Open Geospatial Consortium

Date: 2010-12-11

Internal reference number of this document: OGC 10-191r1

Category: OpenGIS® Discussion Paper

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Requirements and Space-Event Modeling for Indoor Navigation

How to simultaneously address route planning, multiple localization methods, navigation contexts, and different locomotion types

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Document type: OpenGIS® Discussion Paper
Document subtype:
Document stage: Approved for Public Release
Document language: English

Contents

i. Preface

This OpenGIS® Discussion Paper presents a Multilayered Space-Event Model for indoor navigation which simultaneously addresses route planning, multiple localization methods, navigation contexts, and different locomotion types. The paper contains the corresponding data models as well as their encoding in GML 3.1.1 which at first address a fundamental framework for navigation. To facilitate the development of a complete indoor navigation standard on top of this framework, the concepts introduced in this paper will be augmented in the future. This document is meant to serve as a basis for both discussion and development of an OGC Standard on Indoor Navigation.

The research and development presented in this paper has been carried out within the Indoor Spatial Awareness (ISA) project. The ISA project is a R&D project funded by the Ministry of Construction and Transportation, Korea which has been launched in November 2007. ISA is an internal collaboration project with partners from academia and industry in South Korea, USA, Germany, and Denmark.

The concepts for deriving a network topology model from a 3D CityGML building model based on a subdivision of rooms into smaller cells as introduced in "OWS-6 Outdoor and Indoor 3D Routing Services Engineering Report" (OGC Doc. No. 09-067r2) have been considered in the development and are fully covered by the Multi-layered Space Model proposed in this Discussion Paper.

This paper documents the developments that have been presented at OGC 3DIM DWG over the last 18 months. Some of the presentations can be obtained from the OGC Portal at the following URLs:

- June 2009, 3DMIN face-to-face meeting in Boston-MIT:
  http://portal.opengeospatial.org/files/?artifact_id=34587
- December 2009, 3DIM face-to-face meeting in Mountain View:
  http://portal.opengeospatial.org/files/?artifact_id=36918
- September 2010, 3DIM face-to-face meeting in Toulouse:
  http://portal.opengeospatial.org/files/?artifact_id=41027
  http://portal.opengeospatial.org/files/?artifact_id=41079

Suggested additions, changes, and comments on this draft Discussion Paper are welcome and encouraged. Such suggestions may be submitted by email message or by making suggested changes in an edited copy of this document.

ii. Submitting organizations

This Discussion Paper was submitted to the Open Geospatial Consortium Inc. by the following organizations:

- Institute for Geodesy and Geoinformation Science, Technische Universität Berlin
- Department of Geoinformatics, University of Seoul, Korea
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iv. Revision history

Date	Release	Editor	Description
2010-11-11	0.1.0	Nagel, Becker, Kaden, Kolbe	First draft version 0.1.0 of the document
2010-11-28	0.1.0	Nagel, Becker, Kaden, Kolbe	Minor editorial changes to the document structure and introduction of an example for the application of the Multilayered Space-Event Model

Foreword

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. The Open Geospatial Consortium Inc. shall not be held responsible for identifying any or all such patent rights.

Recipients of this document are requested to submit, with their comments, notification of any relevant patent claims or other intellectual property rights of which they may be aware that might be infringed by any implementation of the standard set forth in this document, and to provide supporting documentation.

0 Introduction

Over the last decade, personal navigation systems became an established tool for route planning and guidance of individual traffic using cars and other vehicles. From the technical aspect this was made possible mainly due to the availability of global localization techniques like GPS on the one side and the acquisition and provision of the road network for large parts of the world on the other side. Pedestrian navigation systems are not as successful as car navigation systems yet. The crucial point is that pedestrians can freely move inside and outside of buildings, but satellite localization still only works outdoor and information about navigation space is mainly available for the outdoor environment so far. However, indoor navigation would be helpful for finding locations like shops, police, rest rooms, or (check-in) counters inside of airports, shopping malls, or public buildings. In an emergency response situation indoor navigation could provide escape routes from buildings and fastest routes for rescue personnel to a disaster area.

In general, navigation comprises 1) the determination of the location of a subject or object, 2) the determination of the best path (often the fastest, the shortest, or the cheapest) from a start to an end location, and 3) guidance along the path which includes monitoring of the difference between the current position and the path and enforcement of appropriate actions to minimize the difference. To facilitate a navigation system, consistent geoinformation about the navigable indoor space including lists of localities, e.g. named places and their coordinates, and navigable route sections need to be available. An appropriate localization infrastructure or technology has to be included to determine the current position and (usually) orientation as well as to perform tracking of moving subjects or objects. Navigation requires spatial reference systems which typically include the spatial reference of the localization method which might be a local or world coordinate system as well as the natural spatial reference system of the user for naming of start and end points. The latter one is often not a coordinate system but e.g. addresses or points of interest. Finally, methods for position and route communication are required.

Indoor navigation highly depends on context and requires flexible data structures to support the many use cases and configurations. For example, an indoor navigation system must cope with different and varying localization techniques and infrastructures. Each technology requires different installations and different capabilities of the mobile end-user devices. Also physical constraints from the built-up environment, different modes of locomotion (like walking, driving, or flying), and thematic or logical restrictions like security zones have to be considered. Each of these constraints requires a specific and separate partitioning of indoor space into navigable and non-navigable areas which directly influence the derivation of a navigable route network for a given context of navigation.

In the past, different models for structuring indoor space and localization methods have been proposed. In most cases space is partitioned only due to route planning and addressing criteria. Often localization technology and sensor characteristics are mixed within these models which has the disadvantage that changes to the building structure or sensor configurations may affect the entire model. For example, changes to room topology (e.g., a door will be closed permanently or a new door will be installed within a wall) does not necessarily have an impact on the localization infrastructure like Wi-Fi access points or RFID sensors and vice-versa. Furthermore, these models usually restrict the navigation context to one or a limited subset of possible configurations. Although they are well-suited for their fixed and specific configuration, the proposed models lack the flexibility to support additional configurations such as additional modes of locomotion, different sensors, etc.

From this we can conclude the following minimum requirements for a flexible data model supporting indoor navigation:

- **Support for different and multiple localization methods/infrastructures**
  This includes support for arbitrary indoor sensor technologies and their abstraction, e.g. WiFi, RFID, Bluetooth, or Infrared as well as support for the ad-hoc selection of technologies used by the portable end-user device.
- **Support for different navigation contexts**
  The navigation context comprises the type of locomotion, navigation constraints according to different criteria (e.g.: topographic/geometric constraints, such as door widths, opening directions of doors, zonal constraints such as security zones, or temporal access constraints such as opening hours) and the supported localization technique.

- **3D topographic representation of the interior built environment**
  This is required for route planning and derivation of navigable route section from a model of the indoor built-up space. The representation should avoid duplicating existing concepts and, thus, should be complementary to existing standards like CityGML, IFC, X3D, ESRI BISDM, etc.

This talk will present a Multilayered Space-Event Model for indoor navigation meets addresses these requirements and which simultaneously addresses route planning, multiple localization methods, navigation contexts, and different locomotion types.

REQUIREMENTS AND SPACE-EVENT MODELING FOR INDOOR NAVIGATION

How to simultaneously address route planning, multiple localization methods, navigation contexts, and different locomotion types

1 Scope

This OpenGIS® Discussion Paper presents a Multilayered Space-Event Model for indoor navigation which simultaneously addresses route planning, multiple localization methods, navigation contexts, and different locomotion types. The paper contains the corresponding data models as well as their encoding in GML 3.1.1.

2 Conformance

XML files must be validated against the XML Schema document provided in the normative Annex A and fulfill all further rules and requirements given in this OpenGIS® Discussion Paper.

3 Normative references

The following referenced documents are indispensable for the application of this OpenGIS® Discussion Paper.

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 19123:2005, *Geographic Information – Coverages*

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

OpenGIS® Abstract Specification Topic 0, *Overview, OGC document 99-100r1*

OpenGIS® Abstract Specification Topic 5, *The OpenGIS Feature, OGC document 99-105r2*

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

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

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 Conventions

4.1 Abbreviated terms

The following abbreviated terms are used in this document:

2D	Two Dimensional
3D	Three Dimensional
AEC	Architecture, Engineering, Construction
B-Rep	Boundary Representation
CAD	Computer Aided Design
CAAD	Computer Aided Architectural Design
CSG	Constructive Solid Geometry
DXF	Drawing Exchange Format
FM	Facility Management
GDF	Geographic Data Files
GML	Geography Markup Language
IAI	International Alliance for Interoperability
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
OGC	Open Geospatial Consortium
TC211	ISO Technical Committee 211
UML	Unified Modeling Language
URI	Uniform Resource Identifier
W3C	World Wide Web Consortium
XML	Extensible Markup Language

4.2 UML Notation

The data model specification is presented in this document in diagrams using the Unified Modeling Language (UML) static structure diagram (cf. [23]). The UML notations used in this standard are described in the diagram below (Fig. 1).

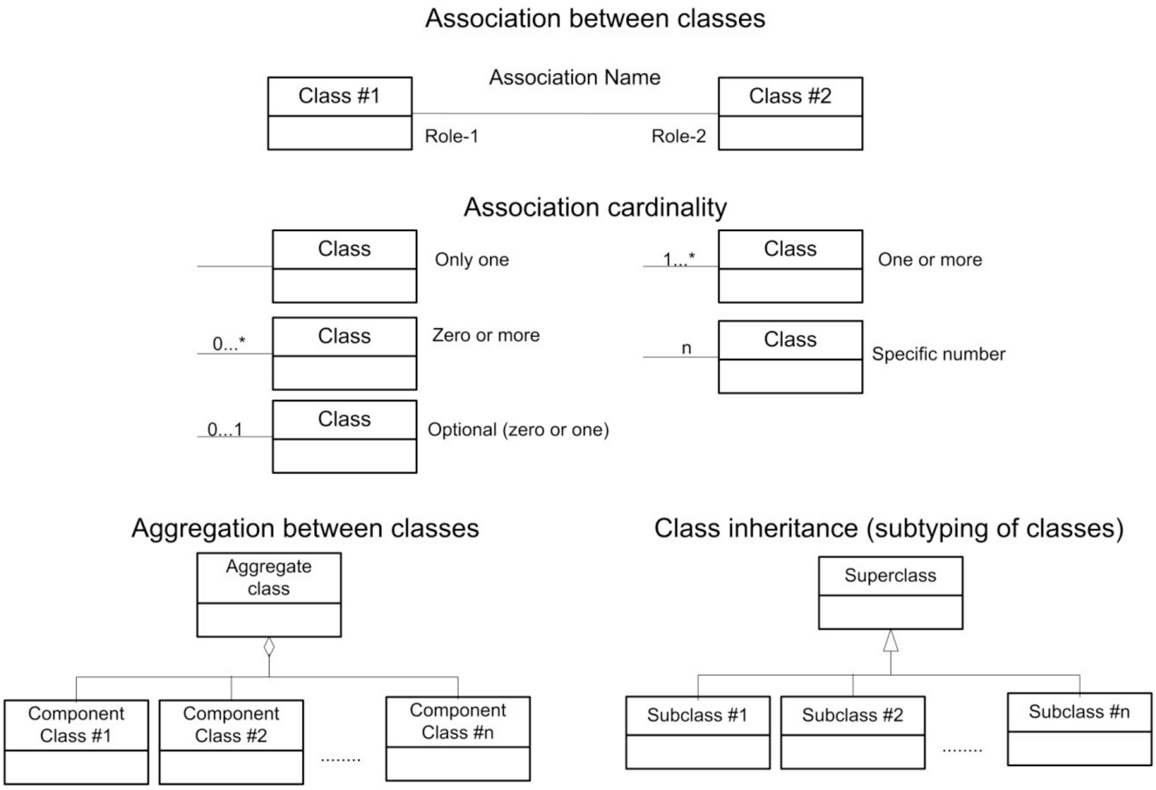


Fig. 1: UML notation (cf. ISO TS 19103, Geographic information - Conceptual schema language).

The following stereotypes are used:

<<Geometry>> represents the geometry of an object. The geometry is an identifiable and distinguishable object that is derived from the abstract GML type *AbstractGeometryType*.

<<Topology>> represents the topology of an object. The topology is an identifiable and distinguishable object that is derived from the abstract GML type *AbstractTopologyType*.

<<Feature>> represents a thematic feature according to the definition in ISO 19109. A feature is an identifiable and distinguishable object that is derived from the abstract GML type *AbstractFeatureType*.

<<Enumeration>> enumerates the valid attribute values.

4.3 XML-Schema

The normative parts of the specification use the W3C XML schema language to describe the grammar of conformant data instances. XML schema is a rich language with many capabilities. While a reader who is unfamiliar with an XML schema may be able to follow the description in a general fashion, this specification is not intended to serve as an introduction to XML schema. In order to have a full understanding of this Discussion Paper, it is necessary for the reader to have a reasonable knowledge of XML schema.

5 Requirements for an Indoor Navigation Standard

Indoor navigation faces a large number of challenges that differ from well established outdoor navigation methods. Absolute positioning and localization methods like GPS are usually not available in indoor environments. Route planning requires geoinformation about the interior navigable space of buildings. The navigable space may not only reflect the physical built environment but has to consider the mode of locomotion of the moving subject or object and logical navigation constraints such as security zones and opening hours. Spatial reference systems are required both for the localization method and for the end-user. Whereas the former might be a locale or world coordinate system, the latter is rather a natural spatial reference system which is used, e.g., for naming of route start and end points. The communication of the current position and of routing commands poses further challenges.

In the following subsections of this chapter, mandatory requirements are deduced from these challenges which have to be addressed and answered by any proposals and approaches aiming at establishing an Indoor Navigation Standard. Based on this discussion, a novel and generic Multilayered Space-Event Model is introduced in the further course of this Discussion Paper which meets these requirements and thus forms the basis and a general framework for an Indoor Navigation Standard.

5.1 Support of Different Navigation Contexts

Indoor navigation comprises route planning as well as localization and tracking of moving subjects or objects within interior built environments. Both aspects of indoor navigation depend to a great extent upon the context of navigation which is constituted by three main factors. A first factor is the mode of locomotion of the moving subject or object such as walking, driving (e.g. using a wheel chair, mobile robots), or even flying (e.g., quadrocopter), which defines and restricts the navigable topographic space. Second, the context of navigation is determined by logical contexts representing pre-knowledge or navigation constraints which result from specific application domains. The third factor is the localization technique and the localization infrastructure. Amongst others, this comprises the methods used for localization and tracking, the positioning and ranges of sensors and transmitters, and the technical characteristics and capabilities of end-user devices.

The support of different contexts of navigation leads to a configuration problem with a high degree of combinatorial complexity. Current models for indoor navigation often reduce this complexity by tailoring the context of navigation to either one specific configuration or a limited subset. The interior built environment is partitioned due to one mode of locomotion and the corresponding route planning and addressing criterions and considering a given localization technology and its sensor characteristics. Often a geometric route network for indoor navigation is proposed, which maps the resulting subdivisions of indoor space to a graph structure representing topological connectivity. Further navigation relevant aspects of the fixed navigation configuration are introduced into this graph as a set of homogenous attributes for nodes and edges. While these approaches are well suited for a single configuration, they lack the flexibility to support multiple contexts such as additional modes of locomotion or different localization techniques. Thus, the support for multiple and different navigation contexts is an essential requirement for a general indoor navigation standard.

5.1.1 Multiple and Different Localization Methods and Infrastructures

The localization of moving subjects and objects is one of the key issues of indoor navigation as there is no absolute positioning method such as GPS available so far. Current approaches usually apply specialized solutions and configurations tailored to their specific application scenario based on sensor technologies such as Barcodes, Radio Frequency ID (RFID), Infrared Beacons, Ultrasound, Bluetooth, Wireless LAN (WiFi) and Pseudo-GPS (Pseudolites). Even though these sensors are different, most of them have comparable spatial characteristics, e.g. visibility area, coverage area or signal propagation. The absolute position of portable devices can be derived from the locality of sensors or transmitters, their covered areas and the observed signals and signal strength. The uncertainty is equal to the size of the respective area of a unique signal constellation. Each technology requires different installations in indoor environments and capabilities of the end-user devices. With the increasing number of available sensor technologies, the degree of combinatorial complexity of the navigation context is increasing as well.

