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OGC® IndoorGML

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Contents

i. Preface

This OGC® standard, called *IndoorGML*, specifies an open data model and XML schema of indoor spatial information. It is an application schema of OGC® GML 3.2.1. While there are several 3D building modelling standards such as CityGML, KLM, and IFC, which deal with interior space of buildings from geometric, cartographic, and semantic viewpoints, IndoorGML intentionally focuses on modelling indoor spaces for navigation purposes.

ii. Submitting organizations

The following organizations submitted this Implementation Specification to the Open Geospatial Consortium Inc.:

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c) Technical University of Munich,

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iv. Revision history

Date	Release	Authors	Paragraph modified	Description
Dec. 11, 2010	Discussion Paper for Indoor Navigation	Claus Nagel, Thomas Becker, Robert Kaden, Ki-Joune Li, Jiyeong Lee, Thomas H. Kolbe		Preliminary Document: Requirements and Space-Event Modeling for Indoor Navigation
June 6, 2012	v.0.1	Jiyeong Lee, Ki-Joune Li, Thomas H. Kolbe, Sisi Zlatanova, Jeremy Morley, Claus Nagel, Robert Kaden		Initial version for draft summary in slide format
Sept. 7, 2012	v.0.2	Jiyeong Lee, Ki-Joune Li, Thomas H. Kolbe, Sisi Zlatanova, Jeremy Morley, Claus Nagel, Robert Kaden		Revised version for draft summary and discussed at teleconference on Sept. 7, 2012
Oct. 9, 2012	v.0.3	Jiyeong Lee, Ki-Joune Li, Thomas H. Kolbe, Sisi Zlatanova, Jeremy Morley, Thomas Becker, Claus Nagel, Robert Kaden		Revised version for draft summary and discussed at Seoul Meeting on Oct. 9, 2012
Jan. 15, 2013	v.0.5	Jiyeong Lee, Ki-Joune Li, Sisi Zlatanova, Thomas H. Kolbe	- navigation module - Deletion of route constraints	Initial version of full draft and discussed at Redland meeting
Jan. 31, 2013	v.0.6.0	Jiyeong Lee, Ki-Joune Li, Sisi Zlatanova, Thomas H. Kolbe	- Data Model: navigation module - XML schema	Revised to reflect the discussion at Redland meeting
Feb. 5, 2013	v.0.6.1, v.0.6.2	Jiyeong Lee, Ki-Joune Li, Sisi Zlatanova, Thomas H. Kolbe	- Data Model - XML Schema	Revised to reflect the teleconference meeting on Jan. 31
Mar. 11, 2013	v.0.6.3	Jiyeong Lee, Ki-Joune Li, Sisi Zlatanova, Jeremy Morley, Thomas H. Kolbe	- Chapter 6, 7, 8, and 9	Revised to reflect the teleconference meeting on Feb. 5 and discussed at Abu Dhabi meeting

Date	Release	Authors	Paragraph modified	Description
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v. Participants in development

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vi. Changes to the OGC® Abstract Specification

The OGC® Abstract Specification does not require changes to accommodate this OGC® standard.

Foreword

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. Open Geospatial Consortium shall not be held responsible for identifying any or all such patent rights. However, to date, no such rights have been claimed or identified.

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This OGC® standard is mainly motivated by the discussion paper "Requirements and Space-Event Modeling for Indoor Navigation", OGC 10-191r1, which addresses the basic requirements and key concepts of IndoorGML. For this reason, many sentences and figures in this standard appear as in the discussion paper.

This OGC 13-0000 document also includes two normative annex in addition to the main part; the XML Schema definition of IndoorGML, and the Abstract Test Suites.

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Introduction

The goal of IndoorGML is to represent and allow for exchange of geoinformation that is required to build and operate indoor navigation systems. Several standards such as CityGML, KML, and IFC have been published to describe 3D geometry and semantics of buildings not only for outdoor space but also indoor space, but they lack of important features, which are required by indoor navigation. This candidate standard aims to provide complementary features of indoor spatial information focused on indoor navigation.

This candidate standard consists of two components; a core data model to describe topological connectivity and different contexts (e.g. topographic space and sensor space) of indoor space, and a data model for navigation in indoor space.

IndoorGML covers geometric and semantic properties of indoor spaces, which are relevant for indoor navigation. These spaces may differ from the spaces described by other standards dealing with indoor environments as CityGML, KML and IFC. To derive the indoor subdivision as defined in IndoorGML, it is recommended to use IndoorGML in combination with these standards. In this respect, IndoorGML is a complementary standard to CityGML and IFC to support location based services for indoor navigation.

OGC® — IndoorGML

1 Scope

This document is an OGC® standard for the representation and exchange of indoor navigation network models, called IndoorGML. It is implemented as an application schema of the Geography Markup Language version 3.2.1.

IndoorGML aims to establish a common schema for indoor navigation applications. It models topology and semantics of indoor spaces, which are needed for the components of navigation networks. However, it contains a minimum set of geometric and semantic modelling of construction components to avoid duplicated efforts with other standards, such as CityGML and IFC.

This OGC® Standard defines the following information about indoor space;

- Navigation context and constraints
- Space subdivisions and types of connectivity between spaces
- Geometric and semantic properties of spaces and connectivity
- Navigation networks (logical and metric) and their relationships

2 Conformance

Conformance targets of this OGC® Standard are IndoorGML instance documents. Conformance with this specification shall be checked whether IndoorGML instance documents achieve the criteria given in clause 7 to 9.

In order to conform to this OGC® standard, IndoorGML document should

a) conform to the rules, specifications, and requirements in clauses 7 to 9,

b) pass all relevant test cases of the abstract test suite given in annex B

3 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this document. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this document are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

ISO 8601:2004, *Data elements and interchange formats – Information interchange –*

Representation of dates and times

ISO/TS 19103:2005, *Geographic Information – Conceptual Schema Language*

ISO 19105:2000, *Geographic information – Conformance and testing*

ISO 19107:2003, *Geographic Information – Spatial Schema*

ISO 19109:2005, Geographic Information – *Rules for Application Schemas*

ISO 19111:2003, Geographic information – *Spatial referencing by coordinates*

ISO 19115:2003, Geographic Information – *Metadata*

ISO/TS 19139:2007, Geographic Information – *Metadata – XML schema implementation*

OpenGIS® Abstract Specification Topic 0, *Overview, OGC document 04-084*

OpenGIS® Abstract Specification Topic 5, *The OpenGIS Feature, OGC document 08-126*

OpenGIS® Abstract Specification Topic 8, *Relations between Features, OGC document 99-108r2*

OpenGIS® Abstract Specification Topic 10, *Feature Collections, OGC document 99-110*

OpenGIS® Geography Markup Language Implementation Specification, *Version 3.2.1, OGC document 07-036*

IETF RFC 2396, *Uniform Resource Identifiers (URI): Generic Syntax*. (August 1998)

W3C XLink, *XML Linking Language (XLink) Version 1.0*. W3C Recommendation (27 June 2001)

W3C XMLName, Namespaces in XML. W3C Recommendation (14 January 1999)

W3C XMLSchema-1, XML Schema Part 1: Structures. W3C Recommendation (2 May 2001)

W3C XMLSchema-2, XML Schema Part 2: Datatypes. W3C Recommendation (2 May 2001)

W3C XPointer, XML Pointer Language (XPointer) Version 1.0. W3C Working Draft (16 August 2002)

W3C XML Base, XML Base, W3C Recommendation (27 June 2001)

W3C XML, Extensible Markup Language (XML) 1.0 (Second Edition), W3C Recommendation (6 October 2000)

4 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

4.1 Indoor Space

A space within one or multiple buildings consisting of architectural components.

4.2 Coordinates Space

A space where location is identified by (x, y) or (x, y, z) coordinates where $x, y,$ and z are real values.

4.3 Cellular Space and Symbolic Space

A space where location is identified by a cell identifier (or symbolic code).

4.4 NR (Node-Relation) Graph

A graph (V, E) where V is a set of nodes representing cells in indoor space and E is the set of edges indicating the topological relationship between two cells, which may be connectivity or adjacency.

4.5 Connectivity NRG

A NR graph (V, E) where V is a set of nodes representing cells in indoor space and E is the set of edges indicating the connectivity.

4.6 Adjacency NRG

A NR graph (V, E) where V is a set of nodes representing cells in indoor space and E is the set of edges indicating the adjacency relationship.

4.7 Accessibility NRG

A NR graph (V, E) where V is a set of nodes representing cells in indoor space and E is the set of edges indicating the accessibility relationship.

4.8 Logical NRG

A NR graph (V, E), where node v in V and edge e in E do not contain any geometric properties.

4.9 Geometric NRG

A NR graph (V, E) where node v in V and edge e in E contain geometric properties.

4.10 Multi-Layered Space Model

A space represented by multiple layers of connectivity graphs and inter-layer connections between two nodes from different layers.

5 Conventions

5.1 Symbols (and abbreviated terms)

The following symbols and abbreviated are used in this standard;

CityGML	City Geographic Markup Language
GPS	Global Positioning Systems
CRS	Coordinate Reference System
IndoorGML	Indoor Geographic Markup Language
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
KML	Keyhole Markup Language
MLSM	Multi-Layered Space Model
NRG	Node-Relation Structure
OGC	Open Geospatial Consortium
UML	Unified Modeling Language
XML	eXtended Markup Language
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional
B-Rep	Boundary Representation

5.2 UML Notation

The diagrams that appear in this standard are presented using the Unified Modeling Language (UML) static structure diagram. The UML notations used in this standard are described in the diagram below.

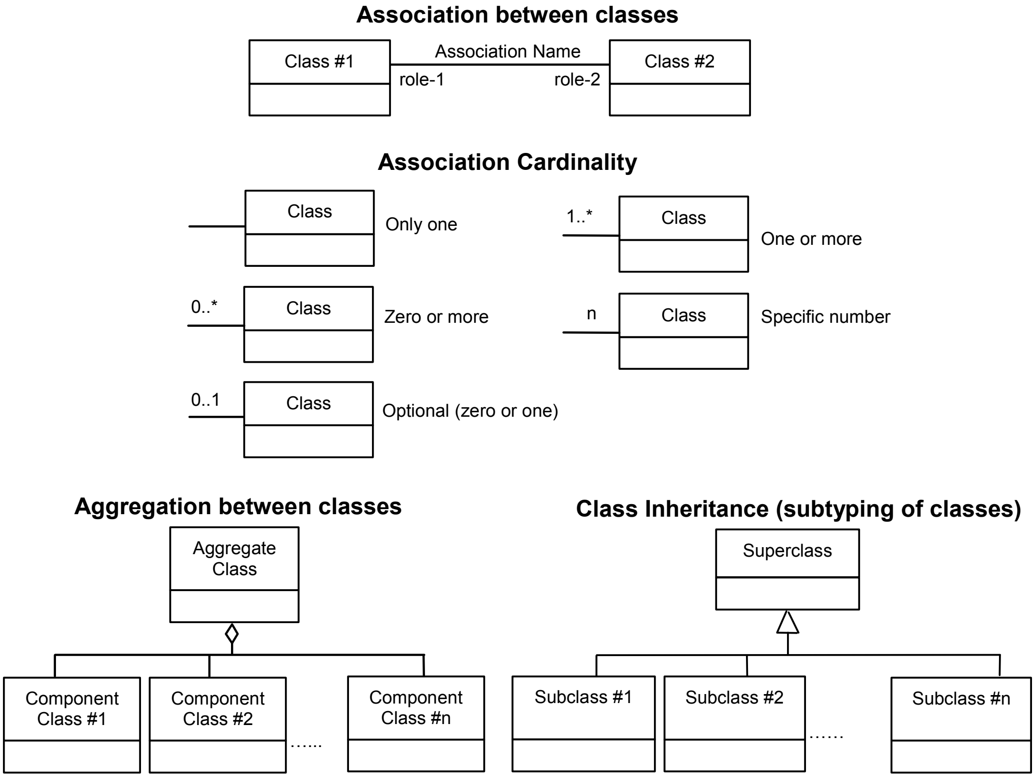


Figure 1: UML notation

In this standard, the following three stereotypes of UML classes are used:

a) <<Interface>> A definition of a set of operations that is supported by objects having this interface. An Interface class cannot contain any attributes.

b) <<DataType>> A descriptor of a set of values that lack identity (independent existence and the possibility of side effects). A DataType is a class with no operations whose primary purpose is to hold the information.

c) <<CodeList>> is a flexible enumeration that uses string values for expressing a list of potential values.

In this standard, the following standard data types are used:

a) CharacterString – A sequence of characters

b) Integer – An integer number

c) Double – A double precision floating point number

d) Float – A single precision floating point number

6 Overview of IndoorGML

6.1 Motivations

Indoor space differs from outdoor space in many aspects. Basic concepts, data models, and standards of spatial information should be redefined to meet the requirements of indoor spatial applications. The requirements of indoor spatial information are differently specified according to the types of applications. In general, the applications of indoor spatial information are classified into two categories as follows;

- Management of building components and indoor facilities, and
- Usage of indoor space.

Building construction and management and facility management belong to the first category. While the main focus of the first category are on building components such as roofs and walls, the second category is focused on usage and localization of features (stationary or mobile) in indoor space. The indoor spatial information of the second category is to represent spatial components such as rooms and corridors, and constraints such as doors. For example, indoor location-based services, indoor route analysis or indoor geo-tagging services belong to the second category.

The goal of this standard is therefore to define a framework of indoor spatial information to locate stationary or mobile features in indoor space and to provide spatial information services referring their positions in indoor space, instead of representing building architectural components. IndoorGML is intended to provide the following functions;

- Representing the properties of indoor space, and
- Providing spatial reference of features in indoor space.

Note that the IndoorGML version 1 is based on the requirements from indoor navigation due to strong and urgent standardization demands, such as indoor LBS, routing services, and emergency control in indoor space. We expect that other requirements including indoor facility management will be handled by the next version of IndoorGML.

7 General characteristics of IndoorGML

7.1 Representation of Indoor Objects in IndoorGML

An important difference of indoor space from outdoor is that an indoor space is composed of complicated constraints such as corridors, doors, stairs, elevators, etc., like a road network space is composed of road constraints. It means that proper representations of indoor constraints are key issues of indoor spatial information modelling and standards. In IndoorGML, indoor constraints are considered from the following aspects;

- Cellular space
- Semantic representation
- Geometric representation
- Topological representation

- Multi-Layered Representation

7.1.1 Definition of Indoor Space

Indoor space is defined as space within one or multiple buildings consisting of architectural components such as entrances, corridors, rooms, doors, and stairs. In IndoorGML, we are not concerned about architectural components themselves (e.g. roofs, ceilings, walls) but the spaces (e.g. rooms, corridors, stairs) made by architectural components, where objects can be located and navigate, and the relationships between spaces. And the components irrelevant to describe the spaces, such as furniture are not within the scope of IndoorGML.

While an indoor space may be given within a single building, it can be also given by multiple buildings or complex. It is not necessarily covered by roof, and for example an inner court or veranda can belong to an indoor space.

7.1.2 Cellular notion of space and cells

One of the difference of IndoorGML from previous standards such as IFC dealing with building interior space is that it does not provide standard for representing architectural components but standard for indoor space. For this reason, we consider an indoor space as a set of *cells*, which are defined as the smallest organizational or structural unit of indoor space [xx-Wordnet, Princeton University, 2010, http://wordnet.princeton.edu]. A cellular space S is defined as follows;

$S = \{c_1, c_2, \dots, c_n\}$, where c_i is i^{th} cell.

Cellular space has important properties. First, every cell has an identifier (namely c.ID) such room number. Second, each cell may have common boundary with others but does not overlap with other cells. Third, postion in cellular space can be specified by cell identifier, although we may employ (x, y, z) coordinates to specify a position for more precise location.

While a set of cells is the minimum information to determine a cellular space, additional information can be also included in cellular space as follows;

- semantics: e.g. classification and interpretation of cells
- geometry: e.g. solid in 3D or surface in 2D
- topology: e.g. adjacency or connectivity

7.1.3 Semantic Modelling of Indoor Space

Semantic is an important characteristic of cells. The Indoor space can be decomposed into different cells if differet criteria are considered. The cell subdivision can represent the topography (contruction) of a building, or the the available wifi coverages, or indicate security areas or public/office areas, etc. Every cell is then given a semantics with respect to the semantics used to the space subdivision. For example, in a topographic space it is possible to have *'room', 'door', 'window',* in wifi space - '*wifi point A', 'wifi point B', etc. and* in a security space - '*check-in area*', '*boarding area', 'crew areas'.*

In IndoorGML, semantics is used for two purposes: to provide classification and to identify a cell and determines the connectivity between cells. Semantics allows to define cells which can be of importance for navigation. For example, the most commonly used classification of cells in topolographic space is into navigable (rooms, corridors, doors) and non-navigable (walls, obstacles) cells.

Cells can be organised in a hierarchical structure according to their semantics, corresponding properties and semantic interrelations (specialisation and generalisation). For example 'room' is a specialisation of 'navigable cell' and 'non-navigable cell' is a generalisation of 'walls' and 'obstacles'. Cells created for one space represenation may be aggregated or subdivided for the purpose of another one. For example, in security space 'check-in area' cell can be an aggregation of several 'room' cells, which have been created for the topography space.

The connectivity, in terms of possibility to navigate through cells, is largely derived from the semantics of cells. For example to be able to go from one room to another, it should be known that at least one common opening (door, window) cell is available, which is between the two rooms.

The properties of a semantically identified cell have impact on the connectivity and can act as a navigation constraint. For example, certain doors might provide access in one direction only (emergency exits), or forbid access to a specific group of users (security areas) or allow access according to specific time intervals (e.g. shops).

IndoorGML allows different space representation to be integrated via the concept of Multi-Layered Space Representation (see 7.1.6).

7.1.4 Geometric Representation of Indoor Space

Every cell of indoor space, such as room or corridor, owns a form, extension and position that can be collected and modelled. Even though this geometric information can be modelled by other standards, it can be included in IndoorGML in several ways. In order to represent geometry of cell, we assume 3D or 2D Euclidean spaces in IndoorGML. Using the concepts of Euclidean space, the geometry provides the means for the quantitative description of the spatial characteristics of cell, where a metric space is defined as [18].

ISO19107 (Spatial Schema) [1] provides conceptual schemas to describe and model real world objects as features, where cells in indoor space are a kind of features. The included geometry package contains various classes for coordinate geometry used in IndoorGML. The mathematical functions which are used for describing the geometry of a cell depend on the type of coordinate reference system which is used to define the spatial position.

The geometric representation of 2D or 3D feature in indoor space does not belong to the major focus of IndoorGML, since they are clearly defined by ISO 19107, CityGML, and IFC. However, for the sake of self-completeness, the geometry of 2D or 3D object may be optionally defined within IndoorGML according the data model defined by ISO 19107. There are three options to represent the geometry of a cell in indoor space as illustrated in Figure 2;

1. External Reference (Option 1): Instead of explicit representation of geometry in IndoorGML, an IndoorGML document only contains external links (namely *c*.xlink, where *c* is a cell in IndoorGML) to objects defined in other data sets such as CityGML, where the referenced objects in external data set include geometric information. Then there must be 1:1 or *n*:1 mappings from cells in IndoorGML to corresponding objects in other dataset.
2. Geometry in IndoorGML (Option 2): Geometric representation of cell (namely *c*.geom, where *c* is a cell in IndoorGML) may be included within an IndoorGML document. It is GM_Solid in 3D space and GM_Surface in 2D space as defined in ISO 19107. Note that solid with holes or surface with holes are allowed in this standard.
3. No Geometry (Option 3): No geometric information is included in IndoorGML document.

