

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 the semantic and constraint 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.

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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 storey's) for route planning and use in combination with additional sensor information. 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. Real world topographic space features can be described by geographical features with a 3D representation in Euclidean space (Nagel et al., 2008). Currently topographic space information is frequently being provided by building models captured for the purposes of urban / building modelling or information captured to support a single navigation task (e.g. localisation). These current sources of information create a number of potential problems including incomplete/inconsistent capture of required indoor navigation topographic space features, 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 out of use during this scenario and that specific types of partition walls could be removed to allow access. 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 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 indoor navigation topographic space information and the corresponding requirements. Therefore there is a need to improve the understanding of the semantics and constraints required for indoor navigation topographic space, supporting the evaluation of existing models and the extension of existing models, where required. The evaluation of existing building models will provide us with a detailed understanding of the comparable suitability of existing models and the developments required to fully meet these requirements. 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 problem is also complicated by topographic space information being only a sub-part of the information required for full indoor navigation. Sensor space (e.g. WiFi) information must be combined together with topographic space information to for localisation. Therefore the inte-

gration of the extended building model within a flexible indoor navigation framework, the Multilayered Space-Event Model (MLSEM), 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.

In Sect. 2 the use cases and corresponding requirements for modelling 3D indoor navigation topographic spaces are discussed in detail. The requirements then support the assessment of the suitability of existing building, semantic and constraint models. In Sect. 4 our conceptual approach for modelling topographic space objects and constraints with respect to the identified requirements is presented. The implementation of the conceptual models for an existing building model and the integration of this information together with additional information sources within an indoor navigation framework is discussed in Sect. 5. In Sect. 6 we draw conclusions and give an outlook to future work.

2 Topographic Space Requirements for Indoor Navigation

2.1 Indoor Navigation Topographic Space Use Cases

Indoor Navigation is a specific application for building models and provides multiple additional challenges to general-purpose building models. These challenges include variations in: navigation tasks (localisation, route planning and route homing); navigation environments (e.g. airports, train/underground stations, hospitals etc); navigation users (persons/groups with complete / limited / no access to specific secure areas); modes of locomotion (pedestrian on foot, pedestrians in a wheelchair, blind pedestrians, Unmanned Aerial Vehicles (UAVs), ground-based robots etc); and scenarios (off-peak / peak / emergency scenarios).

In order to develop a customised building model suitable for use in indoor navigation, a structured process needs to be developed to capture the uses of topographic space information and the resulting requirements. Use cases can provide this structured mechanism to capture and understand the different ways that an indoor topographic space model would be utilised for indoor navigation. 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 indoor navigation 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 a route to a single known destination considering the parameters of the mode of locomotion, current scen-

ario (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 2.1) to abstract the detailed requirements for an indoor navigation topographic space information model.

	Use Case Title	Example Scenario
1	Route a specific user (e.g. human on foot, human in a wheelchair, UAV, emergency services worker) from a start point to an end point	Route Person A travelling in a wheelchair from Departures Entrance 1 of Berlin Tegel Airport to check in desk B2.
2	Route a user from a start point to an end point 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.
3	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.
4	Route a user within a single room in a specific type of building (e.g. airport or library)	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).
5	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.
6	Route a user between different floors 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.
7	Route a user from outside a building (outdoor position) to a position 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.
8	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.