An indoor navigation standard must support multiple and different localization methods and infrastructures based on arbitrary indoor sensor technologies. Furthermore, the ad-hoc selection and combination of technologies used by the portable end-user device must be supported. This requires the abstraction from concrete sensor technologies in order to allow for their integrated representation in a common model.

5.1.2 Multiple and Different Modes of Locomotion

Geoinformation about the interior built environment is nowadays available through semantic 3D city and building models, such as CityGML or IFC, which provide the geometry and the thematic differentiation of indoor structures and areas. This thematic differentiation is already suitable for addressing, route descriptions, and route tracking (homing), e.g. by room numbers. The derivation of navigable spaces and corresponding route networks, however, requires further partitioning of the built indoor space according to the mode of locomotion, e.g. walking, driving, and flying. Each mode of locomotion may lead to a specific and separate partitioning of indoor topographic space into navigable and non-navigable areas. Thus, for different modes of locomotion the resulting navigable areas may be disjoint, overlapping or equal.

For example, the navigable space for persons using a wheel chair may not include areas and obstacles which are inaccessible by a wheel chair, such as stairs, steps or narrow passages. Since those areas may, however, be accessible for pedestrians, the navigable and non-navigable spaces for different types of locomotion have to be modeled separately from each other. An indoor navigation standard must support multiple and different representations of navigable spaces according to various modes of locomotion as well as the selection of the appropriate representation for the individual navigation context of a moving subject or object.

5.1.3 Logical Navigation Constraints

In addition to the mode of locomotion, the derivation of navigable route sections is also strongly affected by thematic or logical constraints and restrictions. For example, security zones or evacuation areas denote logical spaces within buildings which influence the accessibility of indoor areas such as rooms or hallways. Navigation constraints may result from different criteria, e.g. topographic/geometric (door widths, opening direction of doors, etc.), zonal (security zones, fire detector areas, etc.), or temporal access constraints (opening hours, etc.). Although logical spaces may lead to a further partitioning of the navigable space denoted by the mode of locomotion, their spatial extent does not necessarily has to follow the physical built structure of the interior environment. For example, a security zone may split a single room into accessible and non-accessible parts, and may even affect outdoor areas around the building. Furthermore, navigation constraints can vary according to the individual context of navigation. For example, security staff members usually have access permission to interior areas which are not accessible for other persons.

An indoor navigation standard has to support logical navigation constraints. They should be represented independently from the topographic interior space as changes of the interior built environment not necessarily have an impact on their spatial extent. Finally, the context-dependent selection of navigation constraints must be supported.

5.1.4 Support for Dynamic Aspects

Logical spaces may describe temporal and dynamic phenomena, e.g. areas covered by fire detectors which temporally affect the navigable space in case of a fire emergency. An active fire detector indicates a fire incident for its monitored area. This, however, may lead to two different navigation scenarios. The first is to navigate fire fighter forces to the fire spot, whereas the second aims as determining escape routes avoiding the dangerous area in order to evacuate the building. As soon as the fire has been fought, the fire detector will become inactive again giving general access to its monitored area.

Such temporal restrictions in navigable space require a flexible model, especially if the temporal restriction causes ad-hoc changes of the navigation context. For example, the determination of escape routes for immediate evacuation in case of a fire emergency may additionally require the deregulation of access restrictions due to security zones. The support of dynamic aspects and corresponding flexible models are essential requirements for an indoor navigation standard.

5.2 Modeling of Interior Spaces

5.2.1 Compatibility to Existing 3D Building Models

Semantic models for the representation of 3D topographic indoor space nowadays become increasingly available in the context of Building Information Modeling (BIM) and in the field of 3D city modeling. An indoor navigation standard must be complementary to these existing data models and standards, such as OGC CityGML [10, 11], IFC [12], X3D, or ESRI BISDM, in order to avoid duplicating existing concepts for the representation of interior built environment. Also referencing or embedding of the original 3D building models given in one of these formats should be supported. The indoor navigation standard should however not be restricted to 3D models; it should also be open for 2D floor plans.

5.2.2 Hierarchical Grouping of Spaces

Current standards for semantic building models often employ a hierarchical aggregation concept which allows for the semantic and geometric decomposition of a building into storeys which again are decomposed into rooms and hallways. This aggregation hierarchy and decomposition of features into smaller parts reflects the structural and spatial assembly of the built environment. Beyond the physical built structure, rooms may further be subdivided due to specific aspects of the navigation context such as the mode of locomotion or logical navigation constraints, but may also be induced by limited propagation areas of sensor-based positioning systems. This leads to sub-spacing the topographic space into even smaller parts. For example, the navigable space for driving subjects or objects such as wheel chair users or mobile robots is a subset and finer grained partitioning of the topographic space which neglects obstacles such as stairs, steps, or narrow passages. And although an L-shaped hallway might be entirely accessible for mobile robots, a further subdivision into smaller parts could be required in order to derive geometric trajectories between these parts which can be automatically followed by autonomous mobile robots. So different topographical and logical decompositions may constitute different subsets of a room and therefore a separation into hierarchical grouped layers is reasonable.

Also routing algorithms often employ hierarchical strategies. When querying a route, the algorithm has to first search for the correct building before it considers the layer of the building storeys. Once the correct storey is determined, its decomposition into rooms and even further subspaces is taken into account. Therefore, an indoor navigation standard has to support hierarchical grouping of spaces in order to facilitate a separation of spaces due to topographical (e.g. modes of locomotion) and logical (e.g. security zones) aspects and the implementation of effective routing algorithms.

5.2.3 Mathematically Sound Framework

Navigation approaches base on network topology models describing connectivity and adjacency between interior spaces such as rooms and hallways. However, a semi-automatic or even manual derivation of the network topology from the building topography as proposed by several current approaches faces severe disadvantages since it may lead to multiple and different graph structures for even the same interior built environment. An indoor navigation standard must therefore be built on top of a mathematically sound framework which defines a functional dependency between the representation of building topography (including subspaces and logical spaces) and the corresponding topological graph structure denoting adjacency and connectivity. This allows for fully automatic derivation of deterministic network topology models with a consistent reproducibility. And moreover, a mathematically sound framework with a clear definition of how to derive the network topology model from the 3D building topography is a mandatory prerequisite for supporting arbitrary 3D building modeling approaches (cf. section 5.2.1).

5.3 Practical Considerations

5.3.1 One Storage and Exchange Format Covering all Processing Steps

The indoor navigation standard shall include a data format which allows storing and exchanging navigation data over all processing steps and transferring the data with individual application relevant content to the end-user device based on existing OGC standards for the transfer of navigation data. The exchange format must support data storage for selected navigation contexts and the derived routable network sections for different types of locomotion. It is required to be flexible for representing different grades of information, e.g. with or without original 3D input models.

5.3.2 Extensibility

Indoor navigation is subject to multiple influencing factors. New technologies for indoor localization are developed, additional modes of locomotion might have to be considered, and any kind of knowledge may be modeled as logical space restricting the navigable space. Therefore, an indoor navigation standard has to be extensible in order to meet future requirements. This comprises an extension mechanism to augment the standard in order to model and exchange data which is not yet covered (cf. CityGML's Application Domain Extension mechanism). But it also addresses a future integration with outdoor navigation in order to define a general framework for seamless navigation in indoor and outdoor spaces.

6 Theoretical Background

6.1 Geometric Modeling of Buildings and their Interiors

Every relevant topographic object of building space has a shape, extent, position and appearance that can be measured and modeled. The abstraction of the real world can be described by geographical features having a 3-dimensional geometrical representation in the metrical space IR^3. Using the concepts of metrics and metric spaces the geometry provides the means for the quantitative description of the spatial characteristics of features.

A metric space is defined as [18]:

Let X be a set and *d* a real value. A mapping $d : X \times X \rightarrow IR$ is called a metric, if for all elements x, y and z from X the following axioms are fulfilled:

- *d*(x, y) = 0; if and only if y = x
- *d*(x, y) = *d*(y, x)
- *d*(x, y) + *d*(y, z) ≥ *d*(x, z) (Triangle inequality, for x, y, z in X)
- *d*(x, y) ≥ 0

Then, *d* is said to be a *metric* on X; (X, *d*) is called a metric space and *d*(x, y) is referred as the distance between x and y.

The international standard for geographic information (ISO19107 [1]) provides conceptual schemas to describe and model real world objects as features. The included geometry package contains various classes for coordinate geometry. The mathematical functions which are used for describing the geometry of an object depend on the type of coordinate reference system which is used to define the spatial position.

A subset of the metric space is the well known Euclidean Space. The Euclidean space is a metrical space with the Euclidean distance as a metric. In the general case of the n-dimensional space IR^n, the Euclidean distance is defined between two points or vectors by the Euclidean norm of the difference vector between these points. If $x = (x_1, \ldots, x_n) \; and \; y = (y_1, \ldots, y_n)$ are two points of an n-dimensional space,:

$$d(x, y) = |x - y| = \|x - y\|_2 = \sqrt{(x_1 - y_1)^2 + \ldots + (x_n - y_n)^2} = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2}$$

is the Euclidian metric on this n-dimensional space [18].

The Euclidean Space is used to model real world objects like buildings and their interiors in the field of CAD (Computer Aided Design), computer graphic, IFC (Industry Foundation Classes [12]) or CityGML [10], by using cartesian coordinates. CAD systems mostly use the Constructive Solid Geometry (CSG) to represent complex geometrical objects (Solids). Complex solid objects are represented as Boolean combination (union, intersection and difference) of simpler objects (primitives) such as cylinders, cones, spheres, pyramids or cubes. In contrast to CSG, 3D objects modeled in Boundary Representation (B-rep), e.g. as it is realized in CityGML [10], are geometrically represented by its boundary surface in IR^3 [cf. fig. 2]. Using geometric primitives, such as vertices, edges, and faces, allows more flexibility for modeling irregular geometric objects.

The interior rooms of a building are represented as volumes in Euclidean space (3D → IR^3) by boundary representation.

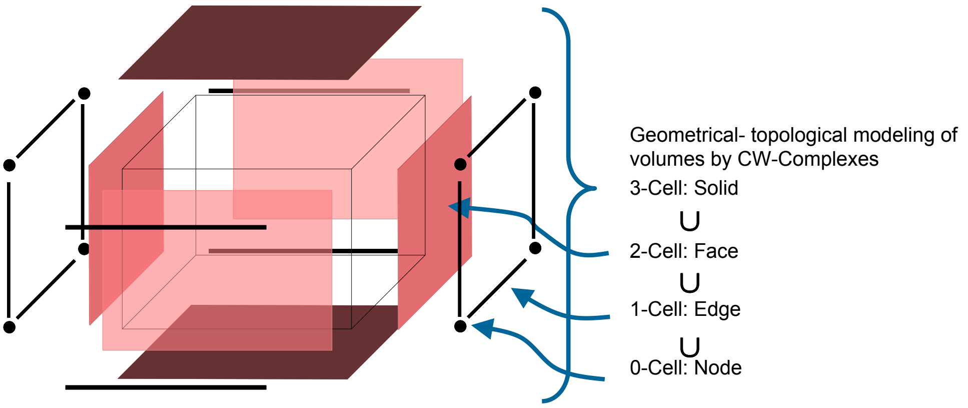


Fig. 2: Representation of a 3D-Solid by B-Rep in Geometry and by CW-Complexes in Topology

Since the Euclidean space is a metric space, a natural topology such as neighborhood, interior, outer and boundary is induced. In case of transforming geographic information from one geodetic reference or coordinate system to another, only geometry will be changed. Topology represents an invariant structure with respect to transformations.

6.2 Topological Modeling of Buildings and their Interiors

Geometric calculations such as point-in-polygon strategies, adjacency and boundary are computationally intensive. Therefore, combinatorial structures, known as topological complexes, are constructed. Computational topology provides information about the connectivity of geometric primitives that can be derived from its corresponding geometry. The introduction of a topology allows a unique interpretation of position relations like “near by” and ”tends to” on quite general structures.

A topological space is a set X consisting of subsets T (called open sets) from X, if the following axioms are fulfilled:

- The empty set and the basic set X are open sets.
- The intersection of any finite open sets is an open set.
- The union of any open sets is an open set.

A set X together with a topology T on X is called topological space (X, T) [8], [18]

Within a topological space every point x has a filter U (x) of surroundings.

A subset U of a topological space (X, T) is called surrounding of the point $x \in X$, if an open set O with $x \in O \subseteq U$ exists. Therefore the concept “Near by” can be specified mathematically. An open subset $U \subseteq X$ which contains x is called (open) surroundings from x. The open surroundings determine the topology (that is the family O of the open sets): a set is open if it contains surroundings to each of its points.

Examples:

1. The IR^n is a topological space, with its topology

$$T := \{U \subseteq IR^n : \textit{for each } x \in U \textit{ contains } U \textit{ a } \varepsilon - \textit{surrounding } B_\varepsilon(x) \textit{ of } x\}$$

2. Is (X, d) a metrical space, so is

$$T_d := \left\{ \begin{matrix} U \subseteq X : \text{ for each } x \in U \text{ there is a } \varepsilon > 0 \\ with \{x \in X : d(x,y) < \varepsilon\} \subseteq \mathrm{U} \end{matrix} \right\}$$

a topology. T_d is referred to as the topology induced by the metric *d*, and (*X, T*) is called the induced topological space [18].

The topological model is closely related to the representation of spatial relationships among objects in geographic phenomena. As mentioned before, the geographic phenomena (features) are mostly geometrically represented in Euclidean space by Cartesian coordinates in IR^3 and this metric space induces a natural topology. Therefore, the metric defines relationships like adjacency, interior, outer, and boundary between objects, e.g. spaces relating to a building. To describe those topological relations, e.g. closure, interior, boundary, separated, and connected, in conjunction with Euclidean distances, the concept of CW-complexes [8] can be applied. The concept bases on a so called n-cell classification where n denotes the dimension of the cell. 0-cell represents a vertex, 1-cell a line or edge, 2-cell represents a face and 3-cell is a solid [cf. fig. 3]. The cells do not need to have the same size but they will all be of some limited range of sizes according to the used granularity of space.

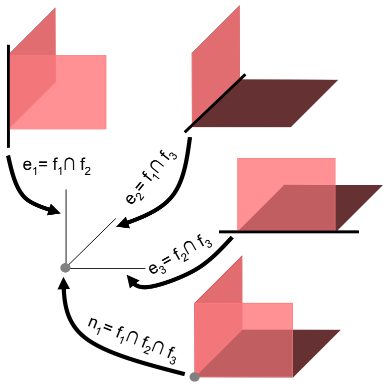


Fig. 3: Topology derived from geometry objects

A conceptual schema for this purpose is defined in the topology package of ISO 19107. The topological system of ISO 19107 is based on algebraic manipulations of multivariate polynomials. The package is defined in a way that geometric problems can be translated from geometric part into algebraic problems in the topology part. Problems can be solved in the topology domain and then translated back.

The most essential information in case of navigation is topology specifying adjacency and connectivity between objects. The most 3D data models such as CityGML or IFC do not employ the topology package of ISO 19107 due to its complexity. However, a solution for getting the topological structure of those models is to derive the topological relationships between objects from their geometrical representation [cf. fig. 3]. This can be done by using the induced natural topology of objects represented in boundary representation (i.e. the result of an intersection of two faces is an edge). In order to implement topology, CityGML uses the XML concept of XLinks provided by GML. The XLink topology is simpler to implement than the topology package of ISO 19107, but a query to detect topologically connected objects can only be performed in one direction. Nevertheless, it is possible to derive an ISO 19107 topology model from such a CityGML dataset.

6.3 The Notion of Cellular Space

In semantic 3D building models, spaces within buildings are modeled by non-overlapping room objects (cf. [10, 11]). This representation of indoor environment is suitable for the derivation of a room-to-room connectivity graph. However, Lorenz [2] and Lefebvre [5] propose a more differentiated decomposition of the semantic room entities. The room itself is geometrically fragmented into so-called cells, which again represent non-overlapping parts of the room. In the context of navigation, the concept of cells is often used but there is no valid definition for cells or cellular space in matters of navigation purposes. Other valid definitions of cells in context of other fields of sciences have been considered in order to increase the understanding:

- In biology a cell is the structurally smallest visible unit of living being and shows an independent, self-preserving, separately system in itself. It contains for its functions and activities all necessary information [16]. The “topological” relations between cells in biology are that they are only adjacent, do not overlap and are not disjoint.
- In the mobile radio technology a cell represents the smallest geographical radio supply area of a radio network. The cells are differentiated into picocells, microcells, and macrocells according to the coverage area of the radio signal transmitted by a radio mast [17]. In contrast to cells in biology, cells in mobile radio may overlap. Mostly, if two radio masts are adjacent their reception areas overlap. For simplifying the reception areas of two radio masts they are considered as a cell and two adjacent cells have

one bounding border (edge). A further possible relation between two radio cells is a disjoint one, if a gap between them exists.