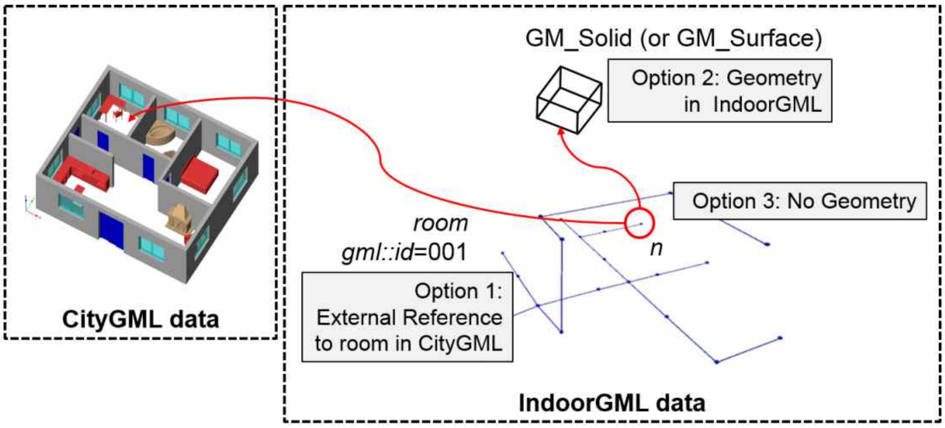


Figure 2: Three options to represent geometry in IndoorGML

When IndoorGML is independently used without combining with CityGML or IFC, it may contain the full 3D geometry of feature as defined in ISO 19107 but it can also include only a 2D footprint. When it is used with CityGML or IFC, it is recommended to make a reference to the geometry defined in CityGML or IFC. Note that these options are not exclusive. For example, while IndoorGML document contain external references to the corresponding objects in CityGML, it also contains geometries of features by either the second or the third option. However, the second and third options are apparently exclusive.

7.1.5 Network Representation of Cellular Space

Topology is an essential component of cellular space and IndoorGML. A natural topology such as neighbourhood, interior, disjoint and boundary may be induced from geometry in Euclidean space. However topological properties are not implicitly included in cellular space and we need to explicitly describe the topological relationship in IndoorGML.

The Node-Relation Graph (NRG) [25] represents topological relationships, e.g., adjacency and connectivity, among indoor objects. The NRG allows abstracting, simplifying, and representing topological relationships among 3D spaces in indoor environments, such as rooms within a building. It can be implemented as a graph representing the adjacency, connectivity relationships without geometrical properties. It enables the efficient implementation of complex computational problems within indoor navigation and routing systems.

The Poincaré duality [8] provides a theoretical background for mapping indoor space to NRG representing topological relationships. A given indoor space can be transformed into a NRG in topology space using the Poincaré duality. It simplifies the complex spatial relationships between 3D by a combinatorial (or logical) topological network model [25]. According to Poincaré duality, a *k*-dimensional object in *N*-dimensional primal space is mapped to (*N*-k) dimensional object in dual space. Thus solid 3D objects in 3D primal space, e.g., rooms within a building, are mapped to nodes (0D object) in dual space. 2D surfaces shared by two solid objects is transformed into an edge (1D) linking two nodes in dual space. The nodes and edges in dual space form an adjacency graph, where the nodes and the edges of dual space represent cells and *adjacency relationships* between cells in primal space, respectively. Figure 3-a and Figure 3-b illustrate this duality transformation. Note that Figure 3-a and Figure 3-b indicates the cases where the primal space is 3D and 2D respectively.

The adjacency graph G_{adj} is defined as follows;

$G_{adj} = (V, E_{adj})$, where V and E_{adj} are sets of nodes and edges in dual space mapped from cells and surfaces in 3D primal space, respectively.

Once adjacency relationships between cells are determined by Poincaré duality, other topological relationships can be defined from adjacency relationships based semantic information. An example of adjacency relationships in dual space is depicted by Figure 4. Figure 4-a shows a primal space with three cells including exterior cell (EXT), and boundaries between cells and the corresponding adjacency graph in dual space is given in Figure 4-b. Adjacency graph of dual space serves as a basic topological graph, since other topological graphs can be derived from the adjacency graph.

While no semantic information is used to generate adjacency graph in Figure 4, a

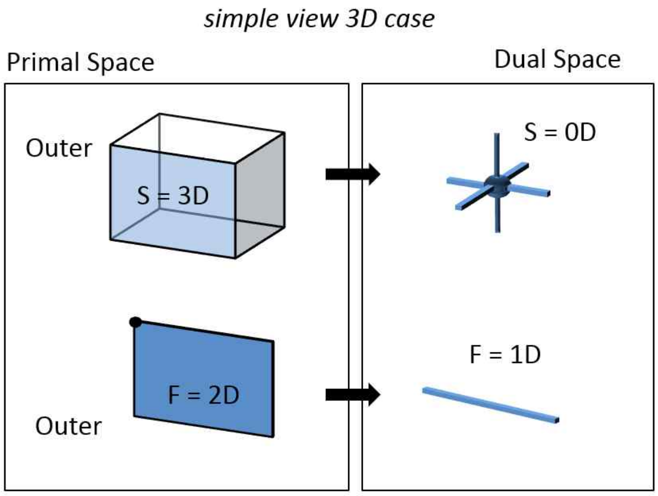


Figure 3-a: 3D Primal space case

different graph can be derived from adjacency graph by using semantic information. In Figure 5, boundaries are classified into walls and doors, then the graph in Figure 4-b becomes a different graph, called *connectivity graph*, which represents connectivity between cells as shown in Figure 5. Among adjacency relationships between cells in Figure 4-b, the edge of doors are included in the graph, while walls are removed from the graph since walls are not navigable. In a similar way, we may derive *accessibility graph* from adjacency graph by using constraint information as shown in Figure 6. If there is a constraint that the width of door `D1` is 1.2 meters, then cell `R1` is not accessible to tables bigger than 1.2 meters via door `D1` and the accessibility graph becomes as Figure 8.

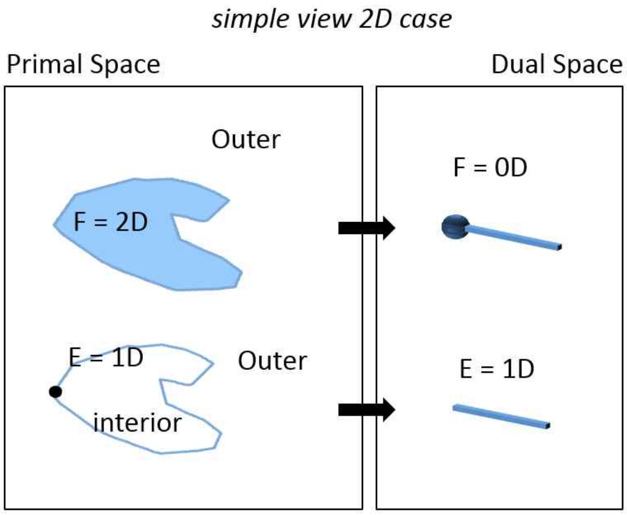


Figure 3-b: 2D Primal space case

Figure 3: Principles of Poincaré duality as shown by Lee [21]
(mathematical definition of Poincaré duality in [8])

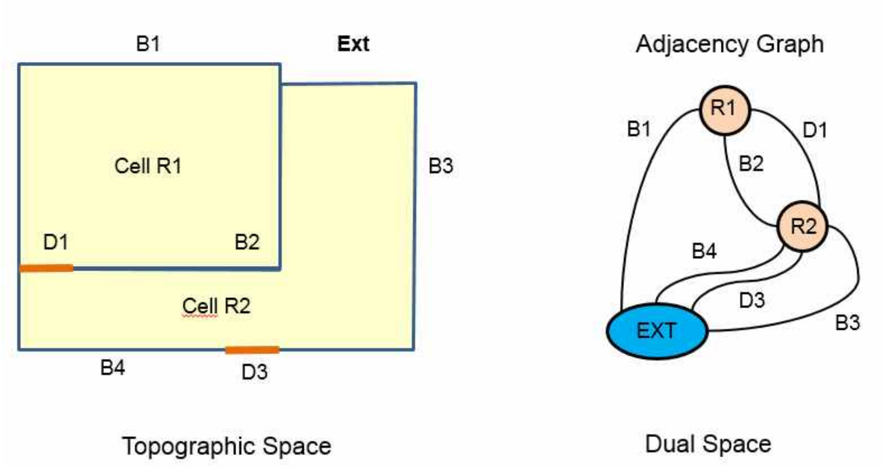


Figure 4-a. Primal space Figure 4-b. Adjacency graph in dual space

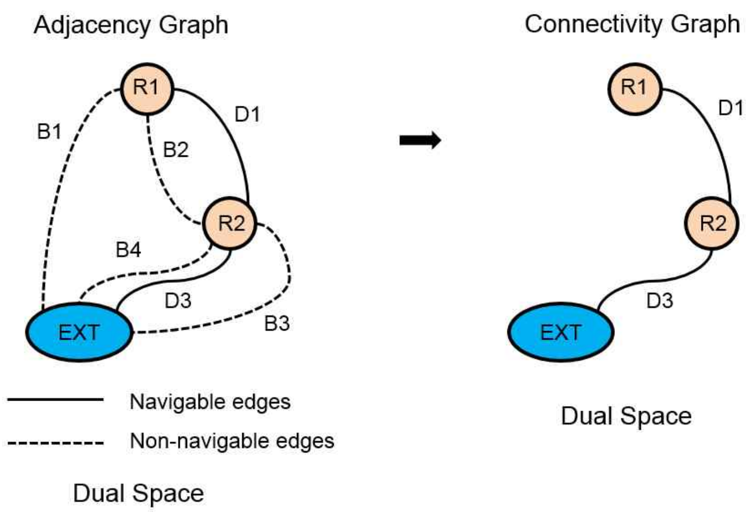


Figure 5: Derivation of connectivity graph from adjacency graph

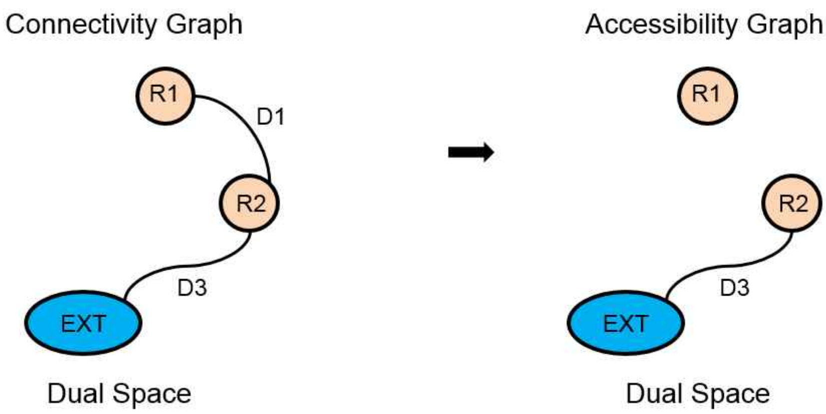


Figure 6: Derivation of accessibility graph

Connectivity graph G_{con} and accessibility graph G_{acc} are defined in similar ways as follows;

$G_{con} = (V, E_{con})$, where V is a set of nodes in dual space mapped from cells in 3D primal space and E_{con} is a set of edges representing connectivity between cells in primal space. Note that $E_{con} \subset E_{adj}$.

$G_{acc} = (V, E_{acc})$, where V is a set of nodes in dual space mapped from cells in 3D primal space and E_{acc} is a set of edges representing accessibility between cells in primal space. Note that $E_{acc} \subset E_{adj}$.

The walls and doors in the primal space are represented as boundaries in Figure 4-a, and they are accordingly mapped to edges in dual space as depicted in Figure 4-b. However, walls and doors may be also represented as cells with certain thickness depending on applications as shown in Figure 7. We call this representation *thick wall model* and the representation in Figure 4 is called *thin* (or *paper*) *wall model*. Then the NRG in dual space should be differently constructed as shown in Figure 7, where walls and doors are mapped to nodes of dual space.

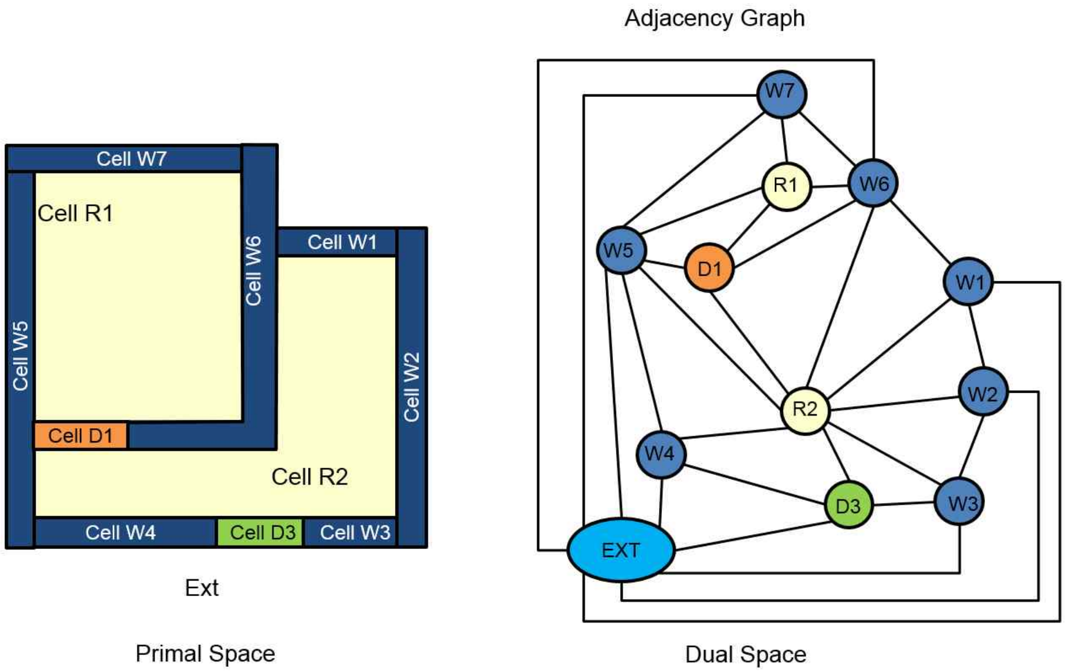


Figure 7: Adjacency graph for thick wall model

While the nodes and edges in NRG of previous examples have no geometric properties, we may embed basic geometric data to nodes and edges such that each node has point coordinates and edge has also the coordinates of starting, ending, and intermediate vertices. We call this geometrically embedded graph *geometric NRG*, while NRG without any geometric properties is called *logical NRG*. In geometric NRG, the geometries of node and edges are defined as GM_Point and GM_Curve of ISO 19107.

7.1.6 Multi-Layered Space Representation

A single indoor space is often semantically interpreted into different cellular spaces. For example, an indoor space is represented as a topographic cellular space composed of rooms, corridors, and stairs, while it is also represented as different cellular spaces with WiFi coverage cells and RFID sensor coverage cells respectively as shown in Figure 8. For this reason, IndoorGML supports multiple representation layers with different cellular spaces for an indoor space. Each semantic interpretation layer results in a different decomposition of the same indoor space, where each decomposition forms a separate layer of cellular space as shown in Figure 8.

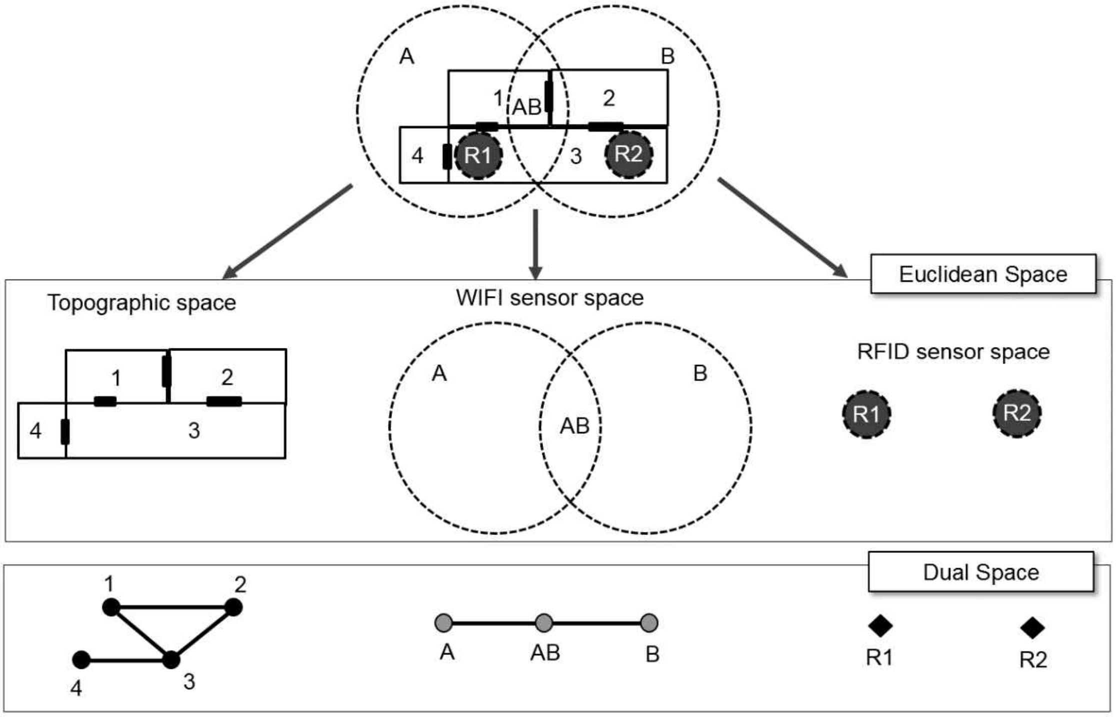


Figure 8: Example - Multiple Layered Space Representation

As shown in Figure 8, an indoor space is interpreted by three semantic representations – Topographic space layer, WIFI sensor space layer, and RFID sensor space. Since they are semantically different in terms of wheelchair movement, each layer forms a different cellular space and derived NRG for dual space.

This representation method with multiple cellular space layers is called *Multiple Layered Space Representation* (MLS Representation). The MLS representation is useful for many purposes. For example, we can represent hierarchical structure of indoor space by MLS representation, where each level is represented as a single space layer and the relationships between two hierarchical levels are represented by inter-layer edges, which will be explained in section 7.3. Another application example of MLS representation is indoor tracking with presence sensors such as RFID. Given an indoor space represented as topographic cellular space layer and RFID sensor coverage layer respectively, we can deduce the movement of a mobile object with RFID tag by the sequence of RFID coverage cells and corresponding inter-layer space edges.

7.2 Structured Space Model

IndoorGML is based on two conceptual frameworks namely *Structured Space Model* and *Multi-Layered Space Model* (MLSM). The Structured Space Model defines the general layout of each space layer independent from the specific space model which it represents. Each layer is systematically subdivided into four segments (see Figure 9).

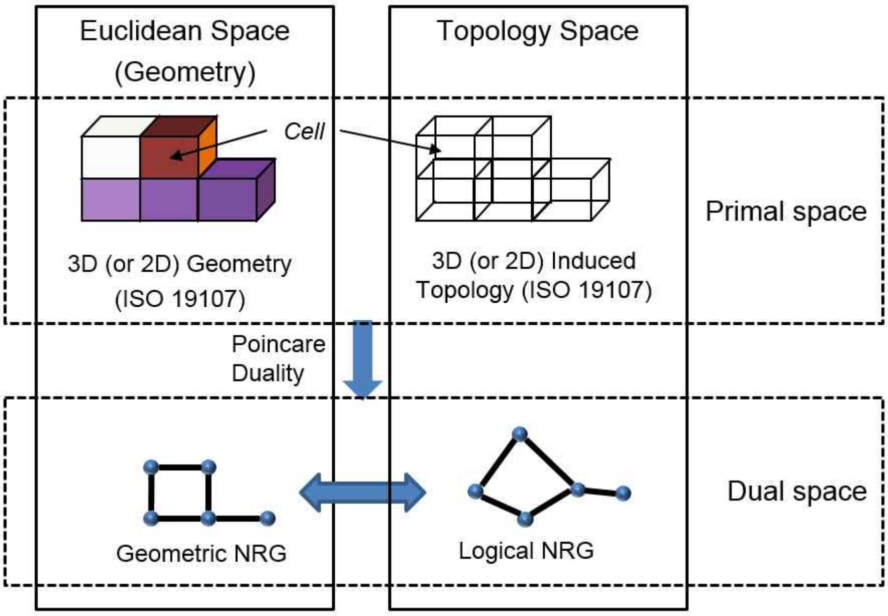


Figure 9 — Structure Space Model

Figure 10 illustrates the structured space model that allows for the distinct separation of primal space from dual space on the one hand, and geometry and pure topology on the other hand. This structure forms the basis for the framework proposed indoor space model.