Table 2.1 Use cases for indoor navigation topographic space information

2.2 *Indoor Navigation Topographic Space Requirements*

From the use cases, defined in section 2.1, the following requirements for indoor navigation topographic space information can be identified:

- **Requirement 1:** An indoor environment 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 6, 7 and 8).
 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 1 and 4).
 Example Scenario: Indoor navigable spaces (e.g. rooms) must be semantically classified and have a geometry so that navigable space can be decomposed 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 5 and 6).
 Example Scenario: All space types will need to be broken down into pre-defined space types for the definition of common constraints (e.g. power-assisted movable door spaces cannot be used in emergency scenarios).
- **Requirement 4:** All spaces belonging to an indoor environment shall be able to be decomposed into smaller space parts (Use cases 2 and 4).
 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 5 and 6).
 Example Scenario: When routing between Room A and Room B on different floors, the floors these rooms are located on is required to support the analysis of whether elevators can be used to travel between these 2 floors.
- **Requirement 7:** All indoor spaces and sub-indoor space parts will be able to be geocoded (relates to use cases 4 and 8).
 Example Scenario: Both room spaces (e.g. a lecture theatre) and POI (e.g. a museum exhibit) must be geocoded to support the searching for these spaces for use as a route start point.

- **Requirement 8:** Storage of semantic information for the function, usage and occupants of an indoor space (relates to use case 5).
 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 5 and 6).
 Example Scenario: When planning a route between 2 rooms, only the spaces that connect together multiple spaces, must be considered in a routing algorithm.
- **Requirement 10:** Specialised types of connecting space with specific semantics shall be used for vertical and horizontal and fixed, assisted and transfer connecting spaces (relates to use cases 6 and 8).
 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.
- **Requirement 11:** Transfer spaces 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 5 and 7).
 Example Scenario: Virtual opening spaces are required when no physical boundaries exist between indoor and outdoor spaces. A virtual opening could define the potential access points into an indoor environment.
- **Requirement 12:** Indoor obstacle spaces should be semantically categorised as fixed, movable and dynamic obstacle spaces, with physical attributes representing the spatial extent, supporting weight, persistency, current state and scenario type (relates to use cases 1, 2 and 4).
 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 semantics defining 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 4).
 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 1, 2 and 4).
 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 representing 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 1, 2 and 5).

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 indoor navigation topographic space models and constraint models against these requirements.

3.1 Building Models

CityGML or Industry Foundation Class (IFC) semantic building models have the potential to provide part or all of the topographic space information required for indoor navigation through semantic enrichment.

3.1.1 CityGML

CityGML is a standard, multi-purpose information model for the representation and exchange of 3D City Models. 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 for the interior of a building (see figure 3.1.1) and is composed of multiple *Room* features, which can be bounded by *BoundarySurfaces*. *Openings* (*Windows* and *Doors*) are represented and related to *BoundarySurfaces*. Immovable and movable objects within a building are also represented by *IntBuildingInstallation* and *BuildingFurniture*, respectively.

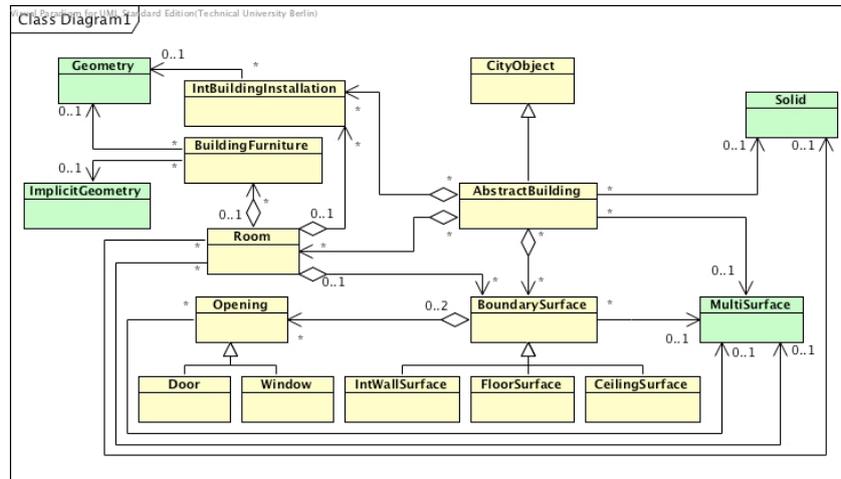


Fig. 3.1.1 Simplified CityGML LOD4 building model

The evaluation of CityGML against the requirements specified in section 2.2, highlighted that CityGML does not fulfil all requirements for the representation of indoor obstacles / non-navigable spaces (requirement 2). 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. 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).