- In the field of robotics one of the main problem is robot motion planning. The emphasis is on providing the robot and its programmer with a basis for a path planning system. Therefore the free space is partitioned into cells. These cells are represented as nodes and stored in a connectivity graph. Within mobile robotics systems a cell represents the structurally smallest unit of the topographic space, in such a kind that the union of all cells located in a space arise again a space [16]. The solid object is decomposed into cells of different size or shape. The cells (e.g. Voronoi cells) can have the same shape like tetrahedra or be arbitrary polyhedra [20]. Unlike the relations between mobile radio cells, in fields of mobile robotics cells do not overlap and are not disjoint. They touch each other in such a way that all cells located in a space arise again a space.
- In topology a cell is a topological space homeomorphic to a simplex or equally to a ball. The standard models used in cellular topology to describe cells are balls and balloons. B_n is the unit ball of dimension n and the boundary of B_n is the sphere with dimension n-1. A cell of dimension n is topologically equivalent with B_n, and an open cell of dimension n is topologically equivalent with the interior of B_n [19]. As mentioned before in section 3, cells in a topological space must not overlap but touch.

There are quite different definitions and understandings of cells, but they all represent the smallest independent structural unit of an overall structure. The Cellular Space itself is composed of cells, which represent the structurally smallest unit of the respective space. Cells can have different sizes or shapes and every cell of the respective space includes information relevant for the navigation model. Smaller partitions of the topographic space according to a semantic decomposition of objects (rooms) provide the necessary means for a more precise indoor route planning. The covered space of 3D solid objects of building and sensor space has to be decomposed or subdivided into a finite set of partitions, i.e. into 3D elements that will be referred to as Cells. Using Cells allows for a closer relation to symbolic representation, as an infinite and unbounded set of points can be now considered as a discrete, finite and bounded set.

6.4 Semantic Modeling of Buildings and their Interiors

Current and new applications of 3D city and building models like environmental and training simulations, urban planning and facility management, disaster management and homeland security, as well as personal (indoor) navigation require additional information about buildings besides their spatial and graphical aspects. In particular, the ontological structure including thematic classes, attributes, and their interrelationships such as specialization and aggregations hierarchies has to be defined. This semantic modeling allows for the decomposition of objects into parts due to logical criteria (and not due to graphical or purely geometrical considerations!) which follow structures that are given or can be observed in the real world. For example, a building will be decomposed into different (main) building parts, if they have different roof types and their own entrances like a house and the garage. The interior areas of each building can be further (hierarchically) partitioned into storeys, as well as rooms and hallways. In the context of indoor navigation, this thematic differentiation forms a basis for addressing, route descriptions and route tracking (homing), e.g. based on room numbers. Furthermore, it reflects the natural spatial reference system of the user of a navigation system for naming of start and end points.

Nowadays, semantic 3D city and building models, such as the international standards CityGML [11] or IFC [12], provide the geometry and the thematic differentiation of buildings and their interior areas. Although CityGML and IFC are targeting different scales and the ontology of each semantic model is tailored to different scopes, both models agree to a great extent in the notion of a building and its semantic decomposition. For further information on CityGML or IFC, please refer to the corresponding specification documents listed in the bibliography.

7 Related Work

Substantial work has already been done in the area of indoor navigation. In the following, we give a brief overview of current developments on specific systems and underlying information structures needed in order to support location services and route planning in indoor environments.

The OntoNav system [3] describes a semantic indoor navigation system. It proposes an indoor navigation ontology which provides semantic descriptions of the constituent elements of navigation paths such as obstacles, exits, and passages. Furthermore, specific user capabilities/limitations are modeled allowing for a user-centric navigation paradigm and the application of reasoning functionality.

In the field of mobile robot navigation, Kulyukin et al. [4] present an indoor navigation system for assisting the visually impaired. The system is designed as a tool to help visually impaired customers navigate a typical grocery store using a robot shopping cart. For localization, the system relies on RFID tags deployed at various locations in the store.

In order to simplify complex spatial relationships between 3D objects in built environment, Lee [6] introduces a topological data model, the Node-Relation-Structure (NRS). The NRS is a dual graph representing the connectivity relationships between 3D entities by Poincaré Duality. In the context of emergency response, Lee et al. [7] show the use of this simplified NRS representation of the indoor environment for routing purposes.

Within the REWERSE project, Lorenz et al. [2, 17] provide an approach for the automated partitioning of the building interior not only into rooms, but also into smaller parts, so called cells. The internal structure of the building is hence represented as a hierarchical graph enabling localization and route planning on different levels of detail. The partitioning is based on the automatic cell-and-portal decomposition of polygonal scenes proposed by Lefebvre and Hornus [5].

Liao et al. [13] propose an approach to track moving objects and their identity in indoor environments. Based on a Voronoi graph providing a natural discretization of the environment, the locations of people are estimated using noisy, sparse information collected by id-sensors such as infrared and ultrasound badge systems.

Kolodziej [9] provides a comprehensive overview and discussion of existing technologies and systems in the context of indoor navigation. Various approaches and algorithms for indoor localization using different kinds of sensor systems are described, which form the basis for Location Based Services (LBS).

7.1 Representing Indoor Spaces Using the Node-Relation-Structure

It is assumed that for realizing navigation systems, built environments are represented geometrically in Euclidean space, particularly in IR^3. Therefore, a building can be described using geometric and topological representations defined in ISO 19107 [1].

7.1.1 The Node-Relation-Structure (NRS)

Network structure has been used to abstract geographical features such as roads or streams. According to the scale of topographic map, area features (e.g. cities, buildings) are represented as nodes and roads are shown as edges in the network [24]. Lee [6] adopted the network structure concept to represent topological relationships, e.g., adjacency and connectivity relationships, among 3D objects. In the network-based topological representation, 2D or 3D geographical features are represented as nodes, and the topological relationships among the features are represented as edges, which is called Node-Relation Structure (NRS) [6]. The NRS is a dual graph structure derived based on three elements, which are Poincaré Duality, graph-theoretical formalisms, and a hierarchical network structure [6]. Lee utilized the NRS to develop Combinatorial Data Mode (CDM), which is a logical data model to abstract, simplify, and represent the complex topological relationships among 3D spatial units in indoor environments, such as rooms within a building [6]. The CDM can be used to find spatial neighbors of a particular feature or spatial unit in a building. As answer to the question "Which other 3D objects are located on top or under a particular 3D object?" will provide information about its neighbors, the CDM can be very useful in environmentally oriented analyses such as noise or air pollution and emergency situations in micro-spatial environments. In order to implement network-based analysis such as optimal routing, allocation, tracing and spatial analysis in the CDM, the logical network model needs to be complemented by a geometric network model that accurately represents these geometric properties. A 3D network data model, called Geometric Network Model (GNM), is developed by transforming the CDM, representing the connectivity relationships among 3D objects. A Straight Medial Axis Transformation Algorithm (S-MAT) is applied to perform one key step in this transformation [25].

7.1.2 Poincaré Duality

The NRS utilizes the Poincaré Duality in order to simplify the complex spatial relationships between 3D objects by a combinatorial topological network model. Solid 3D objects in primal space, e.g., rooms within a building, are mapped to vertices (0D) in dual space. The common 2D face shared by two solid objects is transformed into an edge (1D) linking two vertices in dual space. Thus, edges of the dual graph represent adjacency and connectivity relationships which may correspond to doors, windows, or walls between rooms, depending on the underlying building model concept in primal space. Fig. 4 illustrates this duality transformation. A formal definition of the Poincaré Duality is given in Munkres [8].

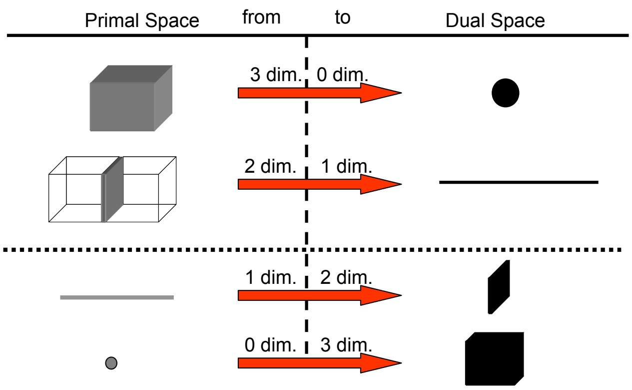


Fig. 4: Principles of Poincaré duality as shown by Lee [6]; for mathematical definition of Poincaré duality, see [8]

Since the resulting combinatorial model only represents topological relations, it does not contain metric information. However, metric information is needed in order to implement 3D spatial queries in the NRS such as shortest path operations. For this purpose, a complementary geometric network model is derived in Euclidean space by applying mathematical skeletonization algorithms and centroid calculations to the 3D spatial objects. By relating both graph representations, a geometric-topological network model can be established applicable to complex 3D spatial queries.

7.2 Combining Cells and Sensor Space in Navigation Systems

Generally, the dual representation of the indoor environment can be understood as a room-to-room connectivity graph. However, indoor navigation approaches like those proposed by OntoNav [3] and Lorenz [2, 17] rely on a further spatial decomposition of rooms according to the mode of navigation, e.g., to represent navigable and non-navigable areas with respect to the capabilities and limitations of moving persons. Moreover, the partitioning of indoor space into smaller units may also be induced by limited propagation areas of sensor-based positioning systems, e.g., systems based on RFID tags, which do not cover the spatial extent of an entire room.

In semantic 3D building models, the free space within buildings is modeled by non-overlapping room objects (cf. [10, 11]). Whereas this representation of indoor environment is suitable for the derivation of a room-to-room connectivity graph, Lorenz [2] and Lefebvre [5] propose a more differentiated decomposition of the semantic room entities. The room itself is geometrically fragmented into so-called cells, which again represent non-overlapping parts of the room. Based on the topological relationships of the resulting cells, a cell-to-cell connectivity graph can be derived by applying the duality transformation proposed by Lee [7].

The importance of a fine-grained subdivision of space and its dual cell-to-cell representation is exemplified within a fire escape scenario illustrated in fig. 5. The figure shows several rooms connected by doors to a corridor. Whereas in 5a) no further partitioning is applied to the topographic room objects, the corridor in 5b) is subdivided into disjoint cells representing partially accessible passages of the corridor with respect to adjacent doors. The corresponding dual graph representations are also shown in fig. 5. The task within this fire scenario is to find an evacuation route from the upper left room to the staircase. As a constraint for the modus of navigation, rooms affected by fire, i.e., the left part of the corridor, are marked as non-navigable. Based on the room-to-room connectivity graph, this task cannot be performed since the corridor is only represented by a single vertex in the dual graph and is completely marked as non-navigable. However, the semantic decomposition of the corridor into single cells allows for its dual representation by several vertices. Since only two cells are affected by fire and thus marked as non-navigable, a valid escape route can be computed based on the cell-to-cell connectivity graph (denoted using black arrows in fig. 5b).

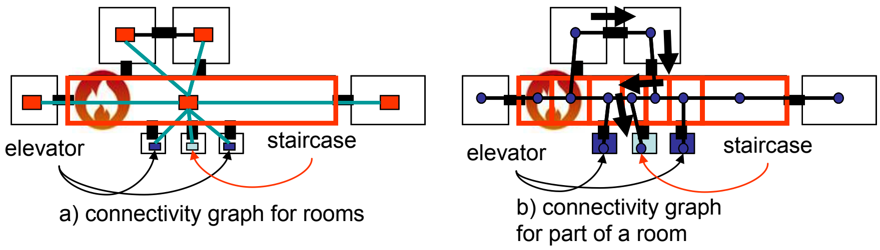


Fig. 5: The effect of spatial decomposition of rooms along escape routes

Smaller partitions of topographic space and the corresponding semantic decomposition of room objects provide the necessary means for a more precise indoor route planning. Although the approach of Lee [7] introduces a multi-scale representation of spatial objects within the geometric network model, this representation is the result of skeletonization processes of 3D spatial objects in Euclidean space and thus does not follow semantic decompositions as proposed by Lorenz et al. [2, 17]. As shown in the previous example, these decompositions of room space allow for a more detailed planning of escape routes.

Furthermore, the single partitions can be individually addressed by sensor-based positioning and tracking systems to provide a more accurate location of moving subjects or objects. Lorenz et al. [2, 17] describe such a system by integrating a Wi-Fi sensor model using so-called fingerprints. Fingerprints represent measurements of the signal strength of Wi-Fi transmitters at discrete locations within a room (cf. fig. 6). The cell decomposition of the room is performed based on different fingerprint measurements which are modeled as attributes of room cells. This approach allows for localization within rooms. However, the illustrated modeling approach also faces substantial disadvantages. Since the partitioning of topographic Euclidean space follows the characteristics of sensor space, there is no separation of the different space concepts anymore. Instead of a spatial partitioning of topographic space according to geometrical, semantic or rule-based aspects, the decomposition is decisively influenced by the sensor model, e.g., by the received signal strength of the transmitter or signal source. Accordingly, both space representations cannot be modeled individually. Changes to building topology or sensor configuration would both affect the entire structure. Furthermore, the integration of another kind of sensors or transmitters, e.g., RFID tags within a Wi-Fi based system, induces further modeling complexities, since the same room cell in topographic space could be covered by various overlapping sensor propagation areas, e.g., based on Wi-Fi signal strength and RFID signal strength.

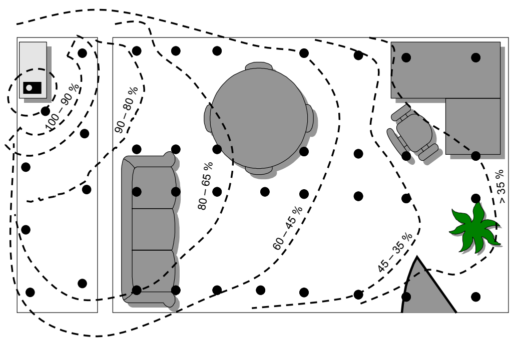


Fig. 6: Signal propagation area of a Wi-Fi transmitter including discrete areas of different signal strength and measurement points referenced to a cell

7.3 Indoor Navigation in OWS-6

The "Outdoor and Indoor 3D Routing Services Engineering Report" (OGC Doc. No. 09-067r2) specified in OWS-6 proposes a service-based framework for indoor navigation utilizing 3D building data encoded in CityGML for route planning and the OGC WMS interface for position and route communication.

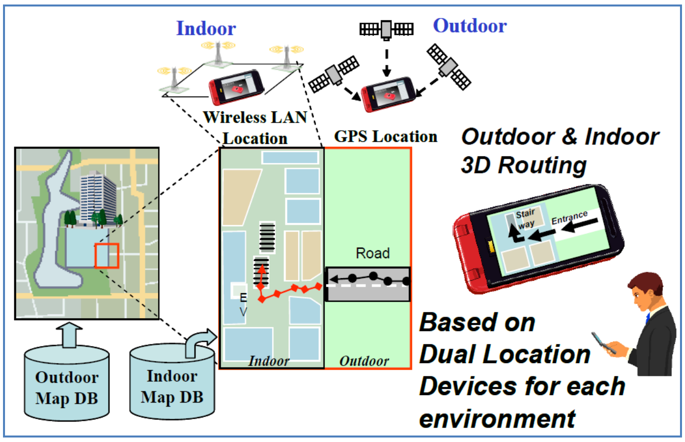


Fig. 7: Overview of the OWS-6 Outdoor and Indoor Routing Services architecture

The Engineering Report defines a network topology model which can be derived from 3D building models given in CityGML and which facilitates route planning in indoor areas. In order to derive the topological graph structure, rooms are subdivided into areas called "cells". Each cell is mapped onto a node within the topological graph. Further nodes are introduced at points where two adjacent cells touch. Edges denote topological adjacency between the nodes. The resulting cell-adjacency graph also has an embedding in geometric space (cf. fig. 8).