The upper and the lower part of Figure 10 follows the rules of ISO 19107 for modelling geometrical features of real world phenomena, but the transition from primal to dual space cannot be modelled or described via the ISO standard. And topological relationships in IndoorGML such as adjacency and connectivity are not defined by means of the topology in ISO 19107 but by explicit associations within the IndoorGML data model.

In the Structured Space Model, topological relationships between 3D (or 2D) spatial objects are represented within topology space (i.e., the lower part of Figure 9). By applying a duality transformation, the 3D cells in primal space are mapped to nodes (0D) in dual space. The topological adjacency relationships between 3D cells are transformed to edges (1D) linking pairs of nodes in dual space. Furthermore, the node of NRG is called *state* and the edge of NRG is called *transition.* The active state is represented by a node within the NRG and denotes the spatial area where the guided object is currently located. Once the object moves into a topologically connected area, another node within the NRG and thus a new active state is reached. The edge connecting both nodes represents the event of this state transition. The NRG representing topological relationships among 3D spatial objects in topological space is a logical *NRG*, while the NRG embedded to Euclidean IR^3 space is a geometric *NRG* as seen Figure 9.

The UML diagram depicted in Figure 10 shows the data model for the Structured Space Model. A SpaceLayer represents a separate interpretation and a decomposition layer explained in section 7.1.6 and it is composed of States and Transitions which represent nodes and edges of NRG for dual space, respectively. The NRG and state-transition diagram for each layer are realized by SpaceLayer. Note that the current version of IndoorGML supports logical NRG and geometric NRG for dual space.

As mentioned above, NRG as part of the Structured Space Model is implemented in IndoorGML model. In dual space, the logical NRG in the lower right part of structured space model as seen in Figure 9 represents topological relationships among spaces in topological space, which is described as the cardinality of State and Transition to *Geometry* classes is 0 in Figure 10. When the cardinality is 1 in Figure 10, the topological model is implemented by coordinate space embedding of NRG (Geometric NRG), which is in the lower left part of structured space model as seen in Figure 9.

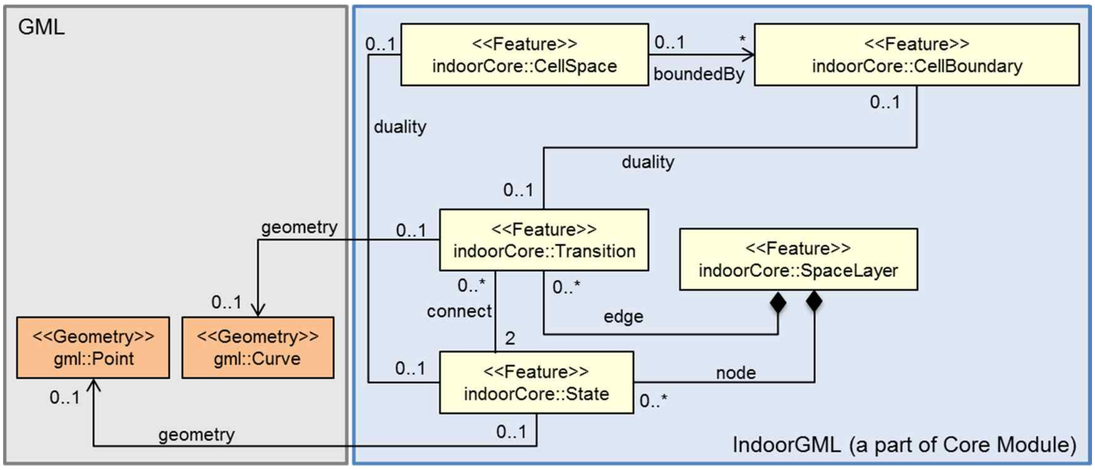


Figure 10: Implementation of Structure Space Model in IndoorGML

7.3 Multi-Layered Space Model

The concept of Structure Space model is further extended to *Multi-Layered Space Model* (MLSM). Multi-Layered Space Model provides an approach for combining multiple space structures for different interpretations and decomposition layers to support full indoor information services.

7.3.1 Multi-Layered Space Model – Key Concepts

A same indoor space is often differently interpreted depending on application requirements as discussed in section 7.1.6. It results in different decompositions of a same indoor space, and each decomposition results in a NRG. For example, the layers for topographic space layer, WIFI sensor space layer, and RFID sensor space of Figure 8 form independent structured spaces and each layer results in three separate NRGs as depicted in Figure 11.

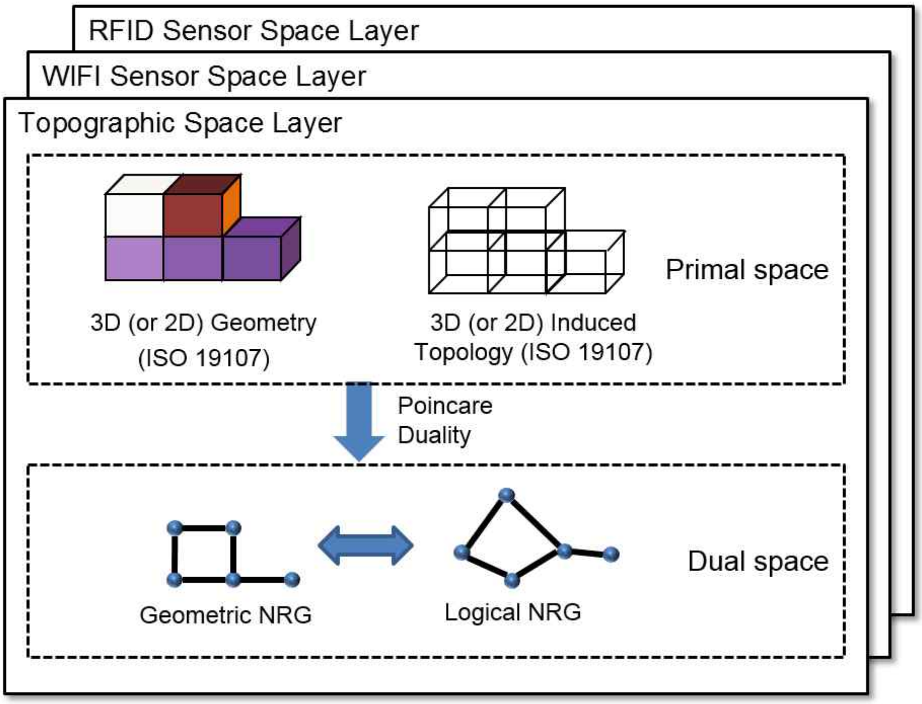


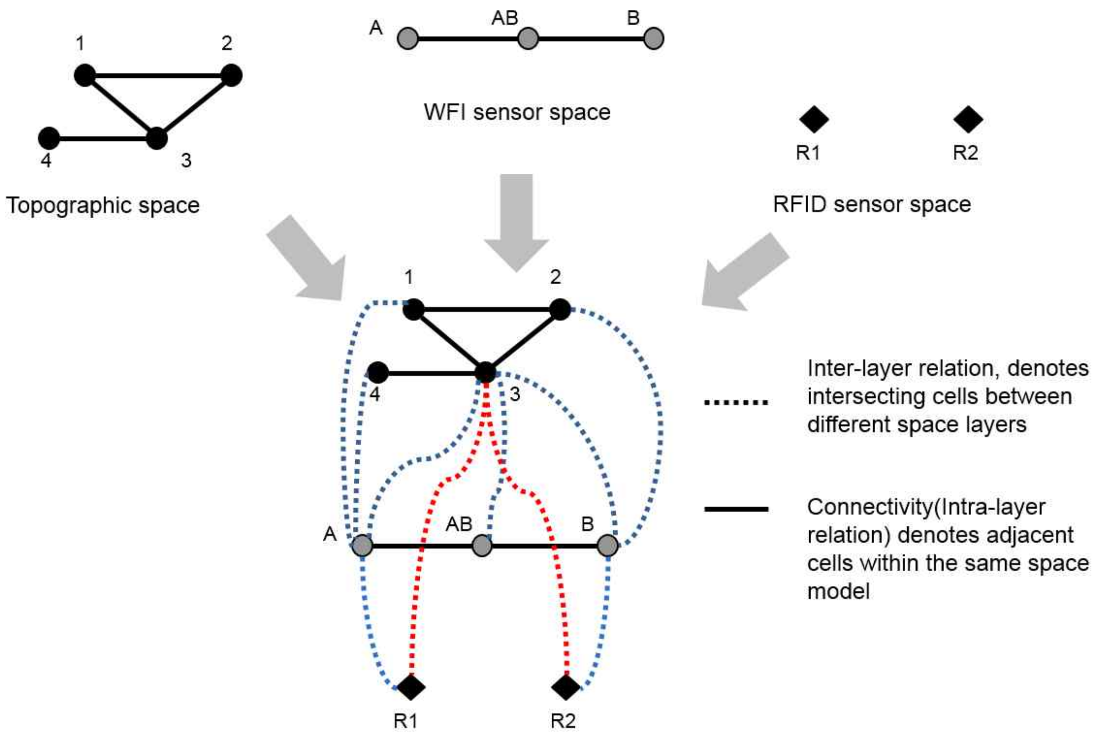
Figure 11: Multi-Layer combination of alternative space concepts

There may be several interpretations of a same indoor space. In most cases, topographic space layer composed of geospatial features in indoor space such as rooms, corridors, staircases, and lift shafts are of the most important layer. For indoor positioning purposes, sensor space layer is also a fundamental one, where the notion of sensor space substantially differs from topographic space. The sensor space is rather decomposed according to signal characteristics such as propagation and signal coverage areas depending on different localization techniques such as Wi-Fi or RFID which differ in signal propagation and signal coverage. There are other possible interpretations, and the number of layers is generally unbounded and any definition for space (e.g., security space, movement space, activity space, visual space etc.) can be given for a semantic modelling of indoor space, where each of them is defined in its own layer.

7.3.2 Inter-Layer Relations

Layers of multi-layered space model can be connected by inter-layer relations. As illustrated in Figure 10, there are three space layers, where each layer constitutes a NRG. In a topographic layer, the nodes represent the possible states of a navigating object and correspond to cells with volumetric extent in primal space (e.g. rooms) while the edges represent state transitions, i.e., the movement of an object from one space to another. They correspond to connectivity relations between the cells in primal space (e.g., neighboured rooms connected with a door). In the sensor space, NRG has a slightly different structure. The nodes represent again the cells with volumetric extend (e.g. the entire coverage space of a WIFI transmitter), while the edges represent the transition from one space to another based on the neighbouring WIFI coverage spaces. Since the layers cover the same real world space, the separated dual graphs can be combined into a multi-layered graph. Figure 12 illustrates overlaid space layers.

Figure 12: Overlaid space layers in dual space



If we assume that each space model, whether it is for topographic or sensor space, is based upon a non-overlapping partitioning of space, a navigating object can only belong to one cell at a time and thus always only one state may be active. Therefore, an object is at any given time exactly in one cell (named *state*) in each layer simultaneously. This overall state is thereby denoted by the combination of active states from all space layers.

However, only specific combinations of states from different layers are valid and can be active at the same time. The combinations are expressed by additional edges linking the nodes between different layers. These so called *joint edges* are derived by pairwise intersecting the cell geometries from different layers. A joint edge between two such nodes is inserted if the intersection of the interior of the two corresponding cells is non-empty. Therefore, the joint edges represent all relationships according to the eight relation model except "disjoint" and "touch" between two cells from different space layers defined in [14] and thus denote *inter-layer relationships*. Figure 13 illustrates the dual graphs of three space layers together with their inter-layer relationships.

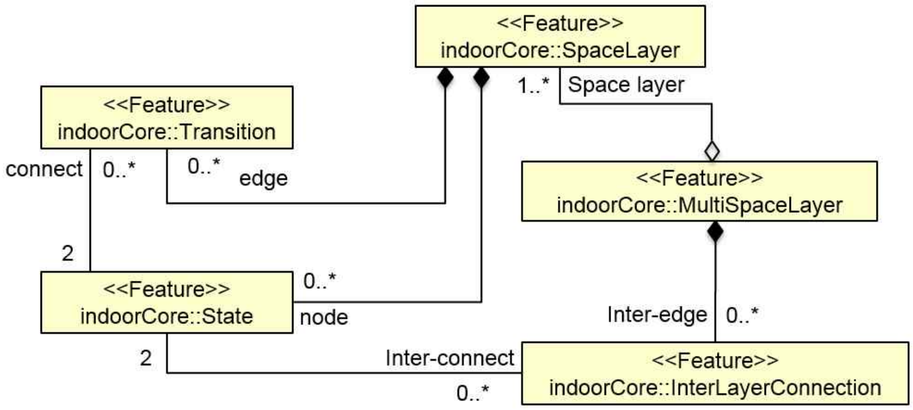


Figure 13: Implementation of Multi-Layer Space Model in IndoorGML

In IndoorGML, the space model for multi-layered space representation, called *multi-layered space model*, is implemented by MultiSpaceLayer class. MultiLayeredGraph consists of SpaceLayers and InterLayerConnections as shown as Figure 13, while SpaceLayer represents each space layer (e.g. topographic space layer, sensor space layer, etc.) and it forms a NRG composed of objects from State and Transition. The inter-layer relationships are implemented by InterLayerConnection class. In Figure 12, {(1,A,Within), (4,A,Within), (3,A,Overlaps), (3,AB,Overlaps), (3,B,Overlaps), (2,B, Within), (A,R1,Contains), (B,R2,Contains), (3,R1,Contains), (3,R2,Contains)} are the set of instances from InterLayerConnection class, where each instance represents the relationship between two cells of different space layers of Figure 8. The MultiSpaceLayer is an aggregation of SpaceLayer and InterLayerConnection.

7.4 External reference

Since the main focus of IndoorGML is on the notion of cellular space and topological representation, it may not contain geometries and detail semantic information of indoor features. Instead, IndoorGML provides a method to reference to an object in external dataset such as CityGML or IFC. Depending on application areas, indoor features may have different geometric and semantic representation models. For example, indoor spaces are often represented by grid model in robotic domain. By separating domain specific representation model from IndoorGML and providing external reference, a high level of flexibility can be achieved.

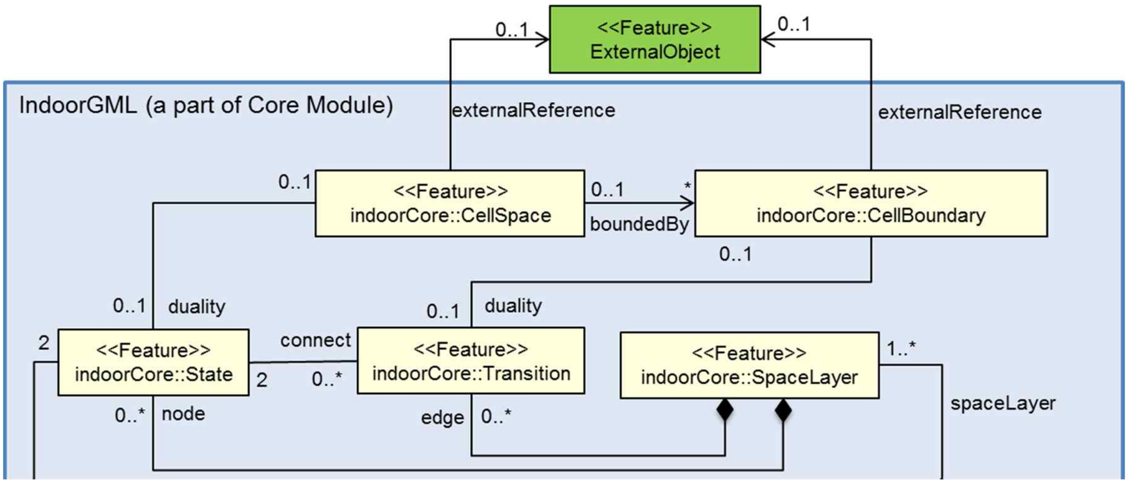


Figure 14: External References in IndoorGML

CellSpace and CellBoundarySpace of IndoorGML core module depicted in Figure 18 may have external references to corresponding objects in external data sets. Note that the external reference is optional and can have at most one target object as shown by the cardinality in Figure 14.

Figure 15-(a) and Figure 15-(b) illustrate examples of external references to CityGML LoD 4 and SensorML respectively. For example, regarding to topography space layer, the subclasses of NavigableSpace can have an external reference to CityGML objects. The GeneralSpace has an external reference to bldg::Room of CityGML and the AnchorSpace and ConnectionSpace refer to bldg::Door in CityGML. bldg::BoundarySurface in CityGML is also referred by NavigableBoundary. Regarding to sensor space layer, all of subclasses of the NavigableSpace class also can have an external reference to sml::Component as shown in Figure 15-(b) which includes all the location and interface properties of any physical process. Note that NavigableSpace, AnchorSpace, and ConnectionSpace belong to IndoorGML navigation module, which will be explained in section 8.

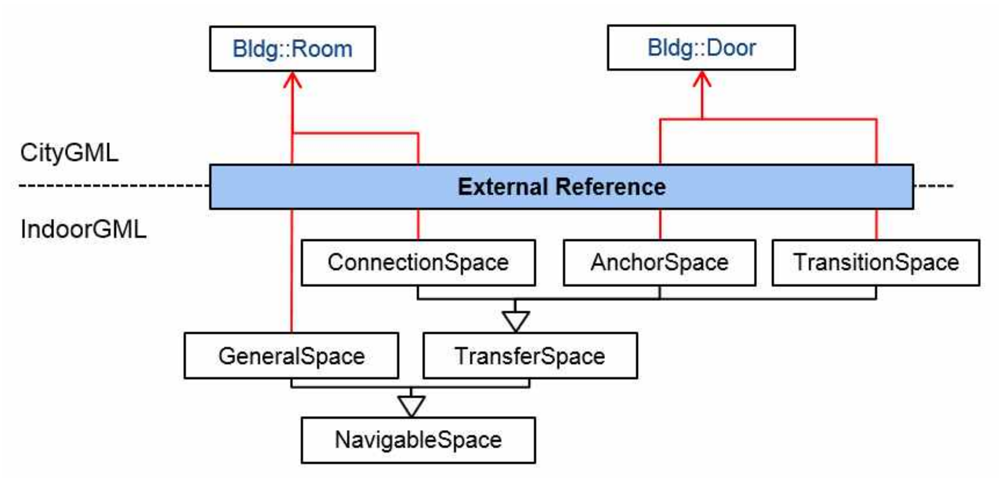


Figure 15-(a): External references to CityGML

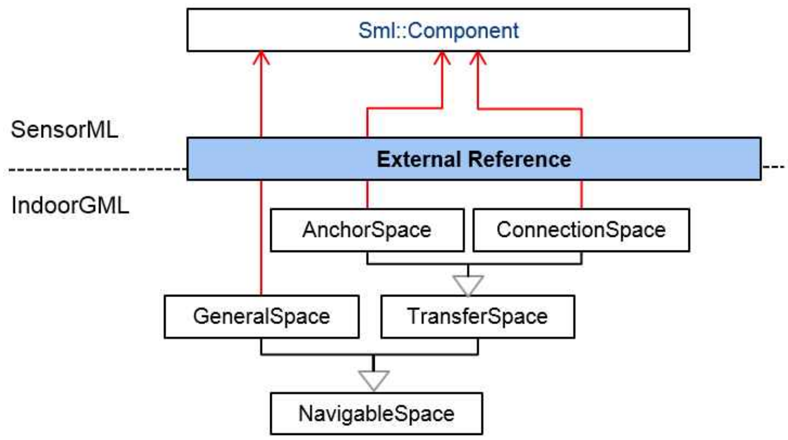


Figure 15-(b): External references to SensorML

7.5 Connection between Indoor and Outdoor Spaces

Connecting indoor and outdoor spaces is an important requirement of indoor spatial information. IndoorGML provides the concept to connect indoor and outdoor spaces by introducing additional topology between indoor and outdoor spaces. Every indoor space contains at least one entrance, and it can be used to connect indoor and outdoor spaces. In IndoorGML, entrance is represented as a special node of topological graph in indoor space, connecting indoor and outdoor as shown in Figure 16. We call it *anchor node*, which differs from other node in topological graph, since it may include additional information for converting indoor CRS to outdoor absolute CRS.