In addition to this CityGML lacked semantic information for required features. Within the CityGML building model a storey feature is not currently included due to high complexities with available modelling approaches. A suitable approach continues to be sought for this problem. The CityGML building model does provide *Opening* classes for *Windows* and *Doors*, limited semantic information is provided, to allow the accessibility between indoor spaces to be determined for differing scenarios.

CityGML lacks semantic information for connecting indoor spaces, including the level of connectivity of a single indoor space and the categorization of different types of connective space (horizontal and vertical and fixed, assisted and transfer spaces), for escalators, elevators etc (requirements 9 and 10).

3.1.2 IFC

IFC was developed as part of the BuildingSMART initiative and has a modular structure for providing detailed semantics for constructive building elements e.g. beams, walls etc. The IFC schema holds around 900 classes, with only a small proportion of these classes being relevant for indoor navigation topographic space.

There is no universally accepted building model for IFC, with work by the IAI and ISO developing an initial IFC building model, as seen in fig. 4.1.2.

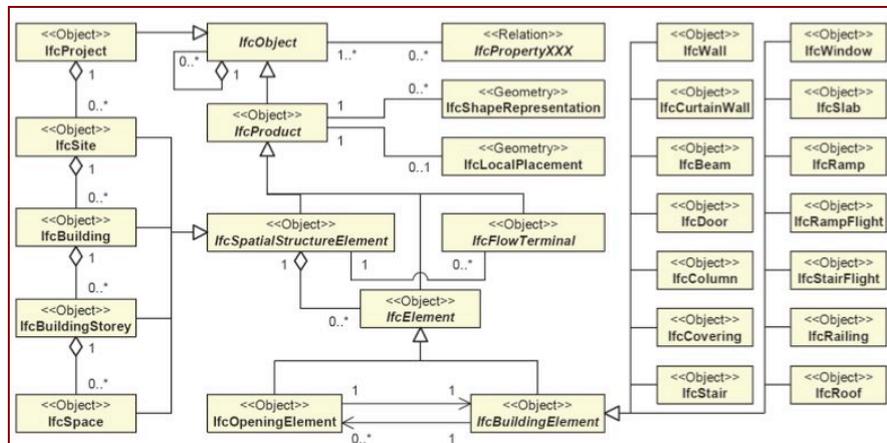


Fig. 3.1.2 Subset of IFC classes relevant for indoor navigation topographic space information

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). All *IFCSpaces* can also be decomposed in parts, where each part defines a partial space. Therefore complex space groups, spaces and partial spaces are all supported (requirement 4). *IFCSpaceType* allows the function of specific spaces to be defined (requirement 8). IFC building models, as with CityGML, lack semantic information for connected indoor spaces, including the level of connectivity of a single indoor space and the differing types of connective space (requirements 9 and 10).

For transition spaces IFC supports the capture and representation of real-world openings (window and door) and can indirectly create virtual openings through the utilization of virtual spaces (*IFCVirtualElement*), that provides imaginary boundaries, e.g. between two adjacent, but not separated, spaces (requirement 11).

IFC has no support for dynamic obstacles (a type of indoor obstacle) and therefore requirement 12 is only partially fulfilled. Detailed semantics are provided for fixed obstacles (*IFCBuildingElements*), as detailed in requirement 13) 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 (requirement 14). *IFCDoor* and *IFCWindow* provide detailed semantics including the opening direction, operation type (e.g. double swing) and operation type, hinge side and construction material. IFC does lack support for

complex topographic space constraints (e.g. defining the directional access permitted through a door for a specific user or the movability of an obstacle in a specific scenario etc), as needed for requirements 12 to 14.