The partitioning of topographic space into smaller cells is mainly based on the positioning accuracy of the localization infrastructure and the corresponding capabilities of the end-user device. The derivation of the network topology model from building topography is only defined in a semi-automatic way. The result is a fixed but non-deterministic graph facilitating routing in a specific navigation context with a predefined and fixed type of locomotion and localization method.

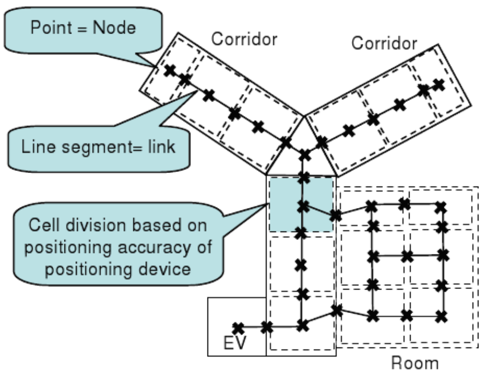


Fig. 8 OWS-6 proposed derivation of network topology focused on the center points of each cell

The indoor navigation approach proposed in OWS-6 already addresses some of the challenges and requirements introduced in chapter 5, e.g. the possibility to subdivide topographic space into smaller cells. However, it still faces open issues such as the usage of a fixed localization method as well as the lacking support for additional modes of locomotion and further space concepts like logical spaces including navigation constraints. The concepts discussed in OWS-6 and proposed by the OGC "Outdoor and Indoor 3D Routing Services Engineering Report" have been considered in the development of the Multilayered Space-Event Model which is presented in the following chapters of this OpenGIS® Discussion Paper. The proposed framework fully covers the OWS-6 approach and additionally meets the further requirements specified in chapter 5.

8 Proposed Indoor Navigation Model

In this OpenGIS® Discussion Paper, we introduce a novel framework for a generic multilayered space-event model [21, 22]. A crucial aspect of this framework is the clear separation of different space models, such as topographic space, sensor space, and logical space. This approach allows for the decomposition of a specific space into smaller units according to respective semantics, without influencing other space representations. Furthermore, we show how to connect the layers, i.e., space models, in a well-defined way and to derive a valid and unique joint state embracing all linked layers at a given point in time. Based on joint states, e.g., between topographic space and sensor space, the proposed multilayer modeling approach can be utilized to enable localization and route planning strategies in indoor navigation.

8.1 Structured Space Model

While route planning requires models which reflect the internal structure of a building as well as additional models providing thematic and logical navigation constraints, localization techniques require complementary models reflecting the characteristics of sensors and transmitters. Since partitioning of building space differs for all these space models, a conceptual separation of different space models is proposed. Within our framework, alternative space models are represented as separate space layers. Each space layer, and thus each distinct space model, is represented according to the Structured Space Model shown in fig. 9.

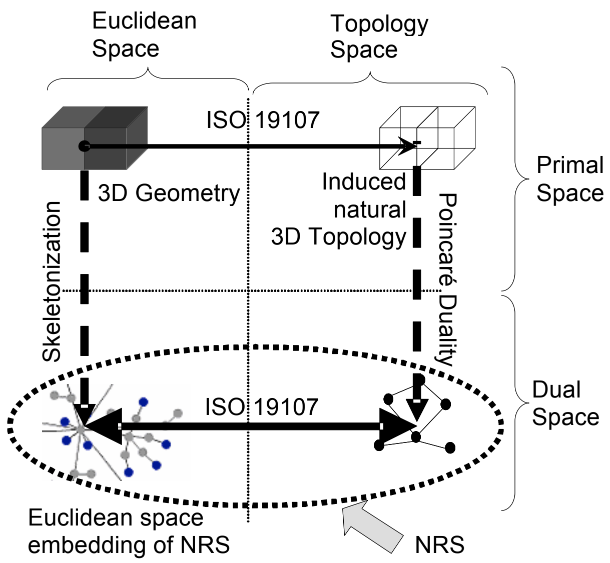


Fig. 9: The Structured Space Model allows for the conceptual separation of alternative space models and their representation as separate space layer

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 (indicated by the dotted lines in fig. 9). The vertical division corresponds to space representations within Euclidean space respectively topology space on the one hand. The horizontal partitioning indicates primal and dual space on the other hand. Consequently, each space model is given by four distinct space representations.

For each space layer, the upper left segment contains the 3D geometry representation of the cells in Euclidean primal space. Topological relationships such as connectivity and adjacency relations between 3D spatial objects are represented within topology space (i.e., the right side of fig. 9). In primal space, topology is induced by the corresponding 3D geometry in Euclidean space and represented in the upper right segment. Both primal space representations follow the ISO 19107 "Spatial Schema" specification for modeling geometry and topology of real world phenomena. Since disjoint partitioning of Euclidean space is required, the relation between both upper segments can be expressed with the "Realization" association between geometric and topological objects defined by ISO 19107. Accordingly, associated objects in either space must share a common dimension and are related by 1:1.

By applying a duality transformation based on Poincaré duality, the 3D cells in primal topology space are mapped onto nodes (0D) in dual space. The topological adjacency relationships between 3D cells are transformed to edges (1D) linking pairs of nodes in dual space. The resulting dual graph represents a Node-Relation-Structure as proposed by Lee [7] and is represented in the lower right segment of the structured space model. As mentioned in section 7.1.1, the NRS does not contain metric information which is, however, necessary in terms of spatial 3D queries such as best path calculations. Therefore, the Euclidean space embedding of this topological graph structure in dual space is given in the lower left segment of the structured space model. The embedding in IR^3 introduces metric information into the topological adjacency and connectivity relationships between the spatial objects. Again, the conceptual model of ISO 19107 can be used to express the relation of both lower segments as 1:1 "Realization" association between the geometric and topological objects in either space. However, the transition from primal to dual topology space based on Poincaré Duality cannot be modeled or described using ISO 19107.

The dual graph is also to be seen as a state transition diagram. Each node of the dual graph represents a state in this diagram denoting a cell in primal space in which a subject or object can possibly be, for example a room or the coverage area of a sender. The event is the transition or movement of such an object or subject from one state to another and is represented as edge in the dual graph connecting the both states. Therefore, events are related to the movement of subjects or objects through the explicit topological representation of space. Accordingly, our modeling approach is to be seen as a generic space-event model. Since each space model has to be subdivided into disjoint cells in primal Euclidean space, a moving subject or object can only be in one cell at one point in time. Thus, exactly one node within the NRS respectively the state transition diagram can be active at this point in time.

The structured space model describes a mathematically sound framework for a generic representation of spaces and their relations as well as spaces and events. It is independent from concrete space models such as topographic space or sensor space, and, thus, provides a conceptual model for the abstraction as well as the consistent specification and interpretation of various space concepts. This generic space-event modeling is even not restricted to the context of (indoor) navigation. In the following two subsections, the modeling of space layers is exemplified for the topographic space layer and a sensor space layer.

8.1.1 Topographic Space Layer

The representation of the topographic space layer using the structured space model is illustrated in fig. 10. For indoor navigation, the topographic space represents the interior built environment of buildings and its semantic decomposition into building elements like rooms and doors in order to enable route planning. Semantic building models for the representation of topographic 3D objects nowadays become increasingly available in the context of Building Information Modeling (BIM), such as the Industry Foundation Classes (IFC) [12] and in the field of 3D city modeling. The City Geography Markup Language (CityGML) [10, 11] defines a geospatial information model for the representation of 3D topographic urban objects including buildings and their interior.

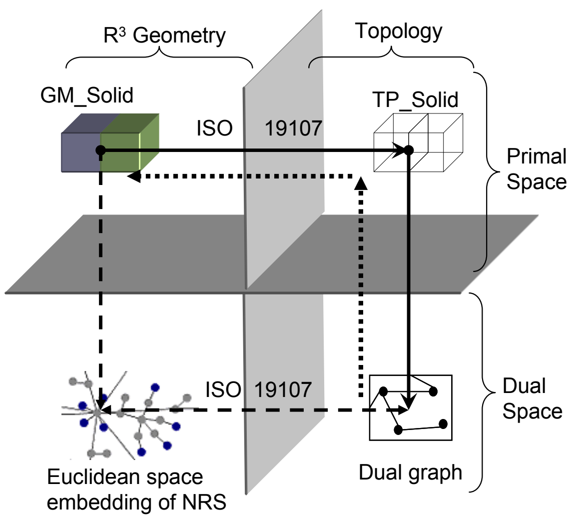


Fig. 10: The topographic space

According to the general space concept of layers as introduced in the previous section, the topographic space can be described by four distinct representations. The upper left element of fig. 10 illustrates the non-overlapping 3D geometry representation of built environment in Euclidean space. This geometry information can be directly derived from IFC and CityGML building models. The 3D primal cells of this segment represent the smallest units of the topographic space model such as rooms, hallways, or doors.

The dual space representation in the lower right segment constitutes a network topology model of the interior built environment whose cell adjacency and connectivity information is already suitable for route planning (cf. fig. 11). The additional Euclidean space embedding of the dual topology graph (cf. lower left part of fig. 10) introduces metric information and results in a geometric network model [7] which, for example, facilitates the determination of the best path (e.g., the fastest, the shortest, or the cheapest) and the definition of route trajectories. Fig. 11 shows an excerpt of a building model describing a floor and five connected rooms as 3D primal cells (left part) as well as the derived dual graph in topology space denoting cell adjacency (right part).

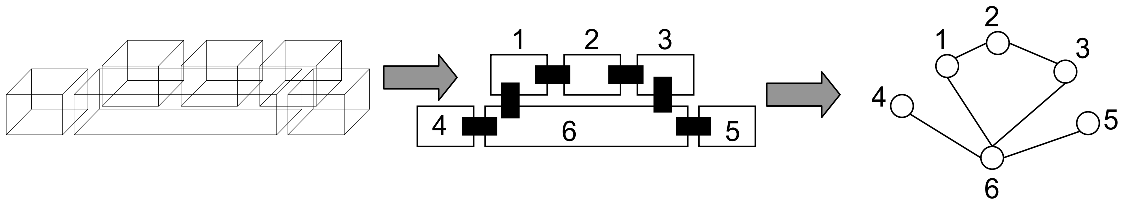


Fig. 11 Example for the partitioning of building interior into rooms and its representation in dual space

In order to integrate metrics, one possible solution is to use the methods “representativePoint()” and “centroid()” defined for GM_Objects in ISO 19107. For 3D solids, these methods return a point geometry representing the centroid of the volumetric object. This point representation could be stored attributively within the NRS. Since nodes of the NRS are directly related to TP_Solids in primal topology space, which, in turn, are directly related to GM_Solids in primal Euclidean space (depicted by dotted arrows in fig. 10), this metric information can be uniquely derived. Furthermore, weights representing, for example, distances between rooms can be assign to the edges of the NRS. These weights could be derived from primal Euclidean space accordingly. Alternatively to the methods defined in ISO 19107, the dual graph representation in Euclidean space may be derived by mathematical functions such as skeletonization processes.

Applying the structured space model to building models from existing standards

Semantic 3D city and building models provide geoinformation about the topographic space. However, different standards for 3D building models exist which result in different representations of the topographic building space. For example, CityGML and IFC vary in the way buildings are described with respect to their spatial and semantic characteristics. A fundamental difference arises from their distinct modeling paradigms which are due to the way 3D models are acquired in the GIS domain respectively in the field of BIM and Computer Aided Architectural Design (CAAD). In GIS, 3D objects are derived from surface observations of topographic features based on sensor-specific extraction procedures. Features are hence described by their observable surfaces applying an accumulative modeling principle. In contrast, BIM models reflect how a 3D object is constructed. They follow a generative modeling approach. Therefore, BIM models are typically composed of volumetric and parametric primitives representing the structural components of buildings [26]. This general classification into surface-oriented models and volumetric elements models of topographic space can also be applied to building models given in further standards or formats such as X3D or ESRI BISDM. A third group of building models is often employed in academic approaches (e.g., Gold et al. [20]). The interior built environment is represented as cardboard model, i.e., a wall between two adjacent rooms is represented by a single surface. Such models often lack a semantic description and ontology of the interior space.

Fig. 12 illustrates the three approaches for building modeling. It shows two rooms on the same floor, which are connected to a hallway through doors. The scene is sketched in top view and the thematic differentiation of indoor features is shown (if provided by the building model).

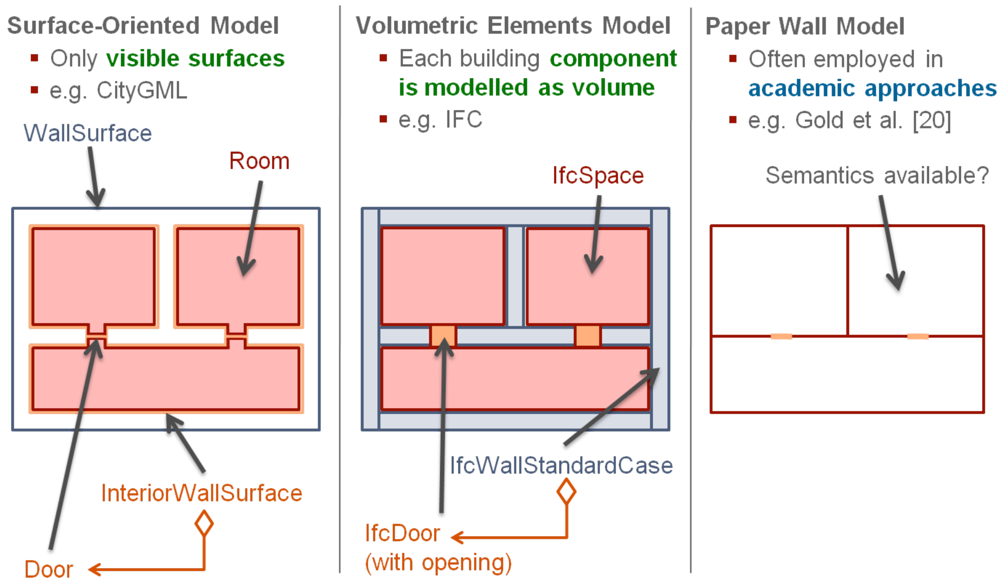
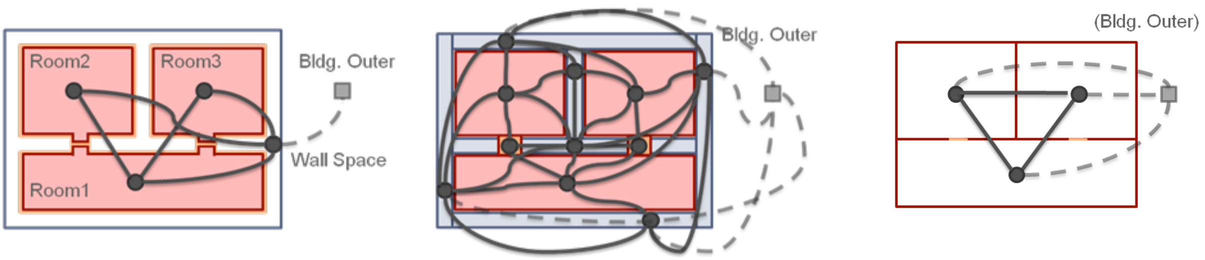


Fig. 12: Approaches for 3D building modeling

As discussed in section 8.1, the structured space model is independent from specific space models or concepts, and, thus, its general framework can be applied to each of the building modeling approaches. Fig. 13 shows the three example models and their resulting connectivity graphs in dual space which result from applying the Poincaré Duality to the 3D cells in primal topology space.