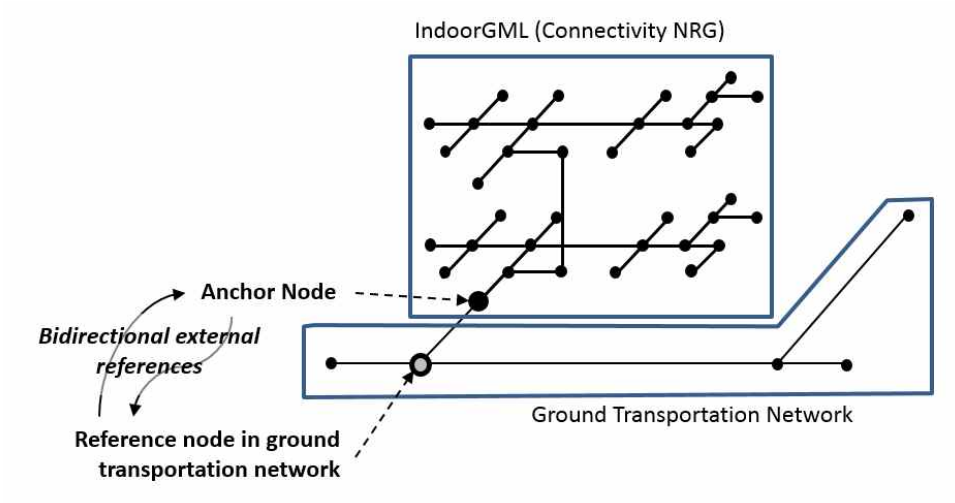


Figure 16: Anchor Node Connecting Indoor and Outdoor Networks [27]

Anchor node contains attributes to support the seamless conversion between indoor and outdoor spaces.

1. External reference to outdoor transportation network: Anchor node includes an external reference to a node in ground transportation network, which is connected to the anchor node as shown in Figure 16. Note that the relationship betwteen anchor node and nodes in outdoor ground transportation is bidirectional. The anchor nodes are not only defined within IndoorGML document but also accessible from external data set such as ourdoor ground transportation network. For example, when a vehicle is entering to a building, we can get the IndoorGML document of the building via the external reference from the node in the ground transportation network.

2. Conversion parameters: In many cases, a relative CRS is applied to an indoor space and it is necessary to convert the coordinates of each point of indoor geometry according to the outdoor absolute CRS. Anchor node therefore contains the parameters for transformation;

   - rotation origin point (x_0, y_0, z_0)
   - rotation angles (α, β, γ, along x, y, and z-axis),
   - rescaling factor (s_x, s_y, s_z), and
   - translation vector (t_x, t_y, t_z).

In cases where absolute CRS is used for indoor space, the conversion parameters are not necessary. However anchor nodes are still useful not only for representing the connectivity between indoor and outdoor spaces but also facilitating seamless services for example by including the URI of radio map of the building for WiFi indoor positioning.

7.6 Subspacing

Indoor space has often hierarchical structures and a careful decomposition of an indoor space is required in many cases to reflect hierarchical structures. A feature such as corridor or hall may be divided to accurately represent the geometric properties of indoor space based on the connectivity relationships among space objects. IndoorGML supports hierarchical subspacing by Multi-Layered Space Model explained in section 7.3.

The subspacing by the first option is explained in Figure 17. In the case of corridor of Figure 17-(a), node n_6 in the NRG representing a corridor within the indoor space (Figure 17-(a), Figure 17-(b)) is considered as a consolidated *Master Node*, which is transformed to a sub-graph preserving connectivity relationship among the compartmentalized spaces of the corridor (Figure 17-(c)). It means that node n_6 in the original NRG is converted into $n_{6\text{-}1}$ and $n_{6\text{-}2}$ and edge e_1 in Figure 17-(c)) in the transformed NRG, which is a sub-graph representing a two-dimensional shape such as a hallway.

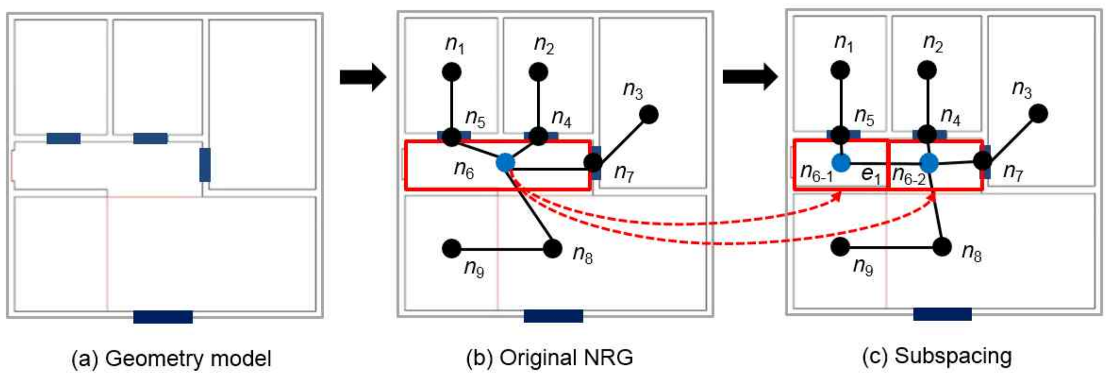


Figure 17: Example of subspacing – Connectivity NRG

IndoorGML supports the subspacing by means of multi-layered space model to reflect hierarchical structure of indoor space as shown in Figure 18. The NRG G_1 is the original graph layer with node n_6, while G_2 is a transformed graph layer with partitioned nodes $n_{6\text{-}1}$ and $n_{6\text{-}2}$. Then the hierarchical structure is represented by means of inter-layer connection of the multi-layered space model. Note that there are default one-to-one inter-layer connection between $G_1.n_k$, $G_2.n_k$ except n_6 as shown in Figure 18.

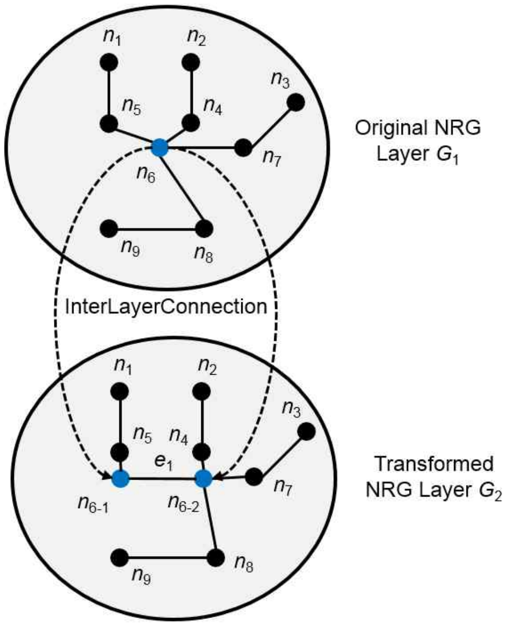


Figure 18: Multi-layered space model for subspacing

In the case where hierarchical subspacing is not required, we may simply replace a space with subdivided spaces and describe the adjacency or connectivity relationships between subdivided spaces. For example in Figure 17, we just replace n_6 with $n_{6\text{-}1}$, and $n_{6\text{-}2}$ and append edges connecting them.

7.7 Modularization

According to the OGC's policy "The Specification Model — A Standard for Modular specifications [15]", the overall IndoorGML is split into a core module and extensions which have a mandatory dependency on the core. Therefore, the IndoorGML data model is thematically decomposed into a core module and thematic extension modules (see Figure 20). The core module comprises the basic concept and each extension module covers a specific thematic field such as navigation applications (e.g. pedestrians, wheel-chair, and robot). Each IndoorGML module is specified by an XML Schema definition file and is defined within an individual and globally unique XML target namespace. According to dependency relationships among modules, each module may, in addition, import namespaces associated to such related IndoorGML modules.

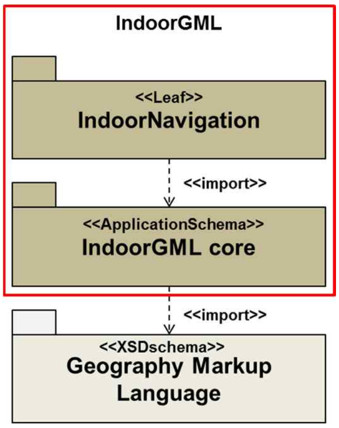


Figure 19: UML Package diagram

The IndoorGML core module defines the basic concepts and component of the IndoorGML data model. While the aspects explained in section 7.1 except semantic modelling are reflected into the core module, extension modules comprise the semantic modelling aspect (see section 7.1.3) of IndoorGML. Based on the IndoorGML core module, the extension module contains a logically separate thematic component of the IndoorGML data model. IndoorGML introduces the first thematic extension module, called *IndoorNavigation* module.

The dependency relationships among IndoorGML's modules are illustrated in Figure 19 using an UML package diagram. Each module is represented by a package. The package name corresponds to the module name. A dash arrow in the figure indicates that the schema at the tail of the arrow depends upon the schema at the head of the arrow. For IndoorGML modules, a dependency occurs where one schema <import>s other schema and accordingly the corresponding XML namespace. In the following sections the modules are described in detail.

8 IndoorGML Core Module for the Multi-Layered Space Model

In the precedent section, we have discussed the basic concepts and overall data model of IndoorGML. In the subsequent sections, we present the detail data model and XML schemas to realize the concepts discussed in section 7. The UML diagram depicted in Figure 20 shows the data model for the IndoorGML core module based on the multi-layered space model. The data model defines the classes and relations needed to describe the geometric and topological representations of each space layer in primal and dual spaces presented in section 7. The XML Schema for this data model is also defined as an application schema of GML 3.2.1. (see also Annex A)

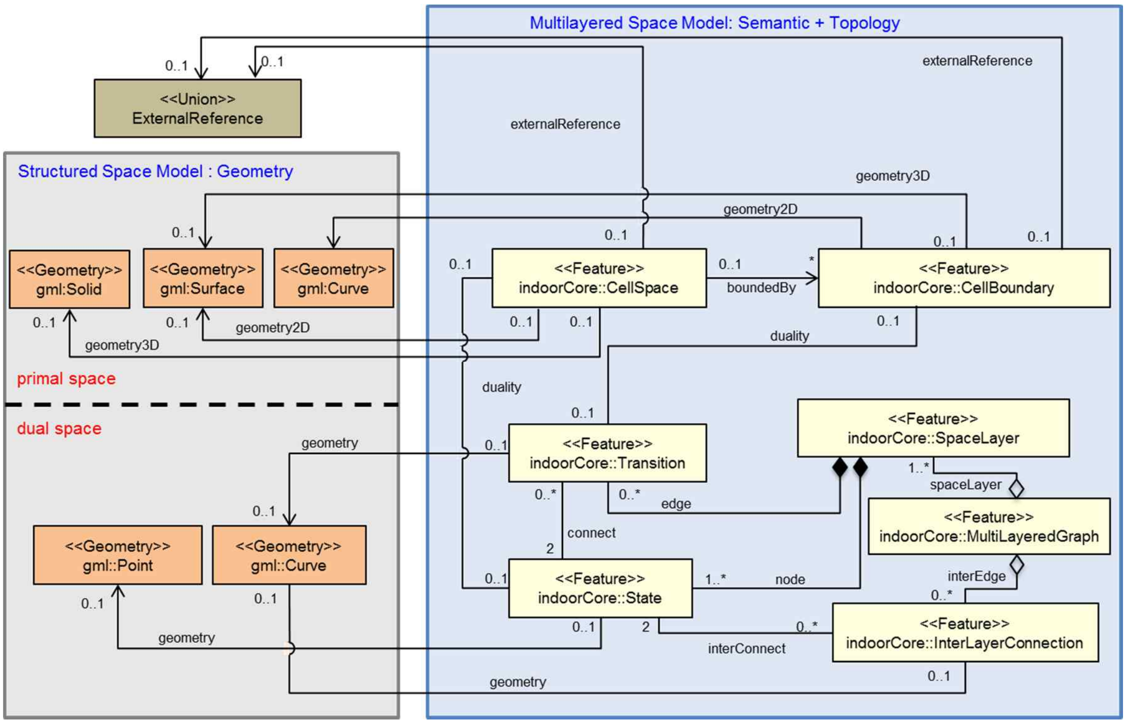


Figure 20: UML diagram of Multi-layered Space Model
(based on ISO19100 standards family and GML3.2.1)

The classes in Figure 20 are arranged according to the Structured Space Model explained in section 7.2 (cf. Figure 9). For each layer, its geometry and topology representations are modeled in primal and dual spaces based upon ISO 19107.

Some classes (CellSpace, CellSpaceBoundary) in IndoorGML may have a geometric object that is represented in 2D or 3D spaces. The classes CellSpace and CellSpaceBoundary represent real world objects in accordance with the notions of geographic features defined by ISO19109. A CellSpace is a semantic class corresponding to one space object in Euclidean primal space of one layer. Accordingly, a CellSpaceBoundary is used to semantically describe the boundary of each space object. Both classes are defined as interface classes which connect the Multi-layered Space Model to exterial geometric models.

According to the dimension of space, the CellSpace class is represented as gml:Solid or gml:Surface and CellSpaceBoundary class is represented as gml:Surface or gml:Curve in 3D or 2D space, respectively. In other words, when is represented on a 2 dimensional space, the CellSpace mapped on gml:Surface. If CellSpace is represented in the three dimensional space, it mapped on gml:Solid.

The separate layers of the Multi-layered Space Model are represented by the class SpaceLayer. A layer aggregates State and Transition objects. SpaceLayer can be connected through the InterLayerConnection class which represents a gml:Curve in Euclidean space connecting two states from separate layers. The inter-layer connections

(InterLayerConnection) together with in intra-layer connections (State and Transition) finally generate the MultiLayeredGraph.

The IndoorGML core module defines the basic concepts and components of the multi-layered space model. The multi-layered space model allows for the coherent combination of different decompositions of space according to different semantics. A decomposition of space is represented by a separate space layer which is systematically subdivided into primal and dual space on the one hand and geometry and topology on the other hand. The multi-layered space model is generally considered as a conceptual framework for the generic representation of space and their topological relationships. Especially, the IndoorGML core module provides to represent the topological relationships of indoor spaces in dual space.

The UML diagram of IndoorGML's core module is depicted in Figure 21, for XML schema definition see blow and annex A. The multi-layered space model consists of 7 classes; State, Transition, CellSpace, CellSpaceBoundary, InterLayerConnection, SpaceLayer, and MultilayeredGraph class.

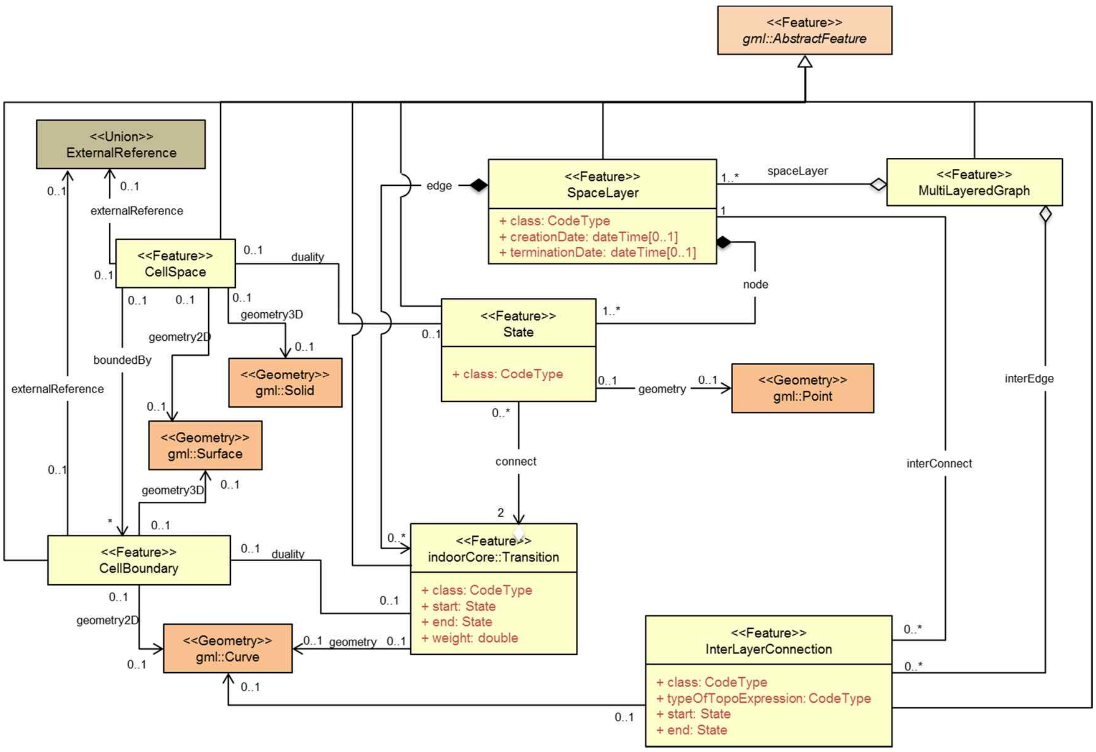


Figure 21: UML diagram of IndoorGML's core module(Multi-Layered Space Model)

The XML namespace of the IndoorGML core module is identified by the Uniform Resource Identifier (URI) *****. Within the XML Schema definition of the core module, this URI is also used to identify the default namespace.

8.1 <State>

State represents a node in dual space of MLSM. Within the topographic space layer, a space can be associated with a room, corridor, door, etc. within a building of the primal space. It is represented geometrically as Point in IndoorGML. It also has association with the corresponding CellSpace class which represents a space in primal space (or referred to a geometry object in primal space). The attribute duality – which can only occur once – represents association with the CellSpace. The connect relation describes the relationships among States on one layer (the same layer), while the attribute interConnects describes the relationships between States on different layers. For the geometrical representation of a State, a Point geometric primitive object defeined in the GML is used.

```
<xs:element name="State" type="StateType" substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>
Within the dual graph structure of one layer a node in dual space represents a space (e.g. a room within a building) in primal space
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="StateType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="duality" type="CellSpaceType" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="connects" type="TransitionPropertyType" minOccurs="0"
maxOccurs="unbounded"/>
                    <xs:element name="interConnects" type="InterLayerConnectionPropertyType" minOccurs="0"
maxOccurs="unbounded"/>
                    <xs:element name="geometry" type="gml:PointPropertyType" minOccurs="0" maxOccurs="1"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="StatePropertyType">
        <xs:sequence>
            <xs:element ref="State"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="StateMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="1">
                    <xs:element ref="State"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

8.2 <Transition>

Within a dual graph structure of one layer, Transition is an edge that represents the adjacency or connectivity relationships among nodes representing space objects in primal space. Transition always connects two States. In the topographic space layer, a Transition can be associated with a boundary of a room in the primary space. The attributes start and end represent States that are boundary objects of Transition. The attribute duality represents an association relation with CellSpaceBoundary class. The attribute weight can be used for applications in order to deal with the impedance representing absolute barriers in transportation problems. For the geometrical representation of a Transition, a Curve geometric primitive object from the GML is used.