3.1.3 Summary

Both CityGML and IFC were qualitatively evaluated against the requirements specified in section 2.2, with the results shown in table 3.1.3. The table clearly shows that an IFC building model fulfils a larger proportion of the overall requirements than CityGML. The minimal support for fixed obstacles (e.g. walls) and the provision of only a recommendation for the modelling of storeys in CityGML can be summarised as being the main differences between these building models.

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

Table 3.1.3 Evaluation of CityGML and IFC against indoor navigation topographic space requirements (++ requirement fully met, + requirement partially met, and dot requirement not met).

3.2 Semantic Indoor Navigation Topographic Space Models

Semantic models are increasingly being developed to meet the topographic space requirements of indoor navigation. 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. (2008) 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 (more than one entrance/exit) and non-accessible (no entrance/exit) sections (requirements 9 and 10). These sections are bounded 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. The utilisation of a surface representation for non-navigable spaces, as seen for CityGML in section 3.1.3, results in requirements 2 and 4 not being fulfilled.

In Goetz and Zipf (2011) a 3D Building Ontology (3DBO) is introduced for indoor environments. In this ontology the Building object 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), fulfilling requirements. This ontology captures indoor spaces as both rooms and passages, transition spaces as doorways and window spaces and obstacles as fixed and movable barriers. In this model there is no top-level building or storey objects represented and 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 indoor navigation topographic space requirements than the building models evaluated. The modelling and method for integrating constraints in a semantic model was generally lacking in the semantic models evaluated.

3.3 Constraint Models

The analysis of the requirements for indoor navigation topographic space information showed that there is a need to be able to add constraints to topographic space entities. Constraints are used in data modelling to provide a mechanism for refining the semantics/form of an element. A constraint expresses a condition / restriction to which a model element must conform. An example of semantic constraints is the opening direction of a door or the user access permissions for a specific door.

The ISO Geographic Data File (GDF) standard uses constraints when modelling features relevant for outdoor routing. This method and structure (e.g. a layered approach) used for defining constraints in GDF can be evaluated and considered for use in modelling constraints of indoor navigation topographic space information. GDF defines constraints as additional restrictions mandated on the syntax or semantics. Constraints are included in a UML class diagram through text enclosed within brackets. An example constraint is {ordered}, whereby a set of supplied values must be provided in a specific order. Constraints have been implemented in GDF for use with prohibited manoeuvres. A general constraint is defined for prohibited manoeuvres, whereby if a Road Element is the first Road Element in a Restricted Manoeuvre, then it cannot be the first element in a Prohibited Manoeuvre with the same Junction. A similar principal may be able to be applied for uni-directional access through a door space (requirement 15). For specific scenarios additional constraints could be added, e.g. to make a Prohibited Manoeuvre only applicable during a peak temporal period. To create this constraint, Prohibited Manoeuvre could be used in conjunction with the attribute temporal validity period to define changing circumstances through time, similar to 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 a sub-part of this work is relevant as perceptual navigation rules and navigation preference are outside the scope of this work. 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, with rules described through the Semantic Web Rule Language (as needed for requirements 12, 13, 14 and 15). Rules are composed of ‘if antecedents, then consequent’. An example of a possible rule is for excluding Stairways for handicapped 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). The specification and evaluation of these constraints will provide a result. The indoor environment objects can then be filtered for those fulfilling these constraints, before the actual routing navigation process.

To summarise, limited work has been undertaken on understanding the constraints needed for indoor navigation topographic space, hierarchically modelling these conceptual constraints and implementing a method for all constraints to be defined within a standardised data model. In addition to the above-mentioned approaches, limited support for spatial constraints is also implemented in the MLSEM.

4 Indoor Navigation Topographic Space Model

Initial work has started on the conceptual modelling of the topographic space features and constraints needed to fully meet the requirements defined in section 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.