For the surface-oriented model (fig. 13 a, e.g. CityGML), each room is modeled as closed volume and hence mapped onto a node in dual space. Since walls are represented by at least two different surfaces which represent the visible parts of the wall, the room geometries do not touch but are separated by a wall space. This wall space is bounded by the interior wall surfaces of the rooms on the one side and the exterior building shell on the other side (illustrated as blue rectangle). The wall space itself is not further partitioned and, thus, is entirely mapped onto a single node. Adjacency edges are introduced between the room nodes and the node representing the wall space because the cells share common faces in 3D topology space. Furthermore, the connection between the rooms and the hallway is introduced as separate edges into the dual graph because the doors are modeled as surfaces which again are shared as common face by the 3D cells of the rooms and the hallway. In case of a volumetric elements model (fig. 13 b, e.g. IFC), all volumetric elements (rooms, walls, doors) are mapped onto separate nodes. Thus, in contrast to the surface-oriented model, the wall space is now represented by many nodes each having edges to the nodes of adjacent rooms, walls and doors. Furthermore, the room nodes are not directly connected through one adjacency edge, but through two edges having an intermediate node which represents the door cell. Finally, the cardboard model results in a simple dual graph consisting of three nodes representing the rooms. All nodes are connected through adjacency edges because the rooms mutually share common faces. If the building model however lacks semantic, it is a complex task to differentiate between a face representing a wall and a face representing a door.

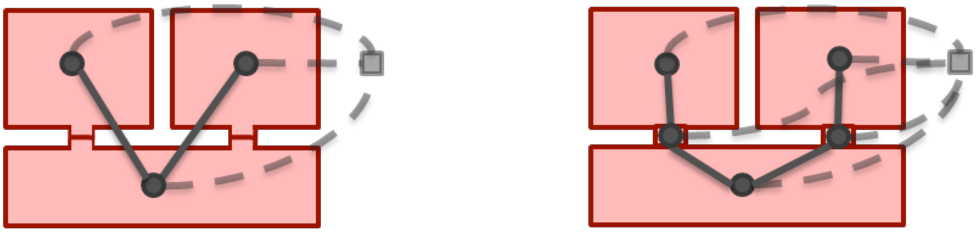


(a) (b) (c)

Fig. 13: 3D building models and their derived dual graphs in topology space by applying the Poincaré Duality

In the context of indoor navigation, it can be sufficient to only consider navigable spaces. Accordingly, nodes representing non-navigable wall spaces could be omitted in order to simplify the dual graph structure. Fig. 14

shows the resulting graphs when applying Poincaré Duality without considering wall spaces, (a) for the surface-oriented model and (b) for the volumetric elements model. However, also information about the wall space can be important in emergency situations. For example, if the hallway is blocked by a fire incident, fire fighter forces equipped with appropriate tools could still move from one room to the other if the wall between the rooms is made of wood. This requires walls to be represented as nodes which are connected to the nodes of adjacent rooms (cf. fig 13 b) as well as additional information such as the wall material.



(a) (b)

Fig. 14: 3D building models and their derived dual graphs in topology space by applying the Poincaré Duality and omitting non-navigable spaces

The support for arbitrary modeling approaches for buildings and their interior, which is due to the mathematically sound definition of the structured space model, is to be seen as one of the essential advantages of the proposed conceptual framework compared to further proposals in the field of indoor navigation. By this means, the proposed framework is not restricted to one specific way of representing the interior built environment but is open to any data model and standard in the field of building modeling.

8.1.2 Sensor Space Layer

The concept of space-event modeling allows for consistent specification and interpretation of various space concepts. This ensures equivalent interpretations of sensor space and topographic space. When arranging sensors within a building (e.g., Wi-Fi), transmission ranges may overlap, which requires their decomposition into disjoint regions in order to define unambiguous states (cf. fig. 15). As a state one can define the range or different signal strength areas. The event can be understood as an entry into a sensor area or as the crossing of a certain threshold value.

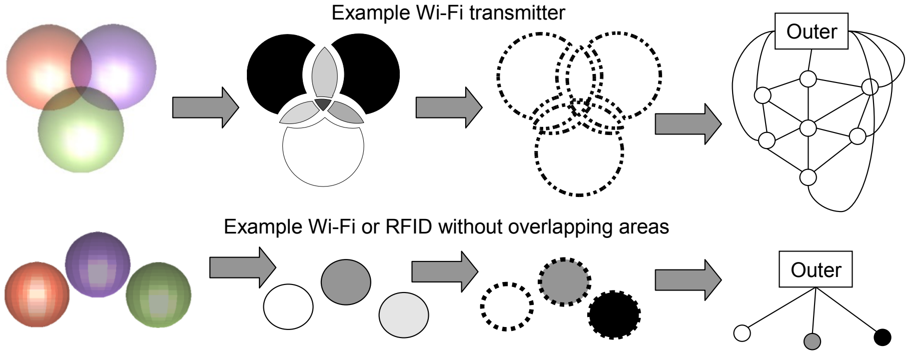


Fig. 15 Example for partitioning into cells and their representation in dual space

Like in the topographic layer, the accuracy of positioning correlates to the granularity of partitioning. Hence with smaller cells, navigation gains in precision. To describe areas with no sensor coverage, an additional state called "outer" is defined for every sensor system. This state is needed when the navigating subject or object leaves the range of a sensor without other sensors around, e.g., when leaving the building. For sensor systems covering the whole interior building area, the state "outer" only represents the outside building environment. Fig. 15 illustrates the modeling of sensor space in the case of overlapping transmitter/sensor ranges. Fig. 16 further shows the different geometric and topological representations of sensor space based on the structured space model.

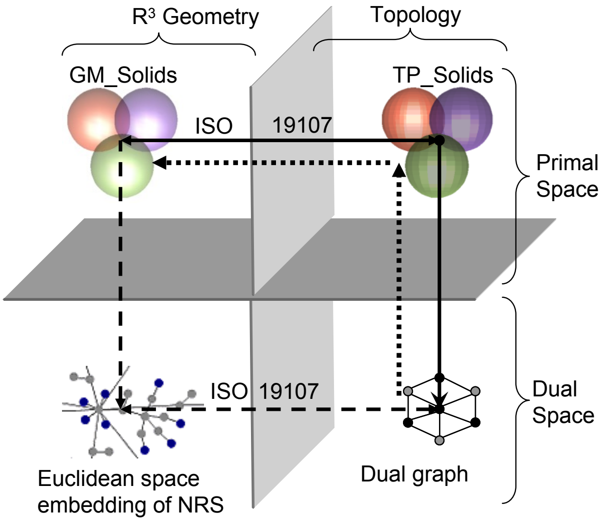


Fig. 16: Sensor space

In IR³, the partitioned sensor areas are represented as GM_Solids (upper left part) and their topological representation as TP_Solids (upper right part). The two representations are linked by the "Realization" association defined in ISO 19107. The Poincaré Duality defines the mapping from the topological representation to a dual graph structure (lower right part), representing a state transition diagram. To allow for quantitative evaluation of state distances, a metric is needed within the graph structure (like in the topographic layer). This metric is defined by explicit linking of nodes and corresponding GM_Solid objects. The distances between GM_Solids are then assigned attributively to the graph edges, resulting in a geometrical network of sensors in IR³ (lower left part). The link between GM_Solids and the sensor network (both defined in Euclidean space) embodies potential mathematical algorithms for network derivation, e.g., Delaunay Triangulation, Voronoi Diagram, etc.

8.2 *Multilayered Space Model*

Based on the structured space model introduced in chapter 8.1, separate and independent space layers represent different space models with different partitioning schemas. However, all of the layers spatially cover the same real world space, i.e. the interior building space. In order to get a comprehensive view of all space models which describe the entire interior building space, they are integrated within our framework into a Multilayered Space Model. The following fig. 17 illustrates this combination of several space layers.

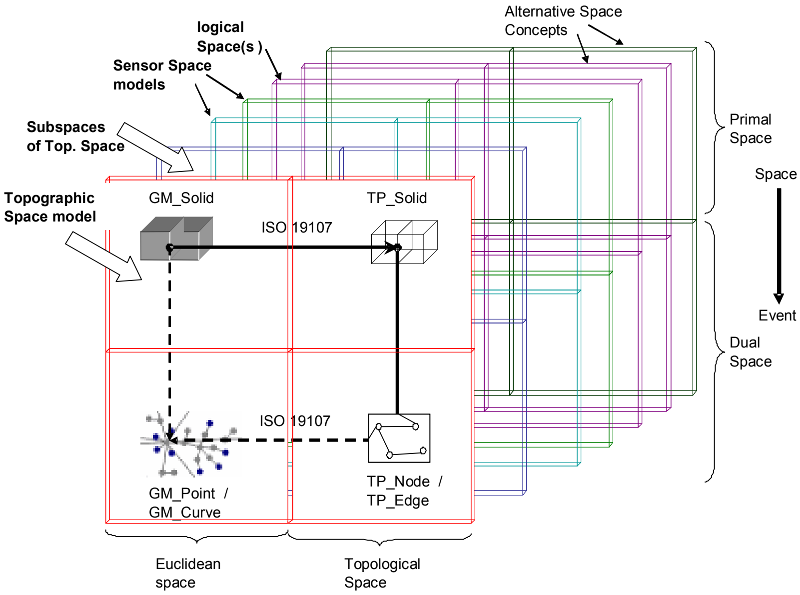


Fig. 17: Multilayer combination of alternative space concepts

The layers in the front of fig. 17 exemplarily represent topographic spaces, whereas sensor spaces are represented by the layers behind. As comprehensively discussed in the previous chapter, geo-objects in topographic space such as buildings may be represented using semantic 3D building models (cf. [10, 12]). Further semantic decompositions into, e.g., rooms, walls, doors, etc. can be applied within these model. However, 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, which requires its representation on separate space layers. Due to this conceptual separation, changes to room topology on the topographic layer do not have an impact on the cell representation of the sensor space layer and vice-versa.

The space which is represented by the Multilayered Space Model can be generally subdivided in two types of space: physical and logical. While physical space layers are qualified by physical conditions (built-up space, sensor coverage), the logical ones subdivide the space according to logical or thematic conditions (e.g. accessibility, navigation constraints). Physical layers comprise, for example, the topographic space and its dependent subspace layers (e.g. mode of navigation) and sensor space. Examples for logical layers are security zones or evacuation areas which denote logical spaces within buildings which influence the accessibility of indoor areas such as rooms or hallways. Navigation constraints may result from different criteria, e.g. topographic/geometric (door widths, opening direction of doors, etc.), zonal (security zones, fire detector areas, etc.), or temporal access constraints (opening hours, etc.). Although logical spaces may lead to a further partitioning of the navigable space denoted by the topography space, their spatial extent does not necessarily has to follow the physical built structure of the interior environment. For example, a security zone may split a single room into accessible and non-accessible parts, and may even affect outdoor areas around the building.

Further alternative concepts of space can be incorporated into the framework by adding additional layers. The number of layers is unbounded. For example, in the area of philosophy different definitions for space (e.g., movement space, activity space, visual space etc.) can be encountered which can also be used to describe the interior built environment. However, the notion of space and its semantic decomposition again differs from physical or logical space. Since each layer provides a valid and consistent representation of space, the common framework itself is to be seen as a valid multilayered space representation, which can be used as a whole to describe, for example, the indoor environment of buildings. The integration of these multiple and different space concepts within the Multilayered Space Model is realized through their common abstraction as well as consistent specification and interpretation as defined by the structured space model (cf. chapter 8.1).

8.3 Multilayered Graph and Joint State of Navigation

As illustrated in the previous sections, the node-relation-structure NRS (bottom right in fig.s 10, 16, 17) within each space layer constitutes a graph. The nodes represent the possible states of a navigating subject or object and correspond to cells with volumetric extent in primal space while the edges represent state transitions, i.e., events caused by the movement of a subject or object from one cell to another. They correspond to adjacency relations between the cells in primal space within the same space model (e.g., neighbored rooms in topographic space).

Joint State of Navigation

Since each space model is based upon a disjoint partitioning of (Euclidean) space, a navigating subject or object can only belong to one cell at a time and thus always only one state may be active. Since we have different space layers with different partitioning, each layer contains such a state transition graph with exactly one active state. Although each layer within the multilayered model describes a specific partitioning of space, the different space models cover the same real space. Therefore, a subject or object is at any given time exactly in one cell (or state) in each layer simultaneously. The overall state is thereby denoted by the joint active states of all space models, i.e. all 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 which link the nodes between different layers, and, thus, establish a connection between the separate layers of the multilayered space model. These so called joint edges are derived by pair wise intersecting the cell geometries from different layers in primal space. A joint edge between two such nodes in the dual graph is inserted, if and only if the intersection of the interior of the two corresponding cell geometries is non-empty. Therefore, the joint edges represent the Egenhofer relations "contains" / "inside", "overlap" and "equals" [14] between two primal cells from different space layers and thus denote inter-space connections. Each tuple of nodes connected in pairs by joint edges is called a joint state. The overall structure of joint edges connecting nodes from different space layers constitutes an *n*-partite graph, where all the nodes from all *n* layers are included but are separated into *n* partitions which are connected by the joint edges (inter-space connections). Fig. 18 illustrates the dual graphs of three space layers together with their inter-space connections. The topography layer contains four rooms. Room3 is a hallway to which rooms 1, 2 and 4 are connected through doors. Room1 and Room2 share a further connecting door. Two sensor space layers are defined. The first one represents two WiFi access points A and B whose coverage areas overlap and thus are partitioned into the disjoint cells A, AB, and B. The second sensor space layer describes the coverage areas of two RFID senders (R1 and R2).

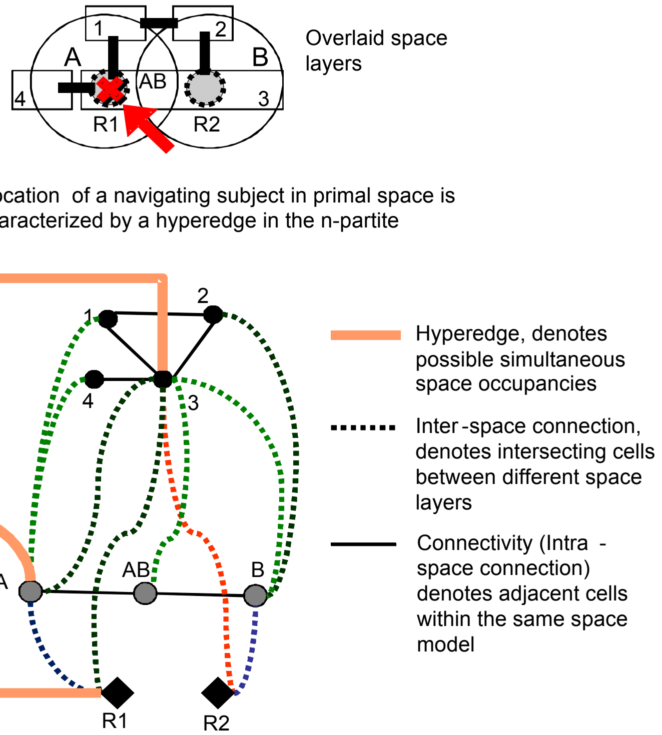


Fig. 18: Resulting n-partite graph with intra-space connections. The hyperedge denotes a possible joint state. The incident nodes of a hyperedge form a clique. Please note that the outer nodes have been omitted for the sake of readability.

The joint state of navigation is exactly a clique of all active states of all space layers and is represented by a hyperedge within the graph structure. The hyperedge denotes the n-ary relationship between all affected layers (see the bold orange line in fig. 18). In fig. 18, the red cross in the upper part marks a possible position of a moving subject or object within a building. For this position, three inter-space connections can be found which determine a ternary relationship or clique between the affected cells from the topographic space (Room3), the WiFi sensor space (cell A), and the RFID sensor space (cell R1). This hyperedge can be stored, for example, as a tuple in a table in an n-ary relation. For the sake of readability, the outer nodes are not included in fig. 18, but nevertheless they also must be reflected on each space layer.

Multilayered Graph

The dual graph of topographic space facilitates route planning within the building. Therefore, it is already useful on its own, e.g. to derive escape routes without the need for an additional sensor model. On the other hand, the dual graph of sensor space can be used in a decoupled way for tracking and localization without knowing the actual position in topographic space. The edge between the two NRS denotes the joint-state connection combining the nodes of both graphs to the *n*-partite graph (in this example a bipartite graph) which defines the valid states of the entire model. A joint-state connection not only allows the determination of relative positions with respect to a sensor, but also the absolute position determination within the sensor and topographic space. The uncertainty about the absolute position in Euclidean space can be restricted to the intersection volume of all 3D cell geometries associated with the active nodes in the joint-state.

In addition, the *n*-partite graph allows also for assessment of localization infrastructure and estimation of location uncertainty with a given building decomposition in topographic space and a given sensor / transmitter configuration in sensor space.