```
<xs:element name="Transition" type="TransitionType">
        <xs:annotation>
            <xs:documentation>Transition </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="TransitionType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="weight" type="xs:double"/>
                    <xs:element name="from" type="StatePropertyType"/>
                    <xs:element name="to" type="StatePropertyType"/>
                    <xs:element name="duality" type="CellSpaceBoundaryPropertyType" minOccurs="0"
maxOccurs="1"/>
                    <xs:element name="geometry" type="gml:CurvePropertyType" minOccurs="0" maxOccurs="1"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="TransitionPropertyType">
        <xs:sequence>
            <xs:element ref="Transition"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="TransitionMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="Transition"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

8.3 <CellSpace>

CellSpace is a base class for representing the indoor space. The class CellSpace contains properties for space attributes and purely geometric representations of space. CellSpace also has references to thematic objects in external data sources; the geometrical representation in primal Euclidean space is referenced by xlink. The attribute externalReference is used for the reference of an object to its corresponding object in an external data set. Each CellSpace is associated with a geometry object which can be represented as several geometry primitive types.

```
<!-- ====================================================================== -->
    <xs:element name="CellSpace" type="CellSpaceType" abstract="true"
substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>
                CellSpace
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="CellSpaceType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:group ref="CellSpaceGeometry" minOccurs="0"/>
                    <xs:element name="duality" type="StatePropertyType" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="externalReference" type="ExternalReferenceType" minOccurs="0"
maxOccurs="unbounded"/>
                    <xs:element name="boundedBy" type="CellSpaceBoundaryPropertyType" minOccurs="0"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="CellSpacePropertyType">
        <xs:sequence>
            <xs:element ref="CellSpace"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:group name="CellSpaceGeometry">
        <xs:choice>
            <xs:element name="Geometry3D" type="gml:SolidPropertyType"/>
            <xs:element name="Geometry2D" type="gml:SurfacePropertyType"/>
        </xs:choice>
    </xs:group>
    <!-- ====================================================================== -->
    <xs:complexType name="CellSpaceMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="CellSpace"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

8.4 <CellSpaceBoundary>

CellSpaceBoundary is used to semantically describe the boundary of each geographical feature in space. The geometry of the CellSpaceBoundary normally will be described by a Surface geometric object in 3D Models. The attribute externalReference is used for the reference of a geometric object to its corresponding object in an external data set. Each CellSpaceBoundary is associated with a geometry primitive object which can be represented as gml:Surface or gml:Curve.

```
<xs:element name="CellSpaceBoundary" type="CellSpaceBoundaryType"
substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation> CellSpaceBoundary
        </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="CellSpaceBoundaryType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="duality" type="TransitionPropertyType" minOccurs="0" maxOccurs="1"/>
                    <xs:group ref="CellSpaceBoundaryGeometry" minOccurs="0"/>
                    <xs:element name="externalReference" type="ExternalReferenceType" minOccurs="0"
maxOccurs="unbounded"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:group name="CellSpaceBoundaryGeometry">
        <xs:choice>
            <xs:element name="geometry3D" type="gml:SurfacePropertyType"/>
            <xs:element name="geometry2D" type="gml:CurvePropertyType"/>
        </xs:choice>
    </xs:group>
    <!-- ====================================================================== -->
    <xs:complexType name="CellSpaceBoundaryPropertyType">
        <xs:sequence>
            <xs:element ref="CellSpaceBoundary"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="CellSpaceBoundaryMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="CellSpaceBoundary"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

8.5 <SpaceLayer>

SpaceLayer class is a top class to represent a structured space model. A SpaceLayer represents each space layers such as topography, sensor, security space, etc. A SpaceLayer aggregates State and Transition which are directly associated with the corresponding geometry classes to represent dual space. To represent spatial objects in primal space, a SpaceLayer also aggregates CellSpace and CellSpaceBoundary which are directly associated with the corresponding geometry classes. The SpaceLayer class has attributes which are class, function and usage. The attribute class – which can only occur once - represents a general classification of the layer. With the function and usage attributes, norminal and real functions of a space layer can be described.

The creationDate and terminationDate attributes can be used to describe the chronology of the layer. The points of time refer to real world times.

The SpaceLayer class has nodes and edges which represent a set of States and Transitions on the layer.

Figure 22 depicted an example of topographic space layer. Each space in real world mapping to State and the relationship between spatial objects is represented by Transition in a dual space of topographic space layer.

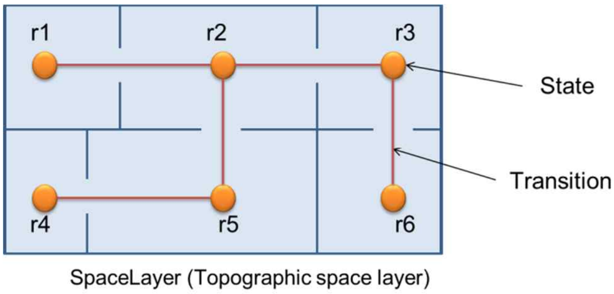


Figure 22: Example of *SpaceLayer* (Topographic space layer)

```
<xs:element name="SpaceLayer" type="SpaceLayerType" substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>;SpaceLayer represent various space concepts such as topography, sensor, security, etc. A SpaceLayer aggregates  State and Transition which are directly associated with the corresponding geometry classes.</xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="SpaceLayerType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="usage" type="gml:CodeType" minOccurs="0" maxOccurs="unbounded"/>
                    <xs:element name="terminationDate" type="xs:dateTime" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="function" type="gml:CodeType" minOccurs="0" maxOccurs="unbounded"/>
                    <xs:element name="creationDate" type="xs:dateTime" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="class" type="SpaceLayerClassTypeType" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="nodes" type="StateMemberType" minOccurs="1" maxOccurs="unbounded"/>
```

```
                <xs:element name="edges" type="TransitionMemberType" minOccurs="0"
maxOccurs="unbounded"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
    <!-- ====================================================================== -->
<xs:complexType name="SpaceLayerMemberType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureMemberType">
            <xs:sequence minOccurs="1">
                <xs:element ref="SpaceLayer"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
```

8.6 <InterLayerConnection>

InterLayerConnection class has two States. Each State is included in different SpaceLayers. Intersecting the geometries of the layer combinations provides an edge if the intersection of their interior geometries is non-empty; the edge, called InterLayerConnection, may express one of following spatial relationships: contains, overlaps, or equals. InterLayerConnection is denoted relationships between States in different SpaceLayers. The start and end attributes are States which are related with each other. The typeOfTopoExpression attribute represents a relationship between two layers. The one layer contains start and the other layer contains end. The comment attribute can contain an additional description for the InterLayerConnection.

```
<xs:element name="InterLayerConnection" type="InterLayerConnectionType"
substitutionGroup="gml:AbstractFeature">
    <xs:annotation>
        <xs:documentation>Denotin the interspace connections between the SpaceLayer
        </xs:documentation>
    </xs:annotation>
</xs:element>
<!-- ====================================================================== -->
<xs:complexType name="InterLayerConnectionType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureType">
            <xs:sequence>
                <xs:element name="typeOfTopoExpression" type="typeOfTopoExpressionCodeType"/>
                <xs:element name="comment" type="xs:string"/>
                <xs:element name="start" type="StatePropertyType"/>
                <xs:element name="end" type="StatePropertyType"/>
                <xs:element name="geometry" type="gml:CurvePropertyType" minOccurs="0" maxOccurs="1"/>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- ====================================================================== -->
<xs:complexType name="InterLayerConnectionPropertyType">
    <xs:sequence>
```

```
            <xs:element ref="InterLayerConnection"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ====================================================================== -->
    <xs:complexType name="InterLayerConnectionMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="InterLayerConnection"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

8.7 <MultilayeredGraph>

MutliLayeredGraph is a root element of IndoorGML Core Module to represent the Multi-layered Space Model. It aggregates SpaceLayers and InterLayerConnections. The overall classes of IndoorGML core module constitutes a MultiLayeredGraph, where all the nodes (States) from all *n* layers (SpaceLayers) are included but they are separated into *n* partitions which are connected by the Transition. Furthermore the graph also contains the state-transition edge (InterLayerConnection). The MultiLayeredGraph contains a set of SpaceLayer as spaceLayers and a set of InterLayerConnection as interEdges.

```
<xs:element name="MultiLayeredGraph" type="MultiLayeredGraphType" substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>The overall structure of the Multilayered Space Model constitutes a multilayered graph,
where all the nodes from all n layers are included but are separated into n partitions which are connected by the inter-
layer connections. Furthermore the graph also contains the state transition edges (intra-space connections)
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="MultiLayeredGraphType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="spaceLayers" type="SpaceLayerMemberType" minOccurs="1"
maxOccurs="unbounded"/>
                    <xs:element name="interEdges" type="InterLayerConnectionMemberType" minOccurs="0"
maxOccurs="unbounded"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

8.8 Requirements for conformance

This clause specifies the conformance requirements for the IndoorGML Core Module. Although most of conformance requiremens are already presented in the model and XML schema of the IndoorGML Core Module, and certain complementary conformance requirements are explicitly given in this clause;

1. The dimensions of CellSpace and CellBoundary should be consistent. If the geometry type of CellSpace is gml:Surface, then that of CellBoundary must be gml:Curve. And if the geometry type of CellSpace is gml:Solid, then that of CellBoundary must be gml:Surface.
2. The instances of CellSpace belonging to the same instance of SpaceLayer should not overlap.
3. When a CellSpace instance is divided into a set of subspaces, the subspace instances should not belong to the same SpaceLayer instance of the original CellSpace instance but form a new SpaceLayer instance. It is to avoid overlapping between CellSpace instances of the same space layer.
4. Every instance of InterLayerConnection should connect two State instances, each of which belongs to different space layers.

9 Data Model of the Indoor Navigation Module

The Indoor navigation model provides semantic information of indoor space for indoor navigation applications. Space features are classified into two groups: NavigableSpace and NavigableSpaceBoundary. NavigableSpace represents all indoor spaces (e.g. rooms, corridors, windows, stairs) that can be used by a navigation application. NavigableBoundary represents all features that connect the navigation spaces (e.g. door). Navigable Spaces and Navigable Boundaries are mapped on CellSpace and CellSpaceBoundary families. These are associated with corresponding classes such as State and Transition in IndoorGML Core Module.

The UML diagram of the conceptual indoor navigation model is depicted in Figure 23. The classes coloured in beige belong to the *IndoorGMLCore* UMLpackage and the classes colured in orange belong to the *GML* UMLpackage.

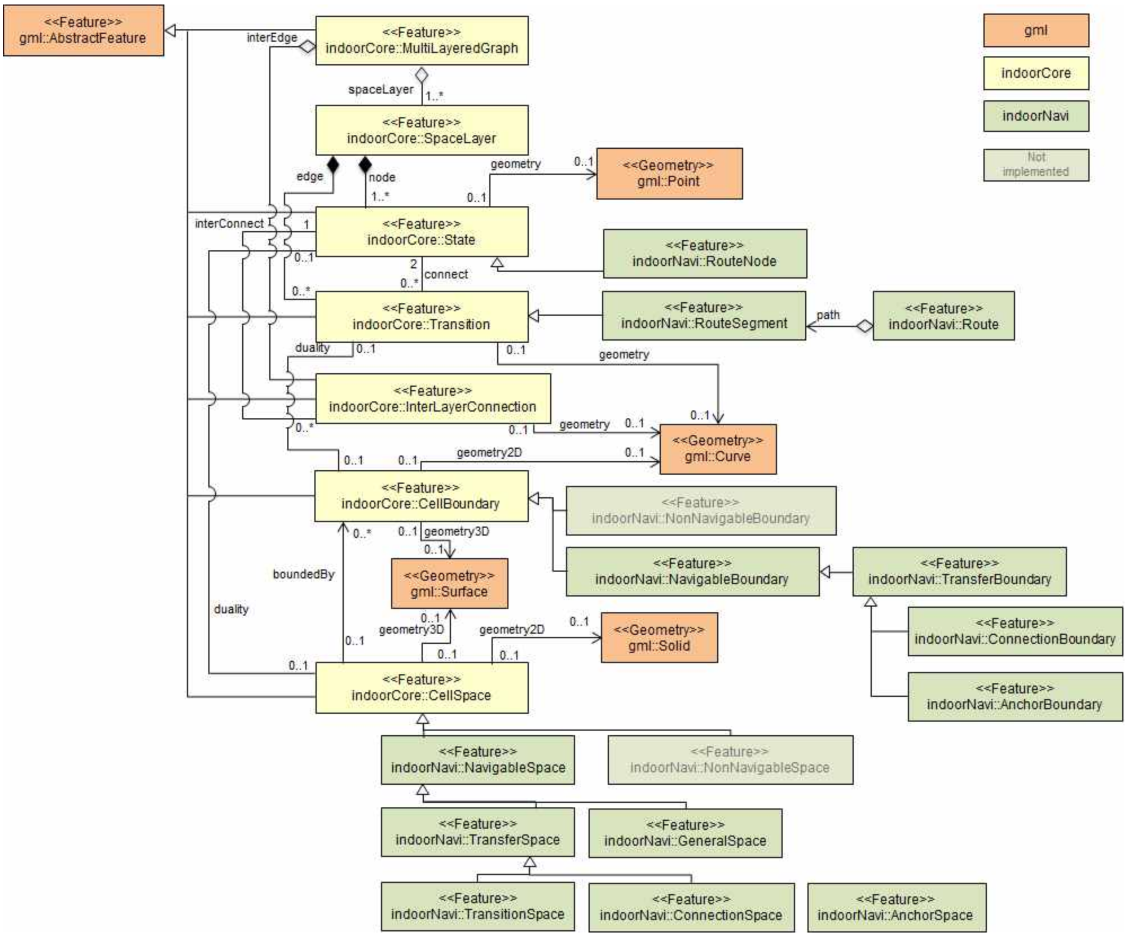


Figure 23: UML diagram of Conceptual Indoor Navigation Model

The Indoor Navigation Module is furthermore specifies in detail the generic concepts of the core module which are required in the context of indoor navigation. This might include the addressing/georeferencing schemas of indoor spaces, the concepts on communicating and visualizing navigable route sections, and the introduction of additional navigation constraints such as temporal access constraints as opening hours, or constraints resulting from material properties of the navigation path.

The following Figure 24 shows an UML diagram of IndoorNavigation module.

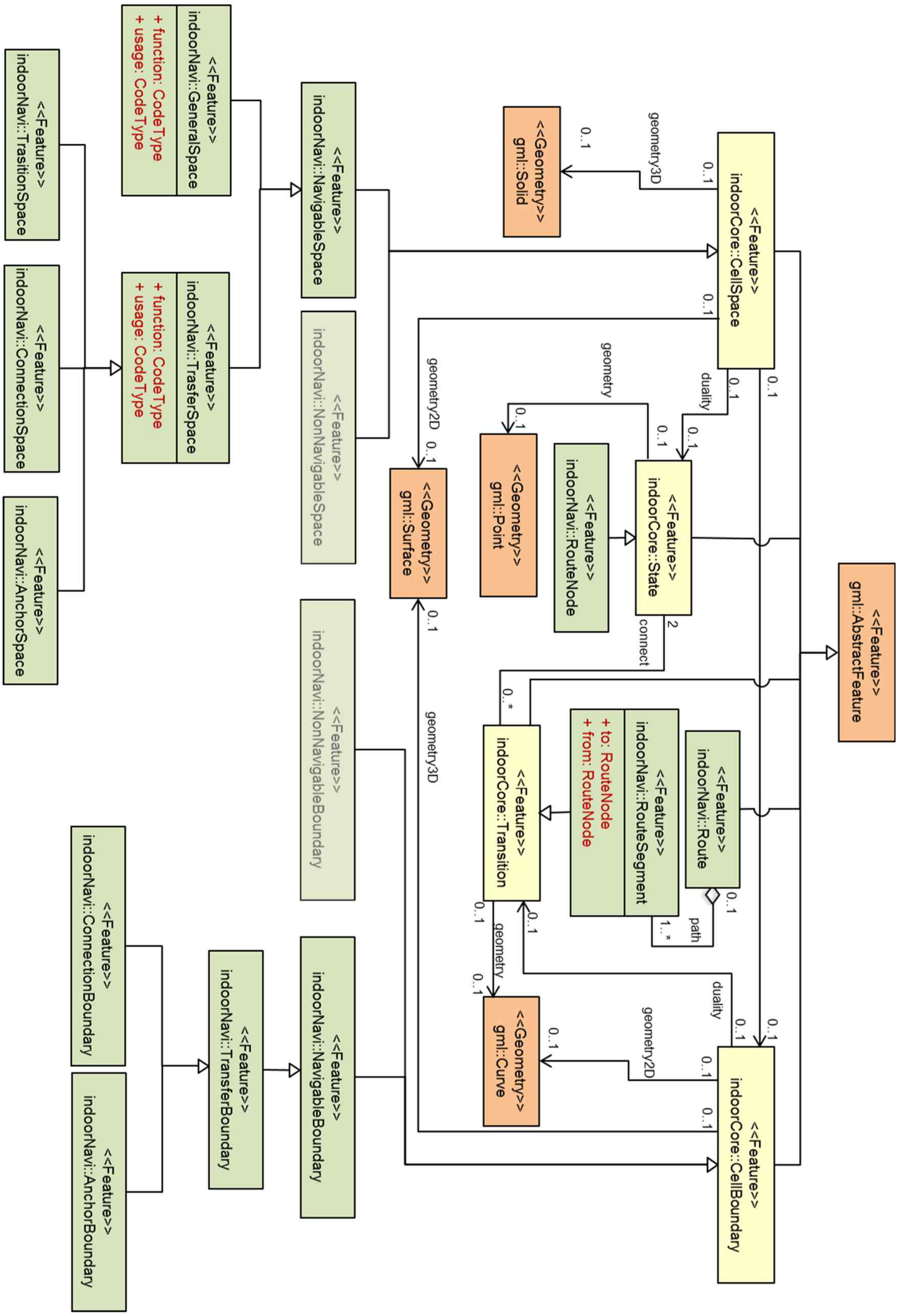


Figure 24: UML diagram of IndoorNavigation module

Figure 25 shows an example of indoor space mapped to IndoorNavigation module classes.