4.1 Conceptual Semantic Model

We define an indoor environment as an abstraction of the collection of all real-world topographic objects being relevant indoor environment components, such as interior walls, doors and rooms. The conceptual modelling of an indoor envi-

environment and its components complies with ISO 19109 and the General Feature Model (GFM) concept.

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 (*IndoorNavigationTopographicSpaceModel*). 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. (2008); Tsetsos et al. (2006); Yang and Worboys (2011); and Goetz and Zipf (2011)), as discussed in section 4.2, to include additional environments (e.g. underground transport systems) to be modelled using the same conceptual model. An *IndoorEnvironment* can be categorised according to the fundamental purpose of the environment (e.g. shopping centre, hospital, transport station) and 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 whereby a CityObjects group could be used to associate all CityObjects belonging to a storey (without the storey being a individual geometric entity) (Groeger et al. (2008)). The constraint of the first approach, that all indoor space must be aggregated to a single storey, results in this approach not being considered at this point in time. Therefore a *Storey* is 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. *IndoorSpaces* 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). An *EndSpace* is a unit of bounded indoor space that only has a single entrance/exit (e.g. an office with a single door entrance). A connector space (*Passage*) has multiple entrance/exits and thus is connecting together multiple indoor spaces (e.g. corridor, elevator, stairs etc.). Similar categorisations are used in existing semantic models (Meijers et al. (2008); 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. (2008); 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 *HorizontalPassages* 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) within an indoor environment (requirement 10). *TransferSpace* is used to capture an object where a user enters a defined space at a known location and then can only leave this space into defined connected spaces. Limited research has been undertaken in the modelling of such spaces for indoor navigation therefore extensive research and testing is required to ensure that this feature is conceptually modelled in a usable way.

An indoor obstacle (*IndoorObstacleSpace*) is any object that can restrict the movement of a user. Within Berlin's main train station obstacles will include ceiling, floor and walls, furniture (e.g. benches), doors and crowds of people. All indoor obstacle spaces are categorised into *FixedObstacleSpace* (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 the *DynamicObstacleSpace* extending the categories defined in these models. There is a need for the surface materials of some *FixedObstacleSpaces* to be defined (e.g. surface material of a floor object is important for wheelchair users). Therefore *IndoorObstacleSpaces* may need to be aggregated to multiple *IndoorObstacleSpaceSurfaces*, with floor surfaces also defined in an existing semantic model (Yang and Worboys (2011)).

A *TransitionSpace* is an opening space providing passage between *IndoorSpaces*. Similar concepts are termed Portal (Yang and Worboys (2011)) and Polygon (Meijers et al. (2008)) but represented significantly differently in other existing semantic models (Tsetsos et al. (2006); and Goetz and Zipf (2011)). At Berlin's main train station *TransitionSpaces* include the door spaces at the main entrance and shop window spaces. *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.

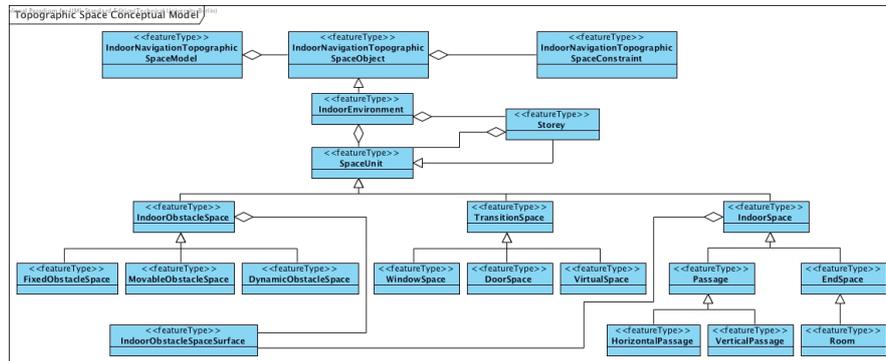


Fig. 4.1 Indoor Navigation Topographic Space Conceptual Model

4.2 Constraints Model

Initial work on the modelling of indoor navigation topographic space constraints follows on from the modelling of indoor navigation topographic space semantics. Topographic space constraints are linked to the topographic space semantic model through the relation of *IndoorNavigationTopographicSpaceConstraints* to *IndoorNavigationTopographicSpaceObject*, shown in fig. 4.1. 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. 4.2.