The *n*-partite graph connecting the nodes of all *n* layers together with the *n* dual adjacency graphs (one per space layer denoting adjacency of the cells in primal space) constitutes a multi-graph structure which is inherent to the Multilayered Space Model itself. Within our framework, this multi-graph structure is therefore called Multi-layered Graph.

8.4 *Subspacing and Hierarchical Grouping of Spaces*

Cells within a space model (e.g. topographic space) may be further subdivided due to specific considerations such as the mode of navigation. The topographic space is well defined and described by different existing standards like CityGML [11] or IFC [12] on a room (space) level, however, a decomposition due to different contexts in smaller parts can occur. The crucial point is that this decomposition may constitute a subset of the entire room and therefore a separation in one "main space layer" and additional context-dependent layers is reasonable (cf. fig. 19). These decompositions of space models are not independent of the higher level layer, because they reflect only a context specific partition of the higher level space. Therefore, the inter-space connection between a main layer and its subspacing layers is restricted to the topological relations qualified as "contains" / "inside" and "equal". This generic subspacing concept allows for hierarchical grouping of arbitrary space models. It is exemplified for the topographic space in the following fig. 19.

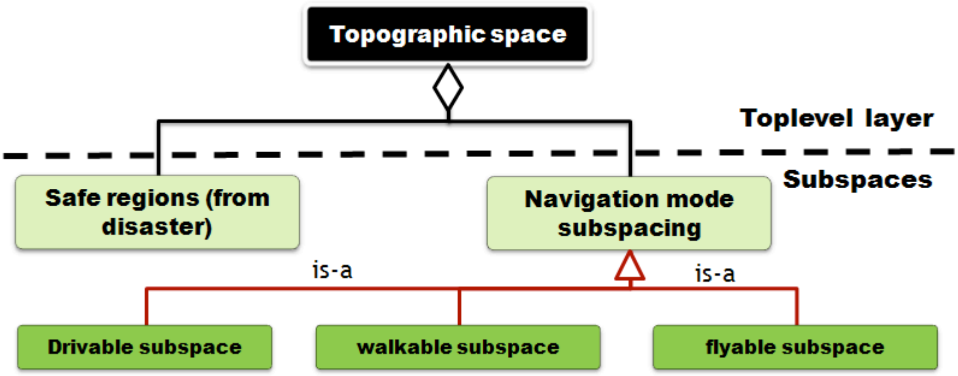


Fig. 19: Some subspace layers of topographic space. The contextual subspacing of topographic space leads to space layers which are not independent from topographic space. Thus, inter-space connections are restricted to topological relations "inside" and "equals".

The following fig. 20 shows an example for a decomposition and subspacing of topography space. The main topographic space is shown in the right part of fig. 20. Its subspace layer representing the navigable space for mode of locomotion "driving" (e.g., wheel chair users) is shown on the left. Inter-space connections between dual graph nodes and their topological relation are illustrated as black arrows between both layers.

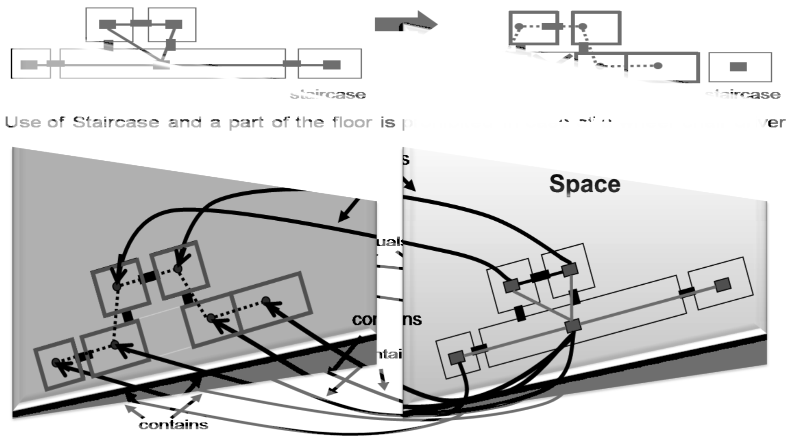


Fig. 20: Example for topographic subspacing

In the example of fig. 20, it is assumed that there is single step in the middle of the floor which can easily be passed by pedestrians. However, it is an obstacle for driving subjects and objects. Therefore, route planning for driving subjects and objects cannot be performed on the main topographic layer but requires a subspace dedicated to this mode of locomotion. In the left part of fig. 20, the non-navigable part of the topographic space which is occupied by the obstacle is not represented in primal space of the subspace layer any more. This leads to a subdivision of the floor into smaller cells. The dual graph denoting cell adjacency within the subspace layer (see dotted edges between the nodes of the subspace) now contains the information, that the floor is not entirely navigable for driving subjects and objects. A route from the left room to the right end of the floor has to pass the two rooms which are illustrated on top of the floor in fig. 20. The subspacing layer is connected to the higher level layer by the inter-space connections which express the topological relations contains or equals (see the black edges between both layers). A further subspacing layer for autonomous mobile robots could be added which introduces a further subdivision of the primal cells in main topographic space into even smaller partitions than those shown in fig. 20. By this means, the Euclidean space embedding of the derived dual graph facilitates optimal planning of route trajectories for autonomous mobile robots.

The example illustrates that not only different space models such as topographic space, sensor space, and logical space may lead to a different partitioning of indoor space. Also the decomposition of a space layer results in a partitioning of its primal cells into smaller subspaces. Subspacing may be applied for different reasons, e.g. to denote the navigable space for a specific mode of locomotion or to be able to derive a geometric network suitable for planning of trajectories. The resulting partitioning of indoor space has to be represented as separate space layer within the multilayered space model. This allows for the support of multiple and different contexts of navigation. For the above example, navigating a wheel chair user has to be performed on the subspace layer depicted in the left part of fig. 20. The main topographic layer could be neglected in this navigation context. For pedestrians, the main topographic layer however is already suitable for route planning and, thus, the subspace layer could be neglected.

8.5 Context as Selection Criterion

Within the multilayered space model all contextual configurations can be represented as separate layers which are connected via the inter-space connection relation (cf. data model in chapter 10). The relevant data for indoor navigation or routing are selected and derived from the set of layers (cf. fig. 21).

The selection is depending on logical or thematic considerations as well as on the existing localization device configurations. In fig. 21 an example for such a selection is shown. In the upper part the precomputed n-partite graph constituted by all different contexts is shown. In the lower part of the fig. 21, the user or application dependent selection of relevant space models from the set of layers (e.g. stored in a database) is shown. After the context-dependent selection, the cliques are detected in order to identify all possible joint states (hyperedges). By intersecting all the geometries which are associated to the incident nodes (see section 8.3) of each hyperedge, a 3D intersection volume results which constitutes the actual area in which the navigating subject or object must be located. The extent of this volume is a measure for the uncertainty of the absolute position of a navigating subject or object.

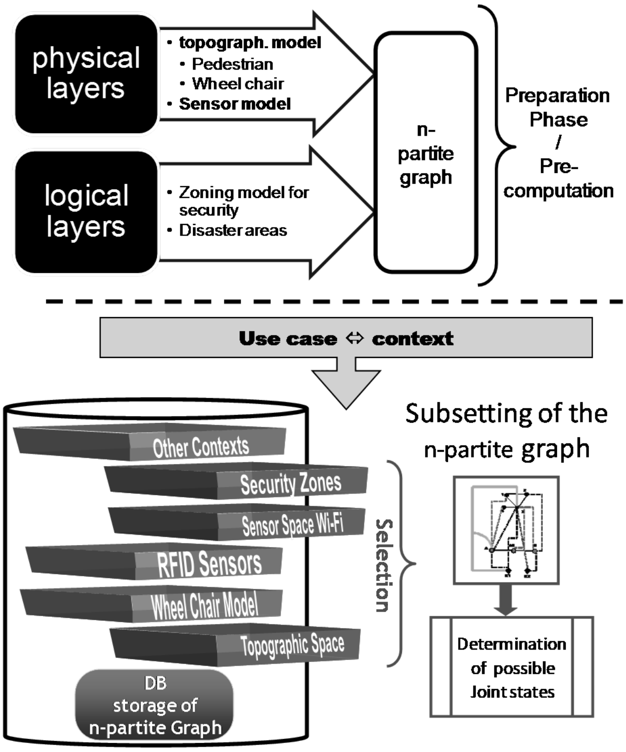


Fig. 21: The actual use case defines the context.
This is reflected by the selection of the according space models

8.6 *Example for the Application of the Proposed Indoor Navigation Model*

The example in this chapter demonstrates the application of the proposed Multilayered Space-Event Model within the context of indoor navigation. The scenario for this example is illustrated in fig. 22. The building model is given as semantic 3D surface model (e.g., CityGML). It contains a floor and two adjacent rooms. Both rooms are connected to the floor through doors. Additionally, a door between both rooms allows for moving from one room to the other without having to use the floor. The building is equipped with WiFi access points which can be used for the localization of end-user devices. The coverage area of two of the WiFi access points (A and B) is sketched as spheres in fig. 22. Of course, this example only shows a small excerpt of an entire building model. Nevertheless, it is already suitable to illustrate the application of the Multilayered Space Model.

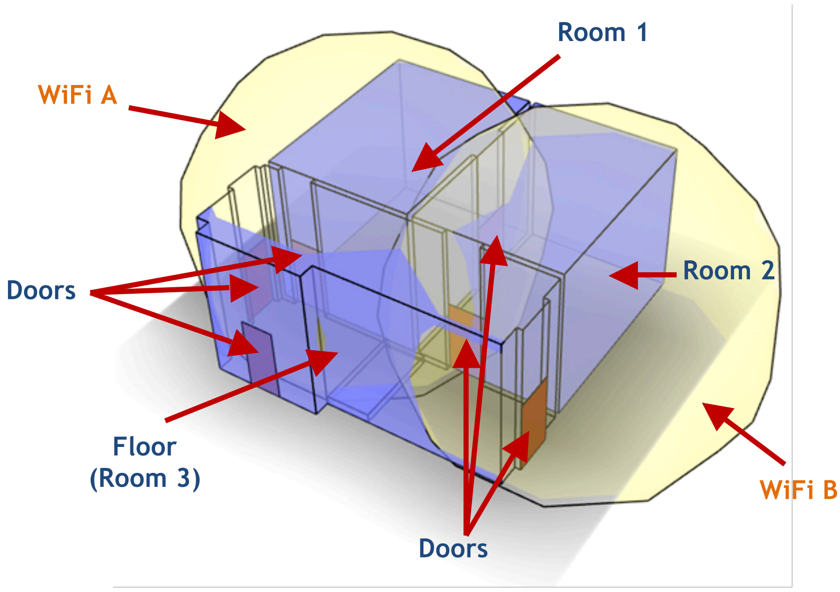


Fig. 22: Example topographic space and sensor space

The floor (Room 3) can only partly be used by driving subjects or objects because of a step which is located in the middle of the floor between the doors connecting the floor to Room 1 and Room 2 (cf. left part of fig. 23). Thus, the building topography illustrated in fig. 22 and modeled by the original 3D building model is suitable for navigating pedestrians. However, the step is an obstacle for driving subjects or and objects and therefore represents non-navigable space for this mode of locomotion. In order to enable route planning and navigation for the mode of locomotion "driving", the floor has to be subdivided into smaller cells following the concept of subspacing. Only the cells representing the navigable space are necessary and have to be kept. Accordingly, the cell denoting the non-navigable space of the step can be omitted. Since both types of locomotion, i.e. walking and driving, shall be supported by the example navigation system, both subdivisions of the interior built environment are important and have to be used in either one of the two navigation contexts.

Applying the concepts of the multilayered space model introduced in the previous sections, both partitioning schemas of the topographic space are represented on their own space layers. The cells in primal space of the main topographic layer which are already suitable for navigating walking subjects and objects are shown in the left part of fig. 23 (blue). In the middle of fig. 23 (green), the primal space geometry of the type of locomotion "Drivable" is illustrated. Detached from the topographic layers, the overlapping WiFi coverage areas of the two access points are modeled separately as a sensor space layer "WiFi", shown in the right part of fig. 23 (beige).

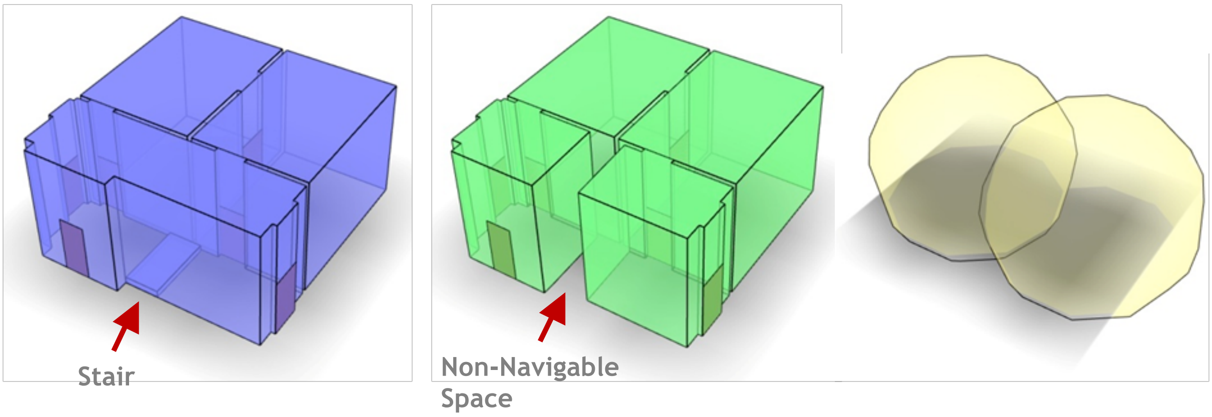


Fig. 23: Primal space geometry of the topographic layers "walkable" (blue) and "wheel chair" (green) representing the navigable space (type of locomotion) and of the sensor space layer "WiFi" (beige) representing the signal coverage

In primal space, the spatial decomposition is modeled as disjoint cells in 3D geometry and 3D topology. Applying Poincaré Duality to the induced 3D topology in primal space (natural topology, cf. Munkres [8]), a graph structure in dual topology space is deduced for each layer which represents the primal cells and their outer space as nodes and their topological adjacency as edges. Fig. 24 illustrates the resulting dual graphs of the topographic space layers "Walkable" and "Drivable" and the sensor space layer "WiFi". Since only disjoint cells are allowed, the dual graph of the sensor space layer contains three nodes each representing a separate WiFi cell having different signal reception (only A, both A and B, and only B).

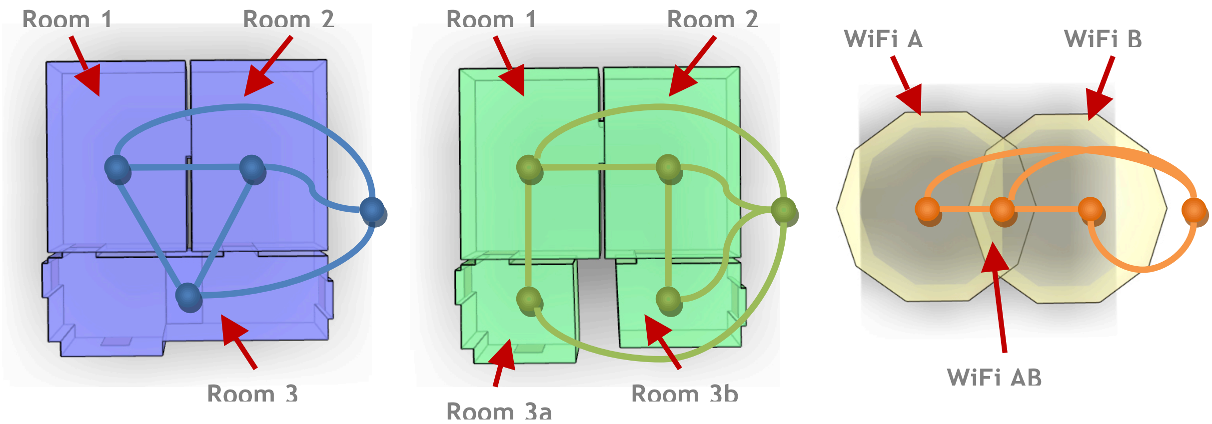


Fig. 24: Derived dual graphs from primal space geometry using induced topology. Cells (rooms respectively WiFi coverage areas) are represented as nodes and shared faces as edges denoting cell adjacency

As shown in fig. 24, the doors in both layers describing topography space (depicted in blue and green) are modeled as surfaces (and not volumetric objects). Applying Poincaré Duality leads to the conversion of the door surface to an edge connecting the rooms whose cells in primal topology space share the door as common face. Doors might also be modeled as volumetric objects, e.g. regarding to the modeling paradigms of IFC. In this case, a door describes a primal cell in topology cell on its own and, thus, is mapped onto a separate node within the dual graph. Accordingly, depending on the applied modeling approach for representing 3D buildings and their interior built environment in primal space, the derived graph structure in dual space might be different (cf. chapter 8.1.1). This support for various 3D building model approaches is to be seen as essential strength of the proposed indoor navigation model.