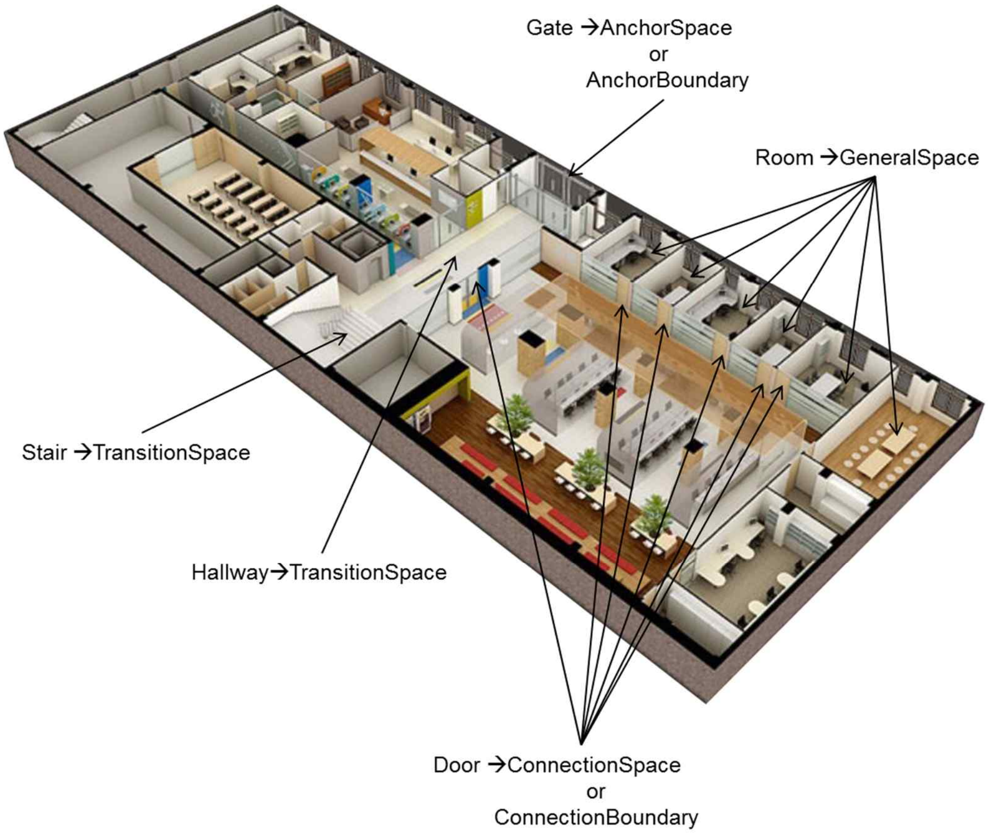
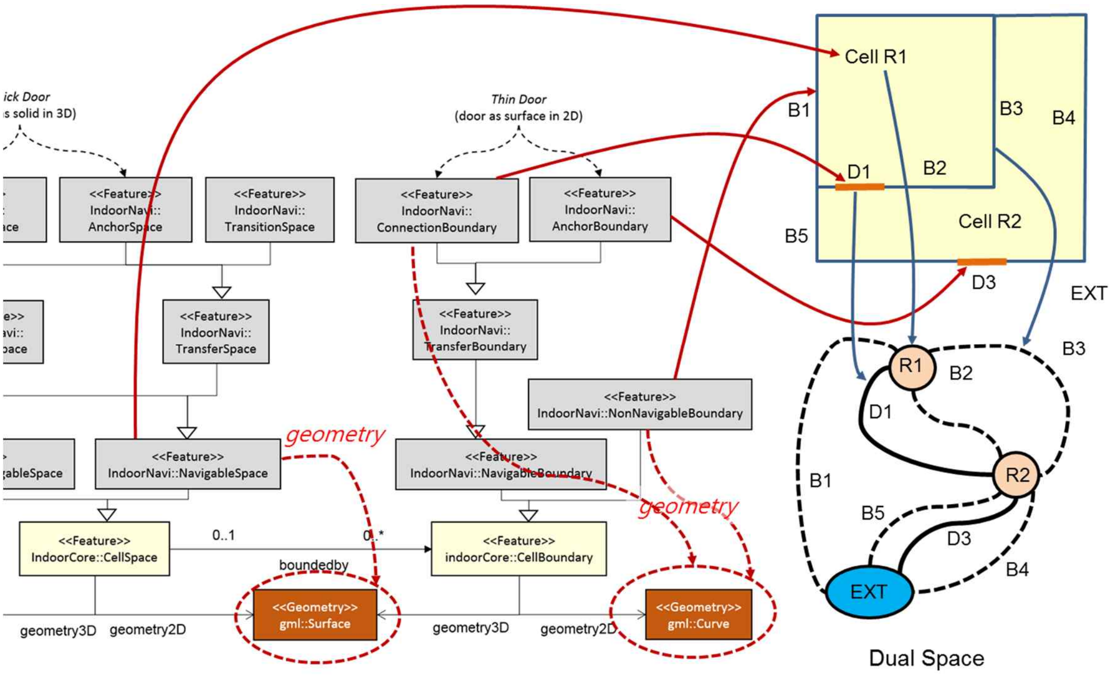
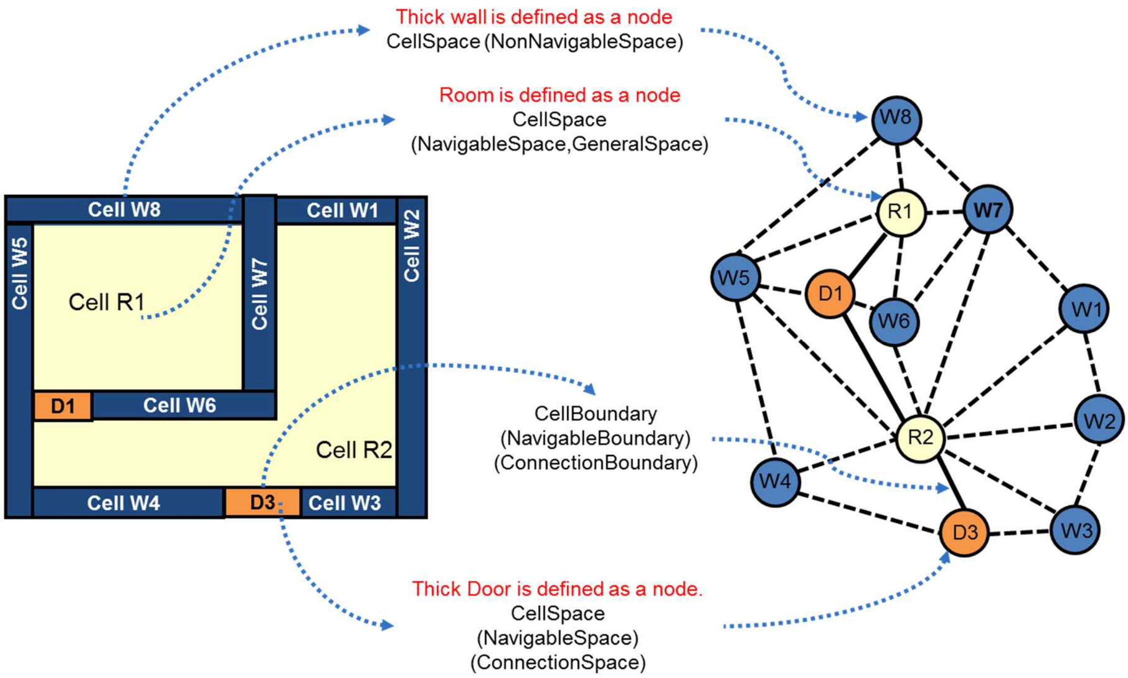


Figure 25: Indoor space mapped to IndoorNavigation module classes

Figure 26 shows an example of geometric mapping in 2D Space. The Room feature mapped to CellSpace and represented as gml:Surface. In the Thin Door Model, the Door feature mapped to CellSpaceBoundary and represented as gml:Curve as seen in the Figure 26-a). In this case, a door is mapped to Transition on dual space. However, in the Thick Door model as seen in the Figure 26-b), the Door feature mapped to CellSpace and represented as gml:Surface. In this case, a door represented as a State in dual space.

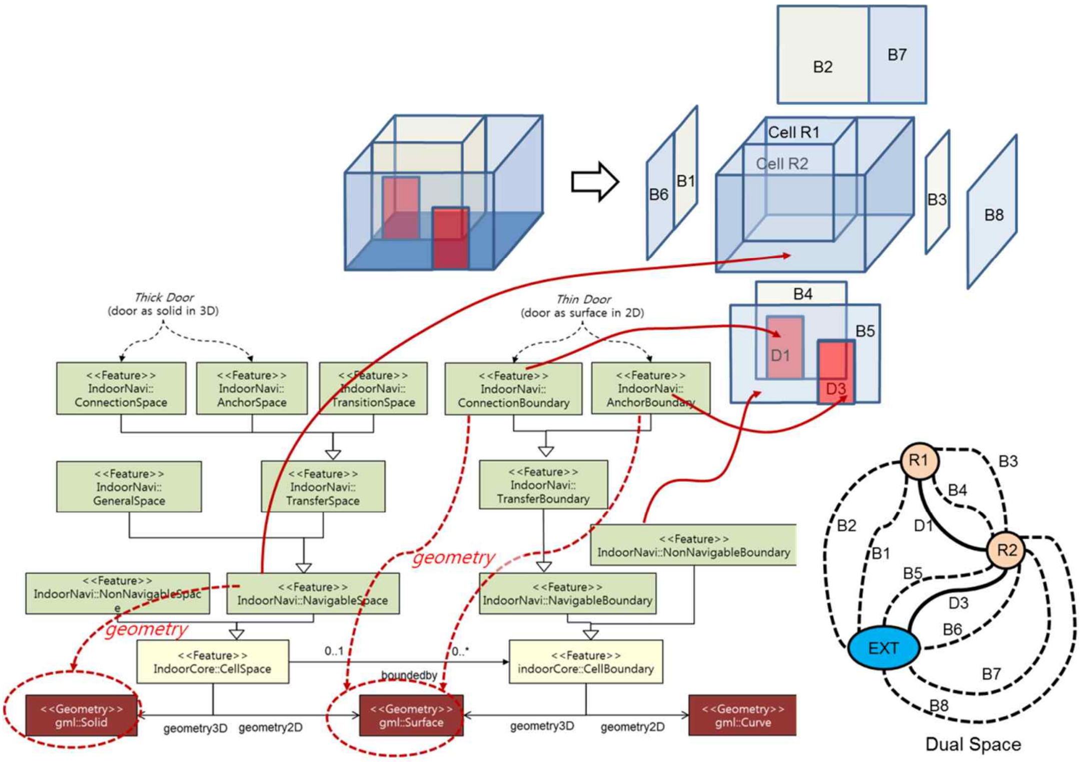


a) Example for Thin Door Model

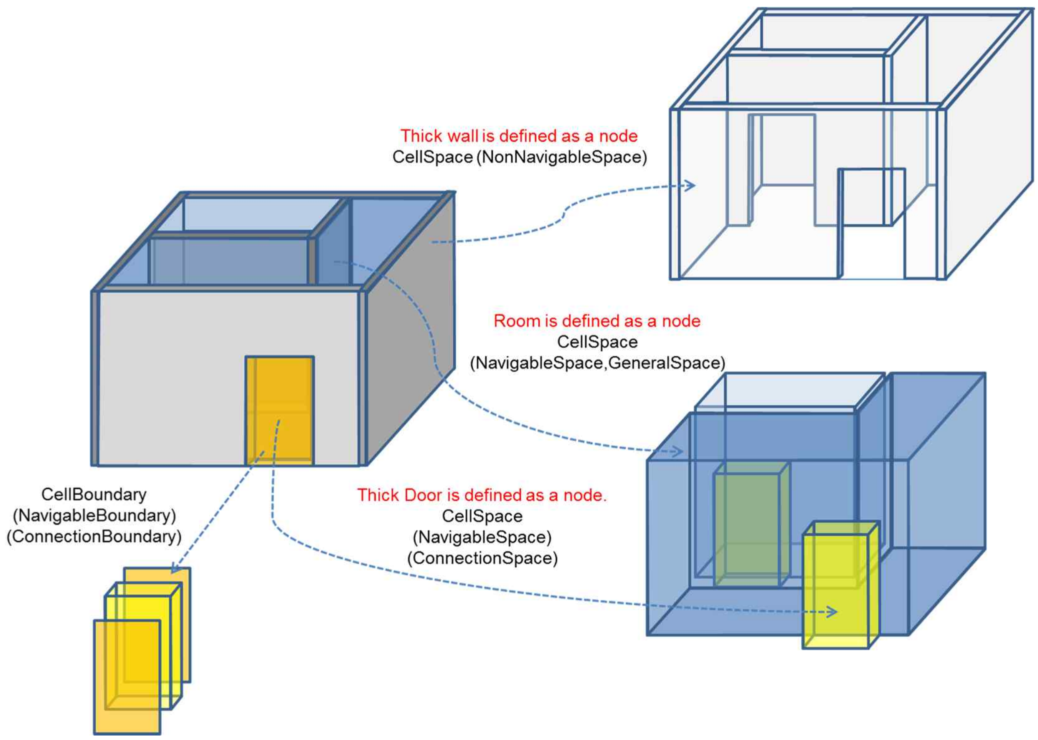


b) Example for Thick Door Model

Figure 26: Realization of CellSpace and CellSpaceBoundary for 2D Space Model



a) Example for Thin Door Model



b) Example for Thick Door Model

Figure 27: Realization of CellSpace and CellSpaceBoundary for 3D Space Model

Figure 27 illustrates an example of geometric mapping for 3D Space. As seen in Figure 27-a) and b), the CellSpace is realized as gml:Solid in 3D space model. If the Door feature is represented as thin door, the geometry of door is represented by gml:Surface and the door is mapped to CellSpaceBoundary as shown as Figure 27-a). In this case, a door is mapped to Transition on dual space. While in 3D data model, the door is represented by gml:Solid and mapped to CellSpace as shown as Figure 27-b). In this case, a door is represented as a State in dual space.

For example, the class CellSpace can be related to a Room in GityGML [11] or an IfcSpace in IFC. The class CellSpaceBoundary can be related to a _BoundarySurface feature in CityGML (e.g. WallSurface, ClosureSurface, InteriorWallSurface, etc) or an IfcWall in IFC. The geometric spaces and their topological relationships in the NRG are realized as gml:Point and gml:Curve.

9.1 <NavigableSpace>

The NavigableSpace class denotes a space that users can move freely in. It has two subclasses GeneralSpace and TransferSpace. The subclasses are classified depending on the purpose of the space. The compartmentalized spaces such as corridor, lobby, hallway, big room are represented as NavigableSpace. Especially, on 3D data mode, door is represented as NavigableSpace as shown as Figure 26-b).

A geometry of NavigableSpace is represented as gml:Solid on 3D data model or gml: Surface on 2D data model as shown as Figure 26 and Figure 27.

```
<xs:element name="NavigableSpace" type="NavigableSpaceType" substitutionGroup="incoorCore:CellSpace">
    <xs:annotation>
        <xs:documentation>Denotin the interspace connections between the SpaceLayer
        </xs:documentation>
    </xs:annotation>
</xs:element>
<xs:complexType name="NavigableSpaceType">
    <xs:complexContent>
        <xs:extension base="incoorCore:CellSpaceType">
            <xs:sequence>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<xs:complexType name="NavigableSpaceMemberType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureMemberType">
            <xs:sequence minOccurs="0">
                <xs:element ref="NavigableSpace"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
```

9.2 <NonNavigableSpace>

The NonNavigableSpace class represents the space that is occupied by obstacles. On 3D data model, a wall is typical NonNavigablespace as shown as Figure 26-b). It is not implemented on XML schema.

9.3 <GeneralSpace>

The GeneralSpace class is one of the two subclasses of NavigableSpace. GeneralSpace is idenfied as any navigable spaces except Transferspace such as rooms, terraces, lobbies, etc as shown as Figure 28. The class attribute represents the classification of the GeneralSpace. The different functions and usage of GeneralSpace can be represented as function and usage.

```
<xs:element name="GeneralSpace" type="GeneralSpaceType" substitutionGroup="NavigableSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ========================================================================= -->
    <xs:complexType name="GeneralSpaceType">
        <xs:complexContent>
            <xs:extension base="NavigableSpaceType">
                <xs:sequence>
                    <xs:element name="class" type="gml:CodeType"/>
                    <xs:element name="function" type="gml:CodeType"/>
                    <xs:element name="usage" type="gml:CodeType"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.4 <TransferSpace>

The class TransferSpace is derived from NavigableSpace. It is used to model a space for providing passages between GeneralSpaces. It has three subclasses as ConnectionSpace, AnchorSpace, and TransitionSpace. Figure 28 shows ConnectionSpace and AnchorSpace in 2D or 3D space Model. Especially, a door (Door in CityGML or IfcDoor in IFC) is refered to ConnectionSpace or AnchorSpace in 3D Thick Door Model. A hallway and stairs also are represented as TransitionSpace. These subclasses of TransferSpace are mapped to State of IndoorGML core module.

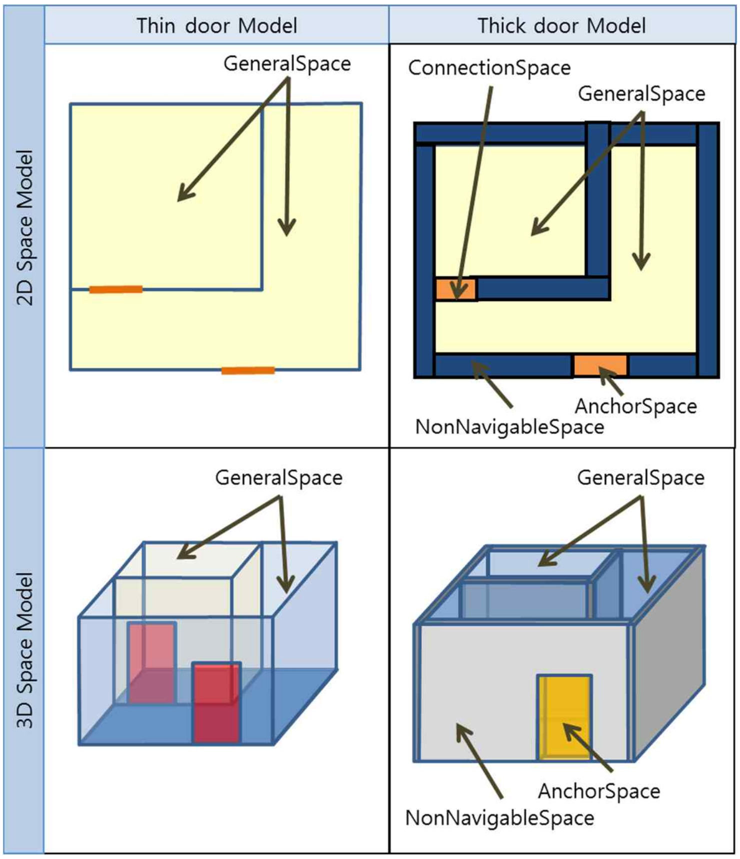


Figure 28: Examples of GeneralSpace, ConnectionSpace and AnchorSpace

```
<xs:element name="TransferSpace" type="TransferSpaceType" substitutionGroup="NavigableSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ========================================================================== -->
    <xs:complexType name="TransferSpaceType">
        <xs:complexContent>
            <xs:extension base="NavigableSpaceType">
                <xs:sequence>
                    <xs:element name="class" type="gml:CodeType"/>
                    <xs:element name="function" type="gml:CodeType"/>
                    <xs:element name="usage" type="gml:CodeType"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.5 <ConnectionSpace>

ConnetionSpace represents an opening space that provides passages between two indoor spaces as shown as Figure 28. It refers to Door features in Thick Door Model. As mentioned before, ConnectionSpace is mapped to State of IndoorGML core module.

```
<xs:element name="ConnectionSpace" type="ConnectionSpaceType" substitutionGroup="TransferSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================== -->
    <xs:complexType name="ConnectionSpaceType">
        <xs:complexContent>
            <xs:extension base="TransferSpaceType">
                <xs:sequence/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.6 <AnchorSpace>

AnchorSpace represents a special opening space that provides connection between an indoor space and an outdoor space. It refers to *Entrance Doors*. It can be used as an AnchorNode, which is used as a control point for indoor-outdoor integrations.

```
<xs:element name="AnchorSpace" type="AnchorSpaceType" substitutionGroup="TransferSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================== -->
    <xs:complexType name="AnchorSpaceType">
        <xs:complexContent>
            <xs:extension base="TransferSpaceType">
                <xs:sequence/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.7 <TransitionSpace>

TransitionSpace represents a real world space that provides passage between two indoor spaces. It refers to corridors, stair and subspaces of hallway or corridor.

```
<xs:element name="TransitionSpace" type="TransitionSpaceType" substitutionGroup="TransferSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
        <!-- ================================================================== -->
    <xs:complexType name="TransitionSpaceType">
```

```
        <xs:complexContent>
            <xs:extension base="TransferSpaceType">
                <xs:sequence/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.8 <NavigableBoundary>

NavigableBoudary is defined as the boundary of NavigableSpace including the boundary of ConnectionSpace and AnchoreSpace.

As shown as Figure 29, a door is mapped to a NavigableBoundary in Thin Door Model. Meanwhile in Thick Door Model, a door has two NavigableBoundary and two NonNavigableBoundary as shown as Figure 29. The boundary which meets with other NavigableSpace is a NavigableBoundary and the others are mapped to NonNavigableBoundary class. It has a subclasses as TrasferBoundary.