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. 4.2. *AccessConstraints* allow the access properties to be defined for Door and Window movable space objects. A sub-type of *AccessConstraints* is *Users*, supporting the provision of access permission levels for individual/groups of users. For example staff at the main train station will have different access rights than the general public. 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 enter-only, exit-only or enter-exit access to be defined. *Direction* of access can be combined with other constraints to allow a specific user group to be allowed to have access permissions to pass in one direction through a door. The representation of *AccessConstraints* is discussed in Stoffel et al. (2007) and contributes to requirement 15.

PhysicalConstraints support the determination of the physical usability of *IndoorSpaces*, *IndoorObstacleSpaces* and *TransitionSpaces* for specific types of navigation. 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 a polygon being removed if required, including the removal of a thin glass interior wall during an emergency evacuation scenario. This then links to *State*, which defines whether a fixed or movable indoor obstacle is currently standing (e.g. if a non-persistent wall has already been removed) or open (e.g. a normally locked window that is currently open). Floor surfaces with a specific *SurfaceMaterial* cannot easily be traversed by specific modes of locomotion, including wheelchairs and blind persons, and therefore the surface material needs specifying. *PhysicalConstraints* fulfil requirements 2, 12, 13 and 14.

A scenario type can be specified using the *ScenarioConstraint* and is designed to be used 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. *ScenarioConstraints* are discussed in Stoffel et al., (2007) and contributes to requirements 12 and 15.

In the indoor navigation topographic space model, lists of types of topographic space objects can be used to differentiate between single objects. These space types can also be combined with other constraints to define specific constraints on all indoor topographic space spaces. An example is an electric powered elevator type of elevator being inaccessible to all users in an emergency evacuation scenario. This constraint type supports requirements 3, 8 9 and 15 being met.

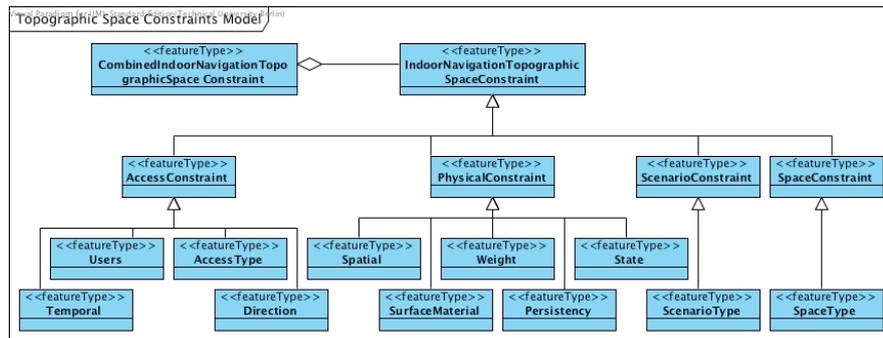


Fig. 4.2 Conceptual model of indoor navigation topographic space constraints

5 Implementation and Integration of Models

Indoor navigation is comprised of the following tasks (Becker, T., et al., 2009a):

1. Determination of position (localisation) – using available sensors to derive the location of a person/object at a specific moment in time.
2. Determination of best route (route planning) – deriving the optimal (i.e. shortest or fastest) route between a start and end position.
3. Route tracking (homing) – comparing the position of a user/object against the planned route and issuing instructions to rectify differences.

Indoor navigation faces multi-factor configuration problems as different localisation techniques, modes of locomotion and logical zones are increasingly being made available and can be combined differently in indoor navigation models (Becker, T., et al., 2009b).