The thematically separated space layers cover the same real world space. In order to establish links between the different space layers, their dual graphs are combined in a Multilayered Graph by linking nodes in different layers, if the corresponding cell geometries in primal space overlap. Fig. 25 shows the Multilayered Space Model for this example including the 3D geometry in primal Euclidean space, the corresponding graph structure in dual topology space and the multilayered graph connecting the two topographic space layers and the sensor space layer. Please note, that the representations of primal 3D topology space and dual Euclidean space as well as the inter-space connections between the topography layer "Walkable" and the WiFi sensor space layer are omitted for readability reasons. Of course, further space layers may be added, for example space layers denoting further and different sensor spaces for localization or representing logical navigation constraints.

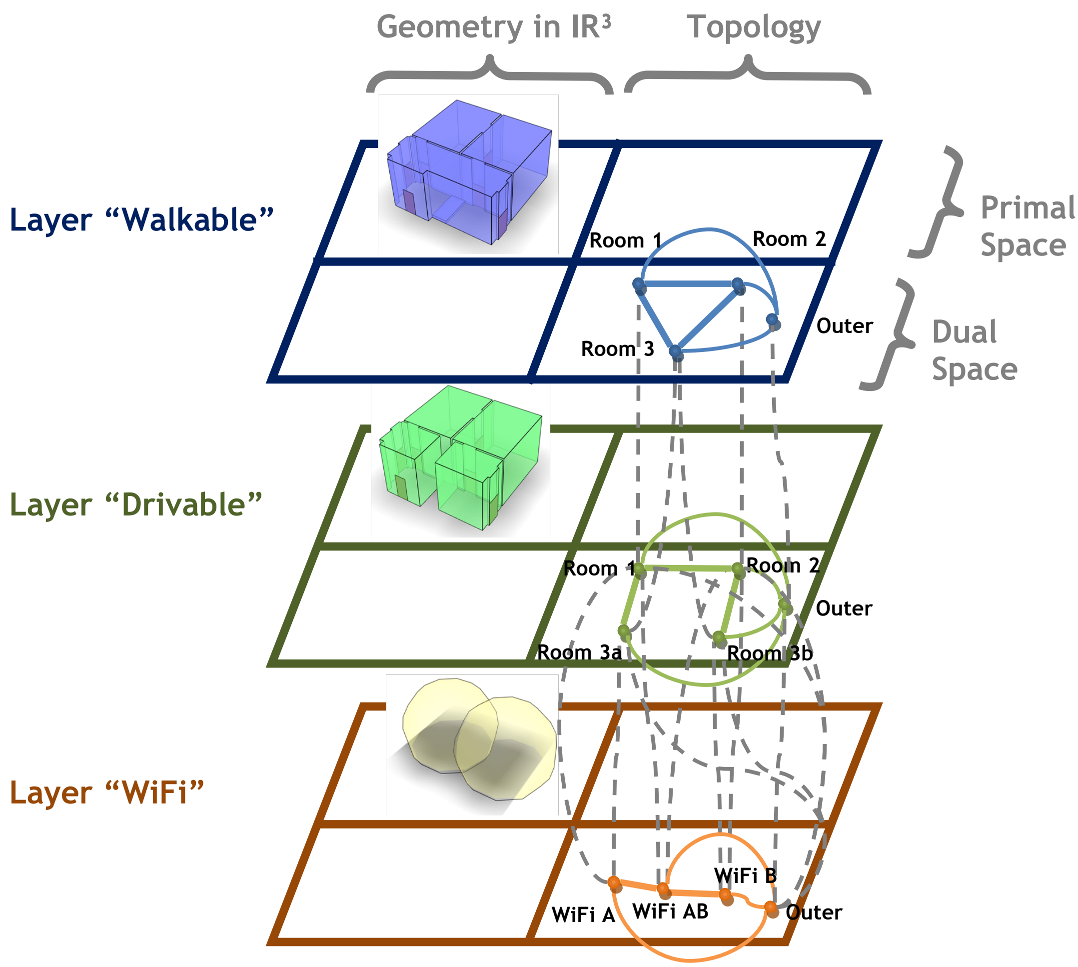


Fig. 25: Multilayered Space Model including the geometry in primal space, the corresponding graph structure in dual space and the multi-layered graph connecting the two topographic space layers and the sensor space layer.

The graph structures in Fig. 25 are stored and can now be used for localization, routing and tracking in different navigation contexts. For example, if a wheel chair user shall be navigated through the building using WiFi for localization, only the space layers "Drivable" and "WiFi" as shown in fig. 25 are required. Thus, the Multilayered Space Model can be reduced by removing all space layers which are not relevant for the selected context of navigation. Fig. 26 shows the reduced example scenario.

The multilayered graph shown in fig. 26 allows for localizing a moving subject or object. For example, if the WiFi receiver of the end-user device only receives the signal of the WiFi access point A, the moving person must be in Room 3a (left part of the floor) or in Room 1. This can be deduced from the inter-space connections between the dual graphs of topography and sensor space which denote possible Joint States. The green dotted inter-space connections shown in fig. 26 link the nodes representing Room 3a and Room 1 in topography space to the node representing the WiFi coverage area of sender A in sensor space. The extend of the 3D intersection geometry between the primal cell of WiFi A and the primal cells of Room 1 and Room 3a is a measure for the remaining uncertainty of the actual position of the moving person. This ambiguity can be reduced, for example, by using further WiFi transmitters and/or other localization methods and infrastructures which would have to be introduced as separate space layers in the Multilayered Space model and, thus, would establish further possible Joint States. Of course, also historic information about previous Joint States of the moving person can be used for reducing the ambiguity. For example, using the cell connectivity information of the sensor space layer given by its dual graph together with the localization algorithm, the changes in location can be tracked (shown by the blue edges in fig. 26) and be fed into a reasoning process.

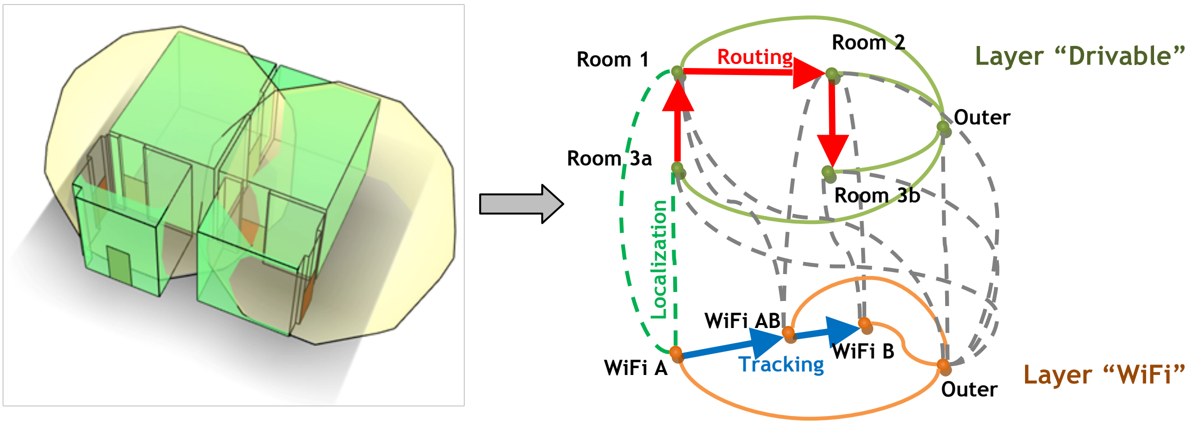


Fig. 26: Example context of navigation "Drivable" and "WiFi" with the overlapping cell geometries of both layers in primal space (left part) and the resulting Multilayered Graph (right part).

Based on the topographic space layer, routing of the moving person can be performed. In the example scenario shown in fig. 26, the context of navigation of the moving person contains the "Drivable" space layer (e.g., a wheel chair user). Thus, if the route of the user leads through the illustrated floor, a route planning algorithm will automatically navigate the user through Room 1 and Room 2 in order to avoid the stair in the middle of the floor, which represents a non-navigable obstacle. In the Multilayered Graph, the corresponding dual graph representation of the "Drivable" space layer which denotes adjacency between cells in primal space does not contain an edge between the nodes representing the navigable spaces of the floor (Room 3a and Room 3b). Thus, a route planning algorithm will follow the edge from Room 3a to Room 1, from Room 1 to Room 2, and finally from Room 2 to Room 3b (or vice versa).

9 Development of a Framework for Indoor Navigation

Based on the concepts introduced in the previous chapters, we propose a general framework for indoor and outdoor navigation which is outlined in fig. 27 using a UML package diagram.

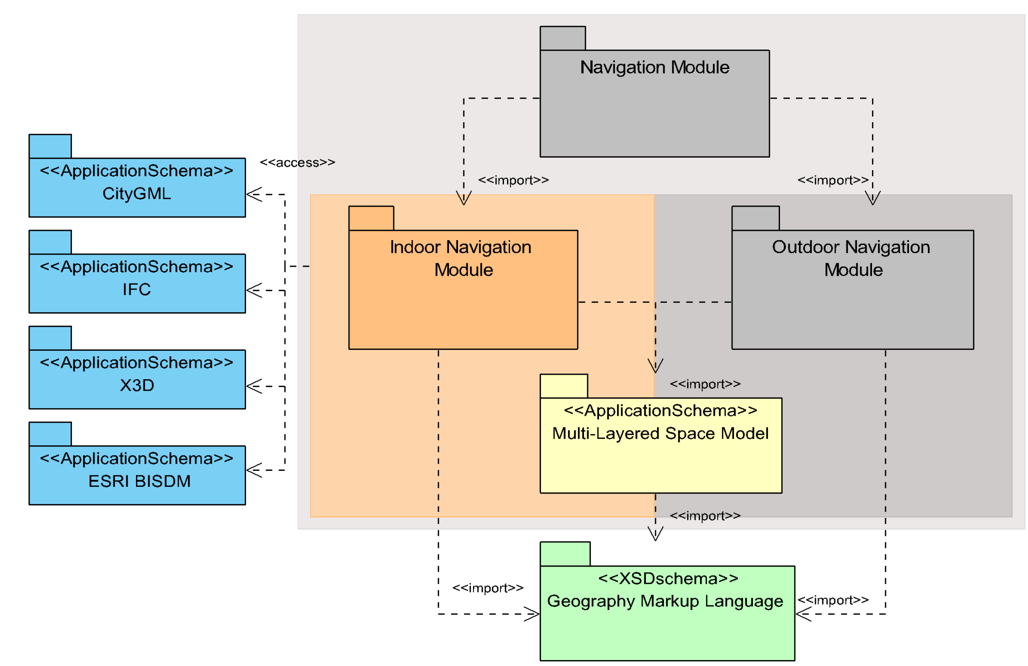


Fig. 27: UML package diagram of the proposed framework for Indoor Navigation

According to the OGC's policy "The Specification Model — A Standard for Modular specifications [15]", the overall navigation framework is split into a core module and extensions which have a mandatory dependency on the core. In figure 21, the separate modules are illustrated as UML packages. The dashed arrows indicate dependency relations between the modules. In the following sections the modules are described in detail.

Core Module: *Multilayered Space Model*

The core of the navigation framework is the *Multilayered Space Model* module. As discussed in chapter 8, the Multilayered Space Model allows for the coherent combination of different decompositions of space according to different semantics. Each spatial decomposition 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. In primal space, the spatial decomposition is modeled as disjoint cells in 3D geometry and 3D topology. By applying Poincaré Duality, for each layer a graph structure in dual topology space can be deduced which represents primal cells as nodes and their connectivity as edges. Since the layers cover the same real world space, the separate dual graphs can be combined into a Multilayered Graph by linking nodes in different layers if the corresponding cells in primal space overlap. Due to these abstract concepts, the Multilayered Space Model is generally to be seen as a conceptual framework for the generic representation of spaces and their relations.

Please note that these fundamental concepts are not restricted to the context of navigation but may also be applied to different application contexts which require a generic and mathematically sound space-relation model. Thus, the proposed Multilayered Space Model module is designed to be context-independent and, thus, may be reused in different application contexts.

Embedded in the context of navigation, the concepts of the Multilayered Space Model facilitate, amongst others, the support for different and multiple localization methods and infrastructures, the support for different navigation contexts with respect to the type of locomotion, the support for arbitrary configurations of space layers, as well as sub-spacing and the hierarchical grouping of space decompositions (cf. chapter 8).

The *Multilayered Space Model* module is implemented as GML 3.1.1 application schema. Its UML data model is illustrated in chapter 10, whereas the corresponding XML Schema definition is given in chapter 11.

Extension Module: *Indoor Navigation Module*

The *Indoor Navigation Module* provides the 3D topographic representation of the interior built environment and the available localization infrastructures. This representation shall be based on already existing data models. However, there is no restriction to a specific data model of the 3D interior built environment due to the generic concepts defined by the *Multilayered Space Model*.

For example, semantic 3D city and building models, such as the international standards CityGML and IFC, provide the geometry and the thematic differentiation of interior areas, e.g. the separation of buildings into building parts, storeys and rooms. This spatial decomposition of the building space can already be used for structuring the topographic space layer within the core module. Moreover, the thematic differentiation is already suitable for addressing, route descriptions and route tracking (homing), e.g. based on room numbers.

The *Indoor Navigation Module* is furthermore meant to provide additions to the generic concepts of the core module which are required in the context of indoor navigation. This might include addressing/georeferencing schemas for indoor spaces, concepts for communication and visualization of position and navigable route sections, and the introduction of additional navigation constraints such as temporal access constraints like opening hours, or constraints resulting from material properties of the navigation path. Again, existing data models and concepts shall be reused.

Extension Module: *Outdoor Navigation Module*

The proposed navigation framework explicitly addresses 3D outdoor navigation in addition to indoor navigation. The generic concepts for representing spaces and their relations defined by the *Multilayered Space Model* within the core module can also be applied to outdoor environments. This facilitates the support of navigation from indoor to outdoor space. The *Outdoor Navigation Module* provides the required topographic representation of the outdoor space as well as additions to the core which are required in the context of outdoor navigation. As with the *Indoor Navigation Module*, existing models and standards, such as GDF, shall be reused or linked.

Extension Module: *Navigation Module*

The *Navigation Module* finally brings together the *Indoor Navigation Module* and the *Outdoor Navigation Module* into a common navigation framework to ensure a seamless transition from indoor to outdoor and vice versa. However, this module is optional which means that the *Indoor Navigation Module* and the *Outdoor Navigation Module* may also be used independently from each other in applications which only require one or the other.

Please note that this OpenGIS® Discussion Paper focuses on the core module and the definition of the Multilayered Space Model. The specification of the *Indoor Navigation Module* is currently carried out within the Indoor Spatial Awareness Project (cf. Preface). Both the *Outdoor Navigation Module* and the *Navigation Module* are subject to future work. Participation and contribution in the development are highly welcomed and encouraged.

10 Data Model of the Multilayered Space Model

The UML diagram depicted in fig. 28 shows the data model for the Multilayered Space Model. The data model defines the classes and relations needed to describe the geometric and topological representations of each layer in primal space and their corresponding mapping in dual space. Furthermore, it contains classes representing the resulting state-transition diagram of each layer, and the multilayered graph linking the states between different layers. The XML Schema definition mapping the conceptual data model specified as UML diagram onto a GML 3.1.1 application schema is given in Annex A.