```
    <xs:element name="NavigableBoundary" type="NavigableBoundaryType"
substitutionGroup="incoorCore:CellSpaceBoundary">
        <xs:annotation>
            <xs:documentation> NavigableBoundary </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -->
    <xs:complexType name="NavigableBoundaryType">
        <xs:complexContent>
            <xs:extension base="incoorCore:CellSpaceBoundaryType">
                <xs:sequence>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

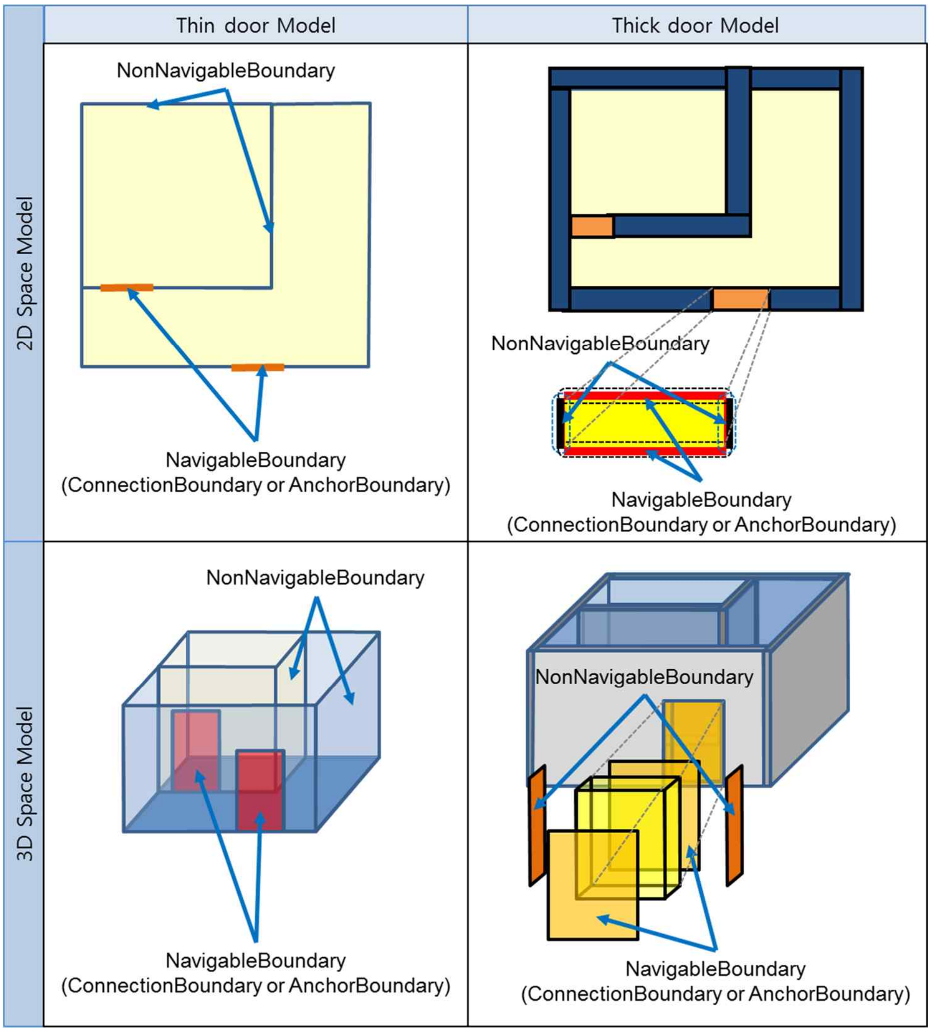


Figure 29: Example of NavigableBoundary

9.9 <TransferBoundary>

The class TransferBoundary is derived from NavigableBoundary. It is used to model a boundary for providing passages between NavigableSpace. It has two subclasses as ConnectionBoundary and AnchorBoundary. As shown as Figure 29, in Thin Door Model a door is mapped to ConnectionBoundary or AnchorBoundary. In Thick Door Model, some part of boundaries of door is mapped to ConnectionBoundary or AnchorBoundary. These subclasses of TransferSpace are mapped to Transition of IndoorGML core module.

```
    <xs:element name="TransferBoundary" type="TransferBoundaryType"
substitutionGroup="NavigableBoundary">
        <xs:annotation>
            <xs:documentation> TransferBoundary </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ============================================================================ -->
```

```
    <xs:complexType name="TransferBoundaryType">
        <xs:complexContent>
            <xs:extension base="NavigableBoundaryType">
                <xs:sequence>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.10 <ConnectionBoundary>

ConnetionBoundary represents a boundary which is connected with two adjacent NavigableSpaces. In 2D space model, the ConnetionBoundary is represented as a gml:Curve. It is represented as a gml:Surface in 3D space model. As mentioned before, ConnetionBoundary is mapped to Transition of IndoorGML core module.

```
    <xs:element name="ConnectionBoundary" type="ConnectionBoundaryType"
substitutionGroup="TransferBoundary">
        <xs:annotation>
            <xs:documentation> ConnectionBoundary </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ======================================================================== -->
    <xs:complexType name="ConnectionBoundaryType">
        <xs:complexContent>
            <xs:extension base="TransferBoundaryType">
                <xs:sequence>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.11 <AnchorBoundary>

AnchorBoundary represents a boundary which is the common boundary between a NavigableSpace and Outdoor. It is represented as a part of boundary of AnchorSpace in Thick Door Model. In 2D space model, the AnchorBoundary is represented as a gml:Curve. It is represented as a gml:Surface in 3D space model. As mentioned before, AnchorBoundary is mapped to Transition of IndoorGML core module.

```
    <xs:element name="AnchorBoundary" type="AnchorBoundaryType" substitutionGroup="TransferBoundary">
        <xs:annotation>
            <xs:documentation> AnchorBoundary </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ======================================================================== -->
    <xs:complexType name="AnchorBoundaryType">
        <xs:complexContent>
            <xs:extension base="TransferBoundaryType">
                <xs:sequence>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
```

```
    </xs:complexType>
```

9.12 <RouteNode>

RouteNode represents a node inherited from State class. Within a dual graph structure of one layer, a node in dual space represents a space (e.g. a room within a building) in primal space.

```
<xs:element name="RouteNode" type="RouteNodeType">
        <xs:annotation>
            <xs:documentation>Route Node
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================== -->
    <xs:complexType name="RouteNodeType">
        <xs:complexContent>
            <xs:extension base="incoorCore:StateType">
                <xs:sequence>
                    <xs:element name="class" type="gml:CodeType"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ================================================================== -->
    <xs:complexType name="RouteNodePropertyType">
        <xs:sequence minOccurs="1">
            <xs:element ref="RouteNode"/>
        </xs:sequence>
    </xs:complexType>
    <!-- ================================================================== -->
    <xs:complexType name="RouteNodeMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="1">
                    <xs:element ref="RouteNode"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.13 <RouteSegment>

RouteSegment represents connectivity relationships between spaces (e.g. a room within a building, door). RouteSegments are directed edges between RoutesNodes. Each edge will have at least two nodes. The RouteSegment contains two RouteNodes for representing start position and end position

```
    <xs:element name="RouteSegment" type="RouteSegmentType">
        <xs:annotation>
            <xs:documentation>RouteSegment
            </xs:documentation>
```

```
        </xs:annotation>
    </xs:element>
    <!-- ========================================================================== -->
    <xs:complexType name="RouteSegmentType">
        <xs:complexContent>
            <xs:extension base="incoorCore:TransitionType">
                <xs:sequence>
                    <xs:element name="from" type="RouteNodePropertyType"/>
                    <xs:element name="to" type="RouteNodePropertyType"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ========================================================================== -->
    <xs:complexType name="RouteSegmentMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="RouteSegment"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

9.14 <Route>

Route represents a possible path to navigate indoor space. The Route has a sequence of RouteNodes. The startRouteNode and endRouteNode represent a start position and end position of the path for indoor navigation. The attribute path contains RouteNode and RouteSegment of possible path in indoor space and it can be represented as sequence of RouteNode and RouteSegment.

```
    <xs:element name="Route" type="RouteType" substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>Route..
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ========================================================================== -->
    <xs:complexType name="RouteType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="startRouteNode" type="RouteNodePropertyType" minOccurs="1"/>
                    <xs:element name="endRouteNode" type="RouteNodePropertyType" minOccurs="1"/>
                    <xs:element name="path" type="RouteMemberType" minOccurs="1"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ========================================================================== -->
    <xs:complexType name="RouteMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence>
                    <xs:element name="routeNodes" type="RouteNodeMemberType" minOccurs="1"/>
                    <xs:element name="segments" type="RouteSegmentMemberType" minOccurs="1"/>
```

```
            </xs:sequence>
            <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
```

9.15 Constraints

NavigableSpaceConstaints and NavigableBoundaryConstraint are linked to the topographic space semantic models through the relations. For providing indoor navigation, different categories of constraints can be identified: PassRestriction, WalkTypeRestriction, UserRestriction, TimeRestriction, and OneWayRestriction, as shown in Figure 30. Additional constraints can be defined as properties of the constraint elements.

The hierarchical conceptual constraint model could be used to create single or combined constraints for single or a series of semantic topographic space entities.

9.16 Requirements for conformance

This clause specifies the conformance requirements for the IndoorGML Indoor Navigation Module. Although most of conformance requiremens are already presented in the model and XML schema of the IndoorGML Indoor Navigation Module, and certain complementary conformance requirements are explicitly given in this clause;

1. Thick door model and thin door model should not be applied in a same IndoorGML.
2. Every thick door should be realized as an instance of either ConnectionSpace or AnchorSpace. And every thin door should be realized as an instance of either ConnectionBoundary or AnchorBoundary.
3. As shown in Figure 29, the boundary between a thick door and a thick wall should be an instance of NonNavigableBoundary.

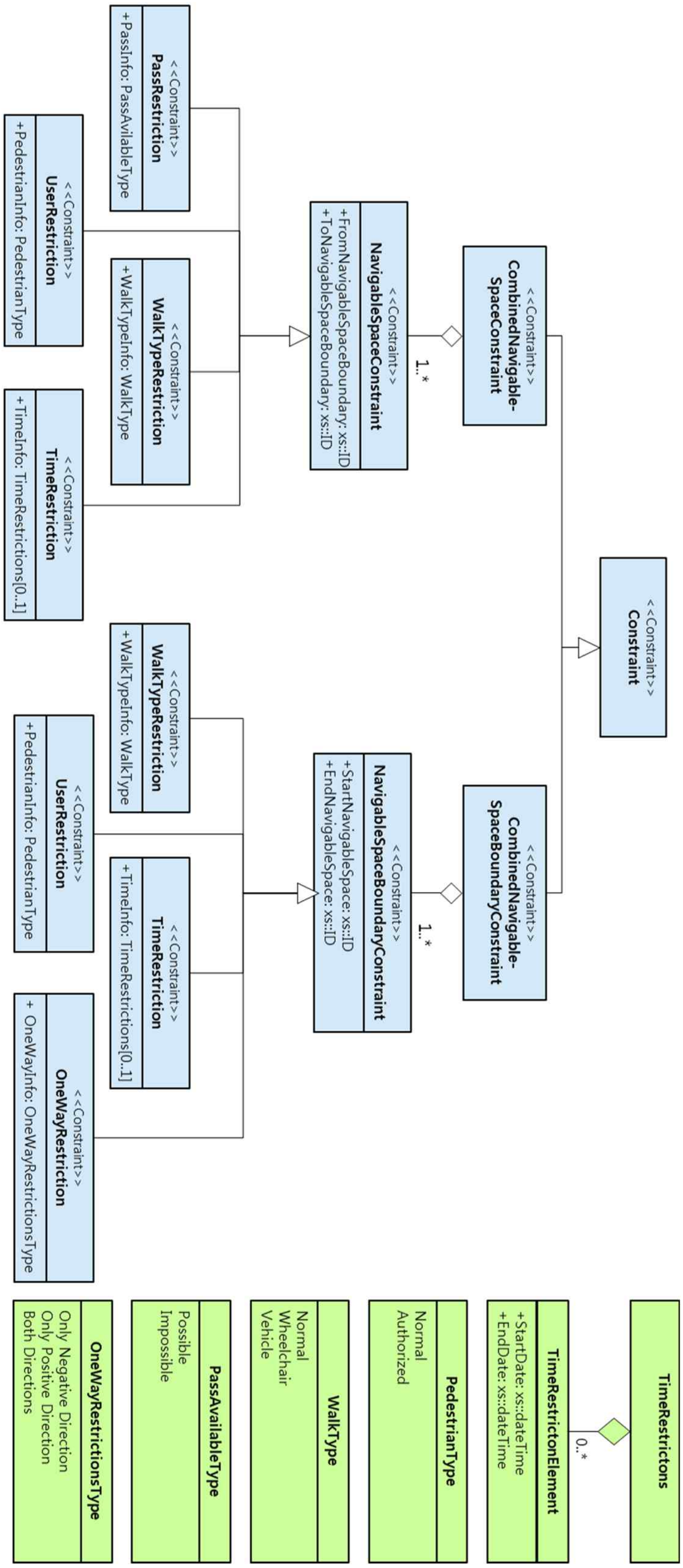


Figure 30: Conceptual model of indoor navigation constraints

Annex A
(normative)
XML Schema for IndoorGML

A.1 IndoorGML Core Module

```
<?xml version="1.0" encoding="UTF-8"?>
<xs:schema xmlns="indoorCore" xmlns:xs="http://www.w3.org/2001/XMLSchema"
xmlns:gml="http://www.opengis.net/gml/3.2" targetNamespace="indoorCore" elementFormDefault="unqualified">
    <xs:import namespace="http://www.opengis.net/gml/3.2"
schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>
    <!-- ================================================================== -->
    <xs:element name="MultiLayeredGraph" type="MultiLayeredGraphType"
substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>The overall structure of the Multilayered Space Model constitutes a multilayered graph,
where all the nodes from all n layers are included but are separated into n partitions which are connected by the inter-
space connections. Furthermore the graph also contains the state transition edges (intra-space connections)
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================== -->
    <xs:complexType name="MultiLayeredGraphType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="spaceLayers" type="SpaceLayersType" minOccurs="1"
maxOccurs="unbounded"/>
                    <xs:element name="interLayerConnectsions" type="InterLayerConnectionsType" minOccurs="0"
maxOccurs="unbounded"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ================================================================== -->
    <xs:element name="InterLayerConnection" type="InterLayerConnectionType"
substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================== -->
    <xs:complexType name="InterLayerConnectionType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="typeOfTopoExpression" type="typeOfTopoExpressionCodeType"/>
                    <xs:element name="comment" type="xs:string"/>
                    <xs:element name="start" type="StatePropertyType" minOccurs="1" maxOccurs="1"/>
                    <xs:element name="end" type="StatePropertyType" minOccurs="1" maxOccurs="1"/>
                    <xs:element name="geometry" type="gml:CurvePropertyType" minOccurs="0" maxOccurs="1"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

```xml
    <!-- ============================================================ -->
    <xs:complexType name="InterLayerConnectionPropertyType">
        <xs:sequence>
            <xs:element ref="InterLayerConnection"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ============================================================ -->
    <xs:complexType name="InterLayerConnectionsType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="interLayerConnectionMember" type="InterLayerConnectionMemberType"
minOccurs="1" maxOccurs="unbounded"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <xs:complexType name="InterLayerConnectionMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="InterLayerConnection"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ============================================================ -->
    <xs:element name="SpaceLayer" type="SpaceLayerType" substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>&lt;SpaceLayer&gt;s represent various space concepts such as topography, sensor,
security, etc. A SpaceLayer aggregates  &lt;State&gt; and &lt;Transition&gt; which are directly associated with the
corresponding geometry classes.</xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ============================================================ -->
    <xs:complexType name="SpaceLayerType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="usage" type="gml:CodeType" minOccurs="0" maxOccurs="unbounded"/>
                    <xs:element name="terminationDate" type="xs:dateTime" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="function" type="gml:CodeType" minOccurs="0" maxOccurs="unbounded"/>
                    <xs:element name="creationDate" type="xs:dateTime" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="class" type="SpaceLayerClassTypeType" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="nodes" type="NodesType" minOccurs="1" maxOccurs="unbounded"/>
                    <xs:element name="edges" type="EdgesType" minOccurs="0" maxOccurs="unbounded"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ============================================================ -->
    <xs:complexType name="SpaceLayersType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="spaceLayerMember" type="SpaceLayerMemberType" minOccurs="1"
maxOccurs="unbounded"/>
                </xs:sequence>
```

```
            <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<xs:complexType name="SpaceLayerMemberType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureMemberType">
            <xs:sequence minOccurs="1">
                <xs:element ref="SpaceLayer"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- ================================================================== -->
<xs:element name="State" type="StateType" substitutionGroup="gml:AbstractFeature">
    <xs:annotation>
        <xs:documentation>
Within the dual graph structure of one layer a node in dual space represents a space (e.g. a room within a building) in primal space
        </xs:documentation>
    </xs:annotation>
</xs:element>
<!-- ================================================================== -->
<xs:complexType name="StateType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureType">
            <xs:sequence>
                <xs:element name="duality" type="CellSpaceType" minOccurs="0" maxOccurs="1"/>
                <xs:element name="connects" type="TransitionPropertyType" minOccurs="0"
maxOccurs="unbounded"/>
                <xs:element name="interConnects" type="InterLayerConnectionPropertyType" minOccurs="0"
maxOccurs="unbounded"/>
                <xs:element name="geometry" type="gml:PointPropertyType" minOccurs="0" maxOccurs="1"/>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- ================================================================== -->
<xs:complexType name="StatePropertyType">
    <xs:sequence>
        <xs:element ref="State"/>
    </xs:sequence>
    <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
</xs:complexType>
<!-- ================================================================== -->
<xs:complexType name="NodesType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureType">
            <xs:sequence>
                <xs:element name="stateMember" type="StateMemberType" minOccurs="1"
maxOccurs="unbounded"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<xs:complexType name="StateMemberType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureMemberType">
            <xs:sequence minOccurs="0">
                <xs:element ref="State"/>
```

```
            </xs:sequence>
            <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- ==================================================================== -->
<xs:element name="Transition" type="TransitionType">
    <xs:annotation>
        <xs:documentation>Within the dual graph structure of one layer, an edge in dual space represents the
adjacencies or connections (e.g. doors or passages as intra-space connections) </xs:documentation>
    </xs:annotation>
</xs:element>
<!-- ==================================================================== -->
<xs:complexType name="TransitionType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureType">
            <xs:sequence>
                <xs:element name="weight" type="xs:double"/>
                <xs:element name="start" type="StatePropertyType"/>
                <xs:element name="end" type="StatePropertyType"/>
                <xs:element name="duality" type="CellSpaceBoundaryPropertyType" minOccurs="0"
maxOccurs="1"/>
                <xs:element name="geometry" type="gml:CurvePropertyType" minOccurs="0" maxOccurs="1"/>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- ==================================================================== -->
<xs:complexType name="TransitionPropertyType">
    <xs:sequence>
        <xs:element ref="Transition"/>
    </xs:sequence>
    <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
</xs:complexType>
<!-- ==================================================================== -->
<xs:complexType name="EdgesType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureType">
            <xs:sequence>
                <xs:element name="transitionMember" type="TransitionMemberType" minOccurs="0"
maxOccurs="unbounded"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<xs:complexType name="TransitionMemberType">
    <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureMemberType">
            <xs:sequence minOccurs="0">
                <xs:element ref="Transition"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- ==================================================================== -->
<xs:element name="CellSpace" type="CellSpaceType" abstract="true" substitutionGroup="gml:AbstractFeature">
    <xs:annotation>
        <xs:documentation>
            Within the dual graph structure of one layer a node in dual space represents a space (e.g. a room within a
building) in primal space
```

```
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ========================================================================== -->
    <xs:complexType name="CellSpacePropertyType">
        <xs:sequence>
            <xs:element ref="CellSpace"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ========================================================================== -->
    <xs:complexType name="CellSpaceType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:group ref="CellSpaceGeometry" minOccurs="0"/>
                    <xs:element name="duality" type="StatePropertyType" minOccurs="0" maxOccurs="1"/>
                    <xs:element name="externalReference" type="ExternalReferenceType" minOccurs="0"
maxOccurs="unbounded"/>
                    <xs:element name="boundedBy" type="CellSpaceBoundaryPropertyType" minOccurs="0"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ========================================================================== -->
    <xs:group name="CellSpaceGeometry">
        <xs:choice>
            <xs:element name="Geometry3D" type="gml:SolidPropertyType"/>
            <xs:element name="Geometry2D" type="gml:SurfacePropertyType"/>
        </xs:choice>
    </xs:group>
    <!-- ========================================================================== -->
    <xs:complexType name="CellSpaceMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="CellSpace"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ========================================================================== -->
    <xs:element name="CellSpaceBoundary" type="CellSpaceBoundaryType"
substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation> Within the dual graph structure of one layer a node in dual space represents a space (e.g.
a room within a building) in primal space
        </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ========================================================================== -->
    <xs:complexType name="CellSpaceBoundaryType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="duality" type="TransitionPropertyType" minOccurs="0" maxOccurs="1"/>
                    <xs:group ref="CellSpaceBoundaryGeometry" minOccurs="0"/>
                    <xs:element name="externalReference" type="ExternalReferenceType" minOccurs="0"
maxOccurs="unbounded"/>
                </xs:sequence>
            </xs:extension>
```

