IFC data model allows additional elements to be created as standard generic IFC elements. However the creation of specialised IFC elements requires a change to the IFC core classes, as there is not an extension mechanism in place for IFC. An extension mechanism is available for CityGML through the use of Application Domain Extensions (ADEs). Therefore only CityGML is considered as being suitable for extension in order to provide all the required topographic space information.

This work has produced conceptual models for both semantic topographic space and constraints. These models will be implemented as a CityGML ADE and will be used by routing algorithms for the calculation of shortest/fastest/optimal routes that are possible between a start and an end location. The focus of this work is not on defining user preferences (soft constraints) but instead focuses on defining the physically passable spaces and traversable/movable obstacles (hard constraints). A routing algorithm can then determine the shortest / fastest / optimal / preferred route, considering additional user preferences created independently of the topographic space information.

Indoor route planning is though only one of the three main navigation tasks: determination of position (localisation); determination of best route (route planning); and route tracking (homing) (Becker, T., et al. 2009). For localisation additional information is required to represent sensor spaces (e.g. for WiFi and Bluetooth sensors). Therefore this information must be integrated with topographic space information to support the complete set of indoor navigation tasks. The MLSEM will provide the framework for integrating all available indoor navigation information sources together. The work presented in the paper has identified the use cases, requirements and conceptual models independent to the MLSEM. Future work will need to look at understanding and defining the relationships between an extended CityGML model (implementing the conceptual semantic topographic space and constraint models) and the MLSEM.

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