The classes in fig. 28 are arranged according to the subdivision of each layer into four distinct regions as discussed in section 8.1 (cf. fig. 9). For each layer, its geometry and topology representations in primal and dual space are modeled in accordance with ISO 19107. Thus, the geometry representation in primal Euclidean space is represented as *GM_Solids* and the corresponding induced topology (natural topology, cf. Munkres [8]) as *TP_Solids*. Both representations are linked by "realization" associations. Following the Poincaré duality, the *TP_Solids* and *TP_Faces* in primal topology space are mapped to *TP_Nodes* respectively *TP_Edges* in dual space.

The resulting dual graph is equivalent to the topological part of the Node-Relation-Structure (NRS) proposed by Lee [6, 7] which allows for a simplified representation of the complex topological relationships between 3D spatial objects. The 3D Euclidean space embedding of the NRS is realized as *GM_Points* and *GM_Curves*.

The separate layers of the Multilayered Space Model are represented by the class *SpaceLayer* which may denote its relation to other *SpaceLayers*, e.g. correlation, dependency, or aggregation (for subspaces), using the association class *TypeOfRelation*. A Layer aggregates *States* and *Transitions* which are directly associated with the corresponding topology classes of the NRS. By this means, the state-transition diagram for each layer is realized. *SpaceLayers* can be connected through the *InterSpaceConnection* class which represents a *TP_Edge* in dual topology space connecting two states from separate layers. The inter-space connections (*InterSpaceConnections*) together with the intra-space connections (*States* and *Transitions*) finally establish the *MultiLayeredGraph*.

The classes *Space* and *SpaceBoundary* represent real world objects in accordance with the notion of geographic features defined by ISO 19109. A *Space* is a semantic class corresponding to one cell in Euclidean primal space of one layer. Accordingly, *SpaceBoundary* is used to semantically describe the boundary faces of each cell. Both classes are seen as interfaces which connect the Multilayered Space Model to existing semantic 3D models describing e.g. the topographic interior built environment. For example, the class *Space* can be related to a *Room* in CityGML [11] or an *IfcSpace* in IFC [12]. The class *SpaceBoundary* can be related to a *_BoundarySurface* feature in CityGML (e.g., *WallSurface*, *ClosureSurface*, *InteriorWallSurface*, etc) or an *IfcWall* in IFC.

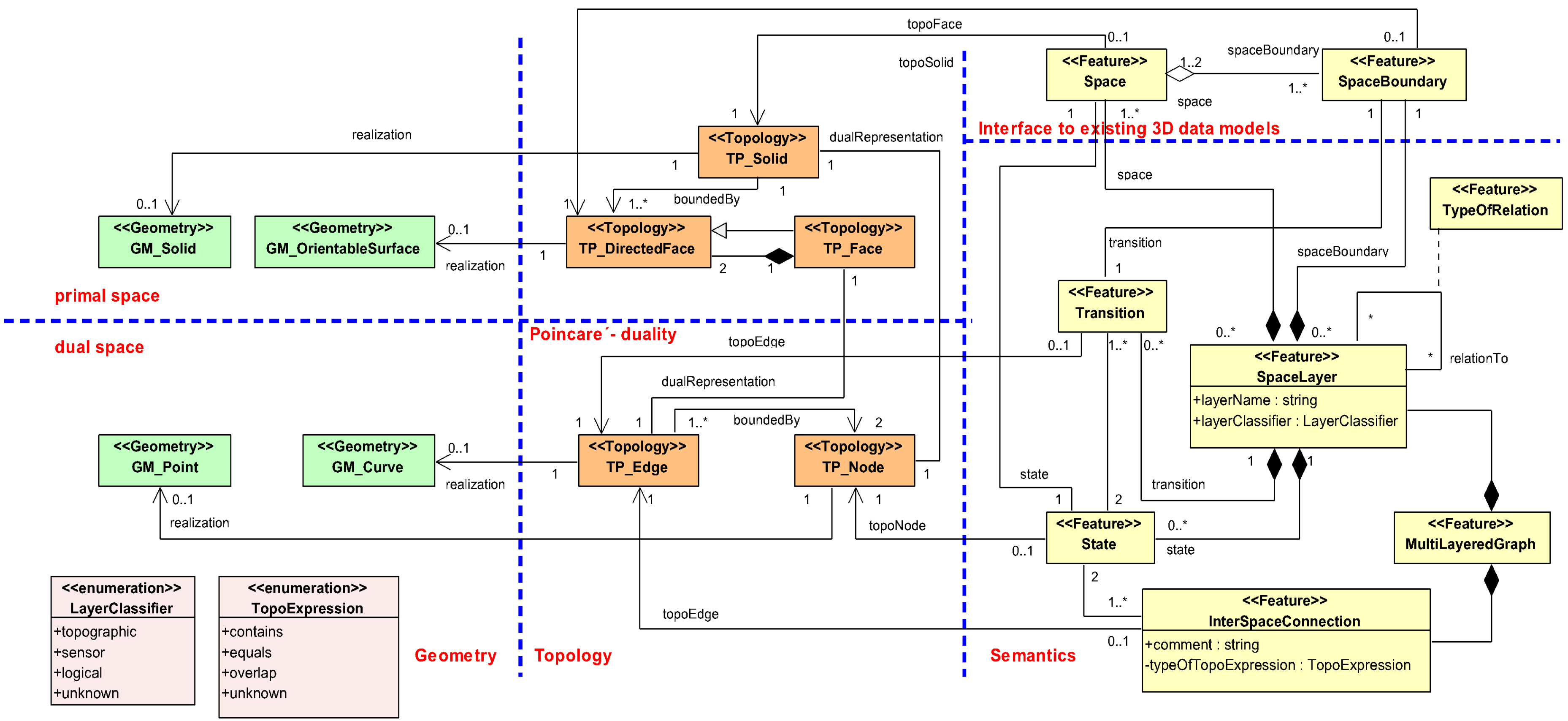


Fig. 28: Data Model of the Multilayered Space-Event Model

Annex A
(normative)

XML Schema Definition

The data model of the Multilayered Space-Event model as introduced as UML diagram in chapter 10 (cf. fig. 28) has been mapped to a GML 3.1.1 application schema. The corresponding XML Schema Definition is given in the following. This XML Schema Definition is normative. Any XML instance document claiming conformance to the Multilayered Space-Event Model specified by this OpenGIS® Discussion Paper must be valid with respect to this XML Schema Definition. Furthermore, the rules and requirements of the Multilayered Space-Event Model specified in clause 8 to 10 must be obeyed.

```xml
<?xml version="1.0" encoding="utf-8" ?>
<xs:schema xmlns:gml="http://www.opengis.net/gml" xmlns="http://www.igg.tu-berlin.de/MLSM/0.1.0"
  attributeFormDefault="unqualified" elementFormDefault="qualified" targetNamespace="http://www.igg.tu-berlin.de/MLSM/0.1.0"
  xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:import namespace="http://www.opengis.net/gml" schemaLocation="3.1.1/base/gml.xsd"/>
  <!-- ============================================================================================ -->
  <!-- ==================================== Highlevel Elements ======================================== -->
  <!-- ============================================================================================ -->
  <xs:complexType name="MultiLayeredGraphType">
    <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 interspace
        connections. Furthermore the graph also contains the state transition edges (intraspace
        connections).</xs:documentation>
    </xs:annotation>
    <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureCollectionType">
        <xs:sequence/>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:element name="MultiLayeredGraph" type="MultiLayeredGraphType" substitutionGroup="gml:_FeatureCollection"/>
  <!--============================================================================================ -->
  <xs:element name="spaceLayerMember" type="SpaceLayerPropertyType" substitutionGroup="gml:featureMember"/>
  <!--============================================================================================ -->
  <xs:complexType name="InterSpaceConnectionPropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:FeaturePropertyType">
        <xs:sequence minOccurs="0">
          <xs:element ref="InterSpaceConnection"/>
        </xs:sequence>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:complexType name="InterSpaceConnectionType">
    <xs:annotation>
      <xs:documentation> Intersecting the geometries of the layer combination provides an edge if the intersection of their
        interior geometries is non-empty. The edge express the Egenhofer relations contains, overlap and equals and is
        called interspace connection. </xs:documentation>
    </xs:annotation>
    <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
        <xs:sequence>
          <xs:element name="state" type="ReferencePropertyType" minOccurs="2" maxOccurs="2"/>
          <xs:element name="topoEdge" type="gml:DirectedEdgePropertyType" minOccurs="1" maxOccurs="1"/>
          <xs:element name="topoRelation" type="InterSpaceTopologyRelationType" minOccurs="0" maxOccurs="1"/>
        </xs:sequence>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:element name="InterSpaceConnection" type="InterSpaceConnectionType" substitutionGroup="gml:_Feature"/>
  <!--============================================================================================ -->
  <xs:element name="interSpaceConnectionMember" type="InterSpaceConnectionPropertyType" substitu-
```



```
tionGroup="gml:featureMember"/>
  <!--============================================================================================ -->
  <xs:complexType name="SpaceLayerType">
    <xs:annotation>
      <xs:documentation>The separate Layers of the Multilayered Space Model are represented by the class SpaceLayer which
        may denote its relation to other layers, e.g. correlation, dependency or aggregation using the association class
        TypeOfRelation. A SpaceLayer aggregates States and Transitions which are directly associated with the
        corresponding topology and geometry classes. </xs:documentation>
    </xs:annotation>
    <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
        <xs:sequence>
          <xs:element name="class" type="SpaceLayerClassType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="relatedTo" type="SpaceLayerAssociationType" minOccurs="0" maxOccurs="unbounded"/>
          <xs:element name="space" type="SpacePropertyType" minOccurs="0" maxOccurs="unbounded"/>
          <xs:element name="spaceBoundary" type="SpaceBoundaryPropertyType" minOccurs="0" maxOccurs="unbounded"/>
          <xs:element name="state" type="StatePropertyType" minOccurs="0" maxOccurs="unbounded"/>
          <xs:element name="transition" type="TransitionPropertyType" minOccurs="0" maxOccurs="unbounded"/>
        </xs:sequence>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:element name="SpaceLayer" type="SpaceLayerType" substitutionGroup="gml:_Feature"/>
  <!--============================================================================================ -->
  <xs:complexType name="SpaceLayerPropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:FeaturePropertyType">
        <xs:sequence minOccurs="0">
          <xs:element ref="SpaceLayer"/>
        </xs:sequence>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:complexType name="SpaceLayerAssociationType">
    <xs:sequence minOccurs="0">
      <xs:element ref="SpaceLayer"/>
    </xs:sequence>
    <xs:attribute name="typeOfRelation" type="TypeOfRelationType" use="required"/>
    <xs:attributeGroup ref="gml:AssociationAttributeGroup"/>
  </xs:complexType>
  <!--============================================================================================ -->
  <!-- ================================= Primal Space Elements ================================= -->
  <!-- =========================================================================================== -->
  <xs:complexType name="SpaceType">
    <xs:annotation>
      <xs:documentation> For each layer, its geometry and topology representations in primal and dual space are modelled in
        accordance with ISO 19107. Thus, the geometry representation in primal Euclidean space is represented as GM_Solids
        and the corresponding induced topology (natural topology) as TP_Solids. </xs:documentation>
    </xs:annotation>
    <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
        <xs:sequence>
          <xs:element name="externalReference" type="ExternalReferenceType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="topoSolid" type="gml:DirectedTopoSolidPropertyType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="state" type="ReferencePropertyType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="spaceBoundary" type="ReferencePropertyType" minOccurs="0" maxOccurs="unbounded"/>
        </xs:sequence>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:element name="Space" type="SpaceType" substitutionGroup="gml:_Feature"/>
  <!--============================================================================================ -->
  <xs:complexType name="SpacePropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:FeaturePropertyType">
        <xs:sequence minOccurs="0">
          <xs:element ref="Space"/>
        </xs:sequence>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================ -->
  <xs:complexType name="SpaceBoundaryType">
```

```
    <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
        <xs:sequence>
          <xs:element name="externalReference" type="ExternalReferenceType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="topoFace" type="gml:DirectedFacePropertyType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="transition" type="ReferencePropertyType" minOccurs="0" maxOccurs="1"/>
          <xs:element name="space" type="ReferencePropertyType" minOccurs="0" maxOccurs="2"/>
        </xs:sequence>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================= -->
  <xs:element name="SpaceBoundary" type="SpaceBoundaryType" substitutionGroup="gml:_Feature"/>
  <!--============================================================================================= -->
  <xs:complexType name="SpaceBoundaryPropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:FeaturePropertyType">
        <xs:sequence minOccurs="0">
          <xs:element ref="SpaceBoundary"/>
        </xs:sequence>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================= -->
  <!-- =================================== Dual Space Elements ===================================== -->
  <!-- ============================================================================================ -->
  <xs:complexType name="StateType">
    <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:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
        <xs:sequence>
          <xs:element name="topoNode" type="gml:DirectedNodePropertyType" minOccurs="1" maxOccurs="1"/>
          <xs:element name="transition" type="ReferencePropertyType" minOccurs="0" maxOccurs="unbounded"/>
          <xs:element name="interSpaceConnection" type="ReferencePropertyType" minOccurs="0" maxOccurs="unbounded"/>
          <xs:element name="space" type="ReferencePropertyType" minOccurs="0" maxOccurs="1"/>
        </xs:sequence>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================= -->
  <xs:element name="State" type="StateType" substitutionGroup="gml:_Feature"/>
  <!--============================================================================================= -->
  <xs:complexType name="StatePropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:FeaturePropertyType">
        <xs:sequence minOccurs="0">
          <xs:element ref="State"/>
        </xs:sequence>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================= -->
  <xs:complexType name="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 intraspace connections) </xs:documentation>
    </xs:annotation>
    <xs:complexContent>
      <xs:extension base="gml:AbstractFeatureType">
        <xs:sequence>
          <xs:element name="topoEdge" type="gml:DirectedEdgePropertyType" minOccurs="1" maxOccurs="1"/>
          <xs:element name="state" type="ReferencePropertyType" minOccurs="0" maxOccurs="2"/>
          <xs:element name="spaceBoundary" type="ReferencePropertyType" minOccurs="0" maxOccurs="1"/>
        </xs:sequence>
      </xs:extension>
    </xs:complexContent>
  </xs:complexType>
  <!--============================================================================================= -->
  <xs:element name="Transition" type="TransitionType" substitutionGroup="gml:_Feature"/>
  <!--============================================================================================= -->
  <xs:complexType name="TransitionPropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:FeaturePropertyType">
```

```
        <xs:sequence minOccurs="0">
          <xs:element ref="Transition"/>
        </xs:sequence>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!-- ==================================================================================== -->
  <!-- ===========================External references ========================================== -->
  <!-- ==================================================================================== -->
  <xs:complexType name="ExternalReferenceType">
    <xs:annotation>
      <xs:documentation>Type describing the reference to an corresponding object in an other information system, for example
        in the german cadastre ALKIS, the german topographic information system or ATKIS, or the OS MasterMap. The
        reference consists of the name of the external information system, represented by an URI, and the reference of the
        external object, given either by a string or by an URI. If the informationSystem element is missing in the
        ExternalReference, the ExternalObjectReference must be an URI, which contains an indication of the
        informationSystem.</xs:documentation>
    </xs:annotation>
    <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"/>
      <xs:element name="uri" type="xs:anyURI"/>
    </xs:choice>
  </xs:complexType>
  <!-- ==================================================================================== -->
  <xs:complexType name="ReferencePropertyType">
    <xs:complexContent>
      <xs:restriction base="gml:AssociationType">
        <xs:sequence/>
      </xs:restriction>
    </xs:complexContent>
  </xs:complexType>
  <!--==================================================================================== -->
  <!--=========================== SIMPLE TYPES ================================================ -->
  <!-- =================================================================================== -->
  <xs:simpleType name="SpaceLayerClassType">
    <xs:annotation>
      <xs:documentation>SpaceLayers can be qualified by the attribute SpaceLayerClassType. The attribute differentiates
        between Topographic and Sensor Space and logical Spaces (like zoning models for security
        areas).</xs:documentation>
    </xs:annotation>
    <xs:restriction base="xs:string">
      <xs:enumeration value="topographic"/>
      <xs:enumeration value="sensor"/>
      <xs:enumeration value="logical"/>
    </xs:restriction>
  </xs:simpleType>
  <!-- =================================================================================== -->
  <xs:simpleType name="TypeOfRelationType">
    <xs:restriction