```xml
        </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -->
    <xs:group name="CellSpaceBoundaryGeometry">
        <xs:choice>
            <xs:element name="geometry3D" type="gml:SurfacePropertyType"/>
            <xs:element name="geometry2D" type="gml:CurvePropertyType"/>
        </xs:choice>
    </xs:group>
    <!-- ==================================================================== -->
    <xs:complexType name="CellSpaceBoundaryPropertyType">
        <xs:sequence>
            <xs:element ref="CellSpaceBoundary"/>
        </xs:sequence>
        <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
    </xs:complexType>
    <!-- ==================================================================== -->
    <xs:complexType name="CellSpaceBoundaryMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="CellSpaceBoundary"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -->
    <xs:complexType name="ExternalReferenceType">
        <xs:sequence>
            <xs:element name="informationSystem" type="xs:anyURI" minOccurs="0"/>
            <xs:element name="externalObject" type="externalObjectReferenceType"/>
        </xs:sequence>
    </xs:complexType>
    <!-- ==================================================================== -->
    <xs:complexType name="externalObjectReferenceType">
        <xs:choice>
            <xs:element name="name" type="xs:string" minOccurs="0"/>
            <xs:element name="uri" type="xs:anyURI"/>
        </xs:choice>
    </xs:complexType>
    <!-- ==================================================================== -->
    <xs:simpleType name="SpaceLayerClassTypeType">
        <xs:restriction base="xs:string">
            <xs:enumeration value="TOPOGRAPHIC"/>
            <xs:enumeration value="SENSOR"/>
            <xs:enumeration value="LOGICAL"/>
            <xs:enumeration value="TAGS"/>
            <xs:enumeration value="LOGICAL"/>
            <xs:enumeration value="UNKNOWN"/>
        </xs:restriction>
    </xs:simpleType>
    <xs:simpleType name="typeOfTopoExpressionCodeType">
        <xs:union memberTypes="typeOfTopoExpressionCodeEnumerationType
typeOfTopoExpressionCodeOtherType"/>
    </xs:simpleType>
    <xs:simpleType name="typeOfTopoExpressionCodeEnumerationType">
        <xs:restriction base="xs:string">
            <xs:enumeration value="CONTAINS"/>
            <xs:enumeration value="OVERLAPS"/>
            <xs:enumeration value="EQUALS"/>
            <xs:enumeration value="WITHIN"/>
```

```
            <xs:enumeration value="CROSSES"/>
            <xs:enumeration value="INTERSECTS"/>
        </xs:restriction>
    </xs:simpleType>
    <xs:simpleType name="typeOfTopoExpressionCodeOtherType">
        <xs:restriction base="xs:string">
            <xs:pattern value="other. \w{2,}"/>
        </xs:restriction>
    </xs:simpleType>
</xs:schema>
```

A.2 IndoorGML Indoor Navigation Module

```xml
<?xml version="1.0" encoding="UTF-8"?>
<xs:schema xmlns="indoornavi" xmlns:xs="http://www.w3.org/2001/XMLSchema"
xmlns:gml="http://www.opengis.net/gml/3.2" xmlns:indoorCore="indoorCore"
targetNamespace="indoornavi" elementFormDefault="unqualified">
    <xs:import namespace="http://www.opengis.net/gml/3.2"
schemaLocation="http://schemas.opengis.net/gml/3.2.1/gml.xsd"/>
    <xs:import namespace="indoorCore" schemaLocation="IndoorGML.xsd"/>
    <!-- =================================================================== -
->
    <xs:element name="Route" type="RouteType" substitutionGroup="gml:AbstractFeature">
        <xs:annotation>
            <xs:documentation>Route..
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- =================================================================== -
->
    <xs:complexType name="RouteType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="startRouteNode" type="RouteNodePropertyType" minOccurs="1"/>
                    <xs:element name="endRouteNode" type="RouteNodePropertyType" minOccurs="1"/>
                    <xs:element name="path" type="PathType" minOccurs="1"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- =================================================================== -
->
    <xs:complexType name="PathType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureType">
                <xs:sequence>
                    <xs:element name="routeMember" type="RouteMemberType" minOccurs="0"
maxOccurs="unbounded"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <xs:complexType name="RouteMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence>
                    <xs:element ref="RouteSegment" minOccurs="1"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AggregationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
```

```
    <!-- ==================================================================== -
->
    <xs:element name="RouteSegment" type="RouteSegmentType">
        <xs:annotation>
            <xs:documentation>RouteSegment
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ==================================================================== -
->
    <xs:complexType name="RouteSegmentType">
        <xs:complexContent>
            <xs:extension base="indoorCore:TransitionType">
                <xs:sequence>
                    <xs:element name="from" type="RouteNodePropertyType"/>
                    <xs:element name="to" type="RouteNodePropertyType"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -
->
    <xs:complexType name="RouteSegmentMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="0">
                    <xs:element ref="RouteSegment"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -
->
    <xs:element name="RouteNode" type="RouteNodeType">
        <xs:annotation>
            <xs:documentation>Route Node
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ==================================================================== -
->
    <xs:complexType name="RouteNodeType">
        <xs:complexContent>
            <xs:extension base="indoorCore:StateType">
                <xs:sequence>
                    <xs:element name="class" type="gml:CodeType"/>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -
->
    <xs:complexType name="RouteNodePropertyType">
        <xs:sequence minOccurs="1">
            <xs:element ref="RouteNode"/>
```

```
        </xs:sequence>
    </xs:complexType>
    <!-- ================================================================ -
->
    <xs:complexType name="RouteNodeMemberType">
        <xs:complexContent>
            <xs:extension base="gml:AbstractFeatureMemberType">
                <xs:sequence minOccurs="1">
                    <xs:element ref="RouteNode"/>
                </xs:sequence>
                <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ================================================================ -
->
    <xs:element name="NavigableBoundary" type="NavigableBoundaryType"
substitutionGroup="indoorCore:CellSpaceBoundary">
        <xs:annotation>
            <xs:documentation> NavigableBoundary </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================ -
->
    <xs:complexType name="NavigableBoundaryType">
        <xs:complexContent>
            <xs:extension base="indoorCore:CellSpaceBoundaryType">
                <xs:sequence>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ================================================================ -
->
    <xs:element name="TransferBoundary" type="TransferBoundaryType"
substitutionGroup="NavigableBoundary">
        <xs:annotation>
            <xs:documentation> TransferBoundary </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ================================================================ -
->
    <xs:complexType name="TransferBoundaryType">
        <xs:complexContent>
            <xs:extension base="NavigableBoundaryType">
                <xs:sequence>
                </xs:sequence>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ================================================================ -
->

    <xs:element name="ConnectionBoundary" type="ConnectionBoundaryType"
substitutionGroup="TransferBoundary">
        <xs:annotation>
```

```
        <xs:documentation> ConnectionBoundary </xs:documentation>
      </xs:annotation>
    </xs:element>
    <!-- ==================================================================== -
->
    <xs:complexType name="ConnectionBoundaryType">
      <xs:complexContent>
        <xs:extension base="TransferBoundaryType">
          <xs:sequence>
          </xs:sequence>
        </xs:extension>
      </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -
->
    <xs:element name="AnchorBoundary" type="AnchorBoundaryType"
substitutionGroup="TransferBoundary">
      <xs:annotation>
        <xs:documentation> AnchorBoundary </xs:documentation>
      </xs:annotation>
    </xs:element>
    <!-- ==================================================================== -
->
    <xs:complexType name="AnchorBoundaryType">
      <xs:complexContent>
        <xs:extension base="TransferBoundaryType">
          <xs:sequence>
          </xs:sequence>
        </xs:extension>
      </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -
->
      <xs:element name="NavigableSpace" type="NavigableSpaceType"
substitutionGroup="indoorCore:CellSpace">
      <xs:annotation>
        <xs:documentation>NavigableSpace
        </xs:documentation>
      </xs:annotation>
    </xs:element>
    <!-- ==================================================================== -
->
    <xs:complexType name="NavigableSpaceType">
      <xs:complexContent>
        <xs:extension base="indoorCore:CellSpaceType">
          <xs:sequence>
          </xs:sequence>
        </xs:extension>
      </xs:complexContent>
    </xs:complexType>
    <!-- ==================================================================== -
->
    <xs:complexType name="NavigableSpaceMemberType">
      <xs:complexContent>
        <xs:extension base="gml:AbstractFeatureMemberType">
          <xs:sequence minOccurs="0">
```

```
                <xs:element ref="NavigableSpace"/>
            </xs:sequence>
            <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- =================================================================== -
->
<xs:element name="GeneralSpace" type="GeneralSpaceType" substitutionGroup="NavigableSpace">
    <xs:annotation>
        <xs:documentation>Denotin the interspace connections between the SpaceLayer
        </xs:documentation>
    </xs:annotation>
</xs:element>
<!-- =================================================================== -
->
<xs:complexType name="GeneralSpaceType">
    <xs:complexContent>
        <xs:extension base="NavigableSpaceType">
            <xs:sequence>
                <xs:element name="class" type="gml:CodeType"/>
                <xs:element name="function" type="gml:CodeType"/>
                <xs:element name="usage" type="gml:CodeType"/>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- =================================================================== -
->
<xs:element name="TransferSpace" type="TransferSpaceType" substitutionGroup="NavigableSpace">
    <xs:annotation>
        <xs:documentation>Denotin the interspace connections between the SpaceLayer
        </xs:documentation>
    </xs:annotation>
</xs:element>
<!-- =================================================================== -
->
<xs:complexType name="TransferSpaceType">
    <xs:complexContent>
        <xs:extension base="NavigableSpaceType">
            <xs:sequence>
                <xs:element name="class" type="gml:CodeType"/>
                <xs:element name="function" type="gml:CodeType"/>
                <xs:element name="usage" type="gml:CodeType"/>
            </xs:sequence>
        </xs:extension>
    </xs:complexContent>
</xs:complexType>
<!-- =================================================================== -
->
<xs:element name="AnchorSpace" type="AnchorSpaceType" substitutionGroup="TransferSpace">
    <xs:annotation>
        <xs:documentation>Denotin the interspace connections between the SpaceLayer
        </xs:documentation>
    </xs:annotation>
</xs:element>
```

```
    <!-- ====================================================================== -
->
    <xs:complexType name="AnchorSpaceType">
        <xs:complexContent>
            <xs:extension base="TransferSpaceType">
                <xs:sequence/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ====================================================================== -
->
    <xs:element name="ConnectionSpace" type="ConnectionSpaceType"
substitutionGroup="TransferSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -
->
    <xs:complexType name="ConnectionSpaceType">
        <xs:complexContent>
            <xs:extension base="TransferSpaceType">
                <xs:sequence/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
    <!-- ====================================================================== -
->
    <xs:element name="TransitionSpace" type="TransitionSpaceType"
substitutionGroup="TransferSpace">
        <xs:annotation>
            <xs:documentation>Denotin the interspace connections between the SpaceLayer
            </xs:documentation>
        </xs:annotation>
    </xs:element>
    <!-- ====================================================================== -
->
    <xs:complexType name="TransitionSpaceType">
        <xs:complexContent>
            <xs:extension base="TransferSpaceType">
                <xs:sequence/>
            </xs:extension>
        </xs:complexContent>
    </xs:complexType>
</xs:schema>
```

Annex B
(Normative)
Abstract Test Suites for IndoorGML Instance Documents

B.1 Test Cases for mandatory conformance requirements

B.1.1 Valid IndoorGML instance document

a) Test purpose	Verify the validity of the IndoorGML instance document against the XML Schema definition of each IndoorGML module that is part of the IndoorGML profile employed by the instance document. This may be any combination of IndoorGML extension modules in conjunction with the IndoorGML core module.
b) Test method	Validate the IndoorGML XML instance document against the XML Schema definitions of all employed IndoorGML modules. The process may be using an appropriate software tool for validation or be a manual process that checks all relevant definitions from the respective XML Schema specification of the employed IndoorGML modules
c) Reference	Annex A
d) Test type	Basic Test

B.1.2 Conformance classes related to IndoorGML modules

a) Test purpose	Verify the validity of the IndoorGML instance document against the conformance classes of each IndoorGML module that is part of the IndoorGML profile employed by the instance document. This may be any combination of IndoorGML extension modules in conjunction with the IndoorGML core module. Note that only indoor navigation extension is defined in IndoorGML v.1.0 but other extension modules are expected to be included.
b) Test method	Follow the test cases provided by the conformance classes for each IndoorGML module in annex B.2.
c) Reference	Annex B.2
d) Test type	Basic Test

B.1.3 Spatial geometry objects

a) Test purpose	Verify that all spatial geometry objects within an IndoorGML instance document adhere to the XML Schema definition of the Geography Markup Language version 3.2.1 and to the IndoorGML spatial model
b) Test method	Inspect the instance document and check that spatial geometry objects are valid with respect to the XML Schema definition of GML version 3.2.1 and satisfy the rules of to the IndoorGML spatial model described in clause 8.
c) Reference	OGC Document No. 03-105r1, Annex A, chapter 8 and 9.
d) Test type	Capability Test

B.2 Conformance classes related to IndoorGML Modules

B.2.1 IndoorGML Core Module

Mandatory conformance requirements

a) Test purpose	Verify that the IndoorGML instance document follows the IndoorGML Core module's rules for encoding of objects and properties and adheres to all its conformance requirements. This test case is mandatory for all IndoorGML instance documents
b) Test method	Inspect the instance document and check that it satisfies the rules of the IndoorGML Core module described in clause 8.
c) Reference	Clause 8
d) Test type	Capability Test

Valid IndoorGML instance document

a) Test purpose	Verify the validity of the IndoorGML instance document against the XML Schema definition of the IndoorGML Core module. This test case is mandatory for all IndoorGML instance documents.
b) Test method	Validate the IndoorGML XML instance document against the XML Schema definition of the IndoorGML Core module in annex A.1. The process may be using an appropriate software tool for validation or be a manual process that checks all relevant definitions from the IndoorGML Core module.
c) Reference	Annex A.1
d) Test type	Capability Test

B.2.2 IndoorGML Indoor Navigation Module

Mandatory conformance requirements

a) Test purpose	Verify that the IndoorGML instance document follows the IndoorGML Indoor Navigation module's rules for encoding of objects and properties and adheres to all its conformance requirements. This test case is mandatory for all IndoorGML instance documents which employ elements defined within the *IndoorNavigation* module
b) Test method	Inspect the instance document and check that it satisfies the rules of the IndoorGML Indoor Navigation module described in clause 9.
c) Reference	Clause 9
d) Test type	Capability Test

Valid IndoorGML instance document

a) Test purpose	Verify the validity of the IndoorGML instance document against the XML Schema definition of the IndoorGML Indoor Navigation module. This test case is mandatory for all IndoorGML instance documents.
b) Test method	Validate the IndoorGML XML instance document against the XML Schema definition of the IndoorGML Indoor Navigation module in annex A.2. The process may be using an appropriate software tool for validation or be a manual process that checks all relevant definitions from the IndoorGML Indoor Navigation module.
c) Reference	Annex A.2
d) Test type	Capability Test

Bibliography

[1] ISO 19107, *Geographic information – Spatial Schema*

[2] Lorenz, B., Ohlbach, H. J., Stoffel, E.-P., Rosner, M., *NL Navigation Commands from Indoor WLAN fingerprinting position data*, Technical Report of REWERSE-Project, Munich, Germany, September 2006

http://www.pms.ifi.lmu.de/publikationen/idefixStatic/rewerse-publications.html#REWERSE-DEL-2006-A1-D7, (accessed November 2010),

[3] Anagnostopoulus, C., Testsos, V., Kikiras, P., Hadjiefthymiades, S. P., *OntoNav: A Semantic Indoor Navigation System*, First International Workshop on Managing Context Information in Mobile and Pervasive Environments, Vol. 165, Ayia Napa, Zypern, 2003

[4] Kulyukin, V., Gharpure, C., Nicholson, J., *RoboCart: Toward Robot-Assisted Navigation of Crocery Stores by the Visually Impaired*, Proceedings of the international Conference on Intelligent Robots and Systems, IROS 2005, IEEE/RSJ

[5] Lefebvre, S., Hornus S. *Automatic cell-and-portal decomposition*. Technical Report 4898, INRIA, 2003. http://artis.imag.fr/Publications/2003/LH03/ (accessed November 2010).

[6] Lee, J., *3D GIS for Geo-coding Human Activity in Micro-scale Urban Environments,* M.J. Egenhofer, C. Freksa, and H.J. Miller (Eds.): GIScience 2004, Springer, Berlin, Germany

[7] Lee, J., Zlatanova, S., *A 3D data model and topological analyses for emergency response in urban areas*. Geospatial Information Technology for Emergency Response – Zlatanova & Li (eds), Taylor & Francis Group, London, UK, 2008

[8] Munkres, J. R., *Elements of Algebraic Topology*, Addison-Wesley, Menlo Park, CA, 1984

[9] Kolodziej, K. W., Hjelm, J., *Local Positioning Systems – LBS Applications and Services*, Taylor & Francis Group, London, UK, 2006

[10] OGC, CityGML, OGC 08-007r1 2008

[11] Kolbe, T.H., Gröger, G. & Plümer, L. *CityGML – Interoperable Access to 3D City Models,* P. van Oosterom, S. Zlatanova & E.M. Fendel (eds), Geo-information for Disaster Management; Proc. of the 1st International Symposium on Geo-information for Disaster Management', Delft, The Netherlands, March 21–23, 2005. Springer.

[12] Adachi, Y., Forester, J., Hyvarinen, J., Karstila, K., Liebich, T., Wix, J., *Industry Foundation Classes IFC2x Edition* 3, International Alliance for Interoperability, 2003, http://www.iai-international.org.

[13] Liao, L., Fox, D., Hightower, J. Kautz, H., Schulz, D., *Voronoi Tracking: Location Estimation Using Sparse and Noisy Sensor Data*, Proc. of the International Conference on Intelligent Robots and Systems, IROS 2003, IEEE/RSJ

[14] Egenhofer, M., Herring, J., *Categorizing Binary Topological Relations between Regions, Lines and Points in Geographical Databases*, NCGIA Technical Report, 1990

[15] OGC, *The Specification Model – A Standard for Modular specifications*, OGC 08-131r3, OGC Version: 1.0.0

[16] LaValle, S. M, *Planning Algorithms* Cambridge University Press, USA, 2006

[17] Lorenz, B., Ohlbach, H. J., Stoffel, E.-P., Rosner, M., *Towards a Semantic Spatial Model for Pedestrian Indoor Navigation,* Lecture Notes in Computer Science - Advances in Conceptual Modeling – Foundations and Applications, Volume 4802/2007, Springer, Berlin, Germany

[18] Morris, Sidney A., *Topology without Tears*, University of Ballarat, Australia, http://uob-community.ballarat.edu.au/~smorris/topology.htm, (accessed November 2010), 2007

[19] Fritsch, R. and Piccinini, R. A., *Cellular Structures in Topology*, Cambridge University Press, Cambridge, England, 2008

[20] Gold, C. M. and Ledoux, H., *Simultaneous Storage of Primal and Dual Three-Dimensional Subdivisions,* Computers, Environment and Urban Systems – Topology and Spatial Databases, Vol. 31, Issue 4, 2007, Elsevier

[21] Becker, T., Nagel, C., and Kolbe, T. H., *A Multilayered Space-Event Model for Navigation in Indoor Spaces*, Lecture Notes in Geoinformation and Cartography - 3D Geo-Information Science, 2008.

[22] Becker, T., Nagel, C., and Kolbe, T. H., 2009. *Supporting Contexts for Indoor Navigation using a Multilayered Space Model*, Tenth International Conference on Mobile Data Management:systems, services and middleware, 2009. MDM '09 ; 18 - 20 May 2009, Taipei, Taiwan. Online available http://ieeexplore.ieee.org/servlet/opac?punumber=5088898 (accessed November 2010)

[23] Booch, G., Rumbaugh, J., and Jacobson, I., *Unified Modeling Language User Guide*, Addison-Wesley, 1997

[24] Lee, Y.C., *Geographic information systems for urban applications: Problems and solutions*, Environment and Planning B: Planning and Design, Vol. 17:463-473, 1990.

[25] Lee, J. *2004. A Spatial Access Oriented Implementation of a Topological Data Model for 3D Urban Entities, GeoInformatica* 8(3), 235-262.

[26] Nagel, C., Becker B., Kaden, R., Li, K-J., Lee, J., and Kolbe, T. H., *Requirements and Space-Event Modeling for Indoor Navigation*, OGC 10-191r1, 2010

[27] Lee, J. *Indoor Spatial Data Model,* Proc. ISA Workshop, Seoul, Korea, Aug. 2008