Indoor navigation topographic space information only supports a subset of the navigation tasks (mainly the route planning task). For localisation additional information is required to represent sensor spaces (e.g. for WiFi and Bluetooth sensors). This information must be integrated with topographic space information to support the complete set of indoor navigation tasks.

A Multilayered Space-Event Model (MLSEM) framework has been proposed in order to fully support the three different navigation tasks. Crucial aspects of this framework are the flexibility in integrating multiple space layers (topographic space, sensor space, and logical space) and the clear separation of these space layers. All space layers used in this MLSEM model can be connected in a well-defined and mathematically sound way and used to derive a valid and unique joint state (e.g., between topographic space and sensor space). Based on joint states the proposed MLSEM approach can be utilised to enable localisation and route planning strategies in indoor navigation (Becker et al., 2008).

This framework is highly flexible and allows a range of different information sources to be used for space layers, including both CityGML and IFC for a topographic space layer. When evaluated against the indoor navigation topographic space requirements this model fulfils a number of the requirements as it 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 the semantics and constraints for topographic space need to be provided outside of the MLSEM. Whilst indoor navigation topographic space semantic models have been implemented (section 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 Do-

main Extensions (ADE's). Therefore only CityGML is considered as being suitable for extension in order to provide all the required indoor navigation topographic space information.

The MLSEM overall navigation framework (as detailed in Nagel et al., 2010) is split into a core module and extensions, which have a mandatory dependency on the core. The Indoor Navigation module will provide the 3D topographic space representation of the interior built environment (Becker, T., et al., 2009a) and will use existing data models to provide specialist additions to the generic concepts of the core module. A customised/extended building model would need to be mapped to the MLSEM Indoor Navigation module. Amendments to the MLSEM may be required, to ensure that no topographic space information from the Indoor Navigation module is lost.

7 Conclusions and Outlook

Indoor navigation requires a range of different information be integrated for the tasks of: localisation, route planning; and route homing. Topographic space represents the real-world interior environment of buildings and its semantic decomposition into building elements, but this alone is not sufficient for complete indoor navigation. At the very least sensor information is required to support the localisation of a user within the context of topographic space. Therefore indoor navigation provides an overall requirement for the complete capture of all topographic space features required for indoor navigation and the integration of this information with other information sets (e.g. WiFi sensor information). In this paper we have presented a structured process for defining topographic space requirements, the evaluation of existing topographic space models, a conceptual semantic and constraint model and a proposed method for integrating within a wider indoor navigation framework.

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. These detailed requirements supported the review of existing building models, topographic space semantic models and constraint models. None of the existing models were able to fully meet the requirements identified, with the semantic models capturing a large proportion of the required features but lacking support for the modelling of constraints. For this reason, we present initial work on defining conceptual models containing hierarchical semantic features and constraints. These conceptual models provide hierarchical categorisation of semantic features and constraints and model relationships between these concepts. The need for defining combined constraints is also included in the conceptual constraints model through the inclusion of a combined constraint feature. In addition to this, the separate semantic and constraints hierarchies have been linked, due to the requirement for single/combined constraints to be associated to semantic features. Finally, we have proposed the implementation of a customised/extended CityGML

building model based upon the conceptual semantics and constraints required and the integration of this enhanced building model within the MLSEM to support all tasks of indoor navigation.

Future work will include the development of a CityGML indoor navigation ADE, based upon the semantics and constraint hierarchies required. The developed CityGML ADE will be tested and evaluated against the requirements captured and integrated into the Indoor Navigation module of the MLSEM framework. The Indoor Navigation module will need to be mapped to the Core MLSEM module and the core module evaluated to support all the requirements for topographic space can be supported when this information is combined with additional information sets. This work could provide further requirements for the customisation/extension of the core MLSEM module and thus contribute to the OGC MLSEM standardisation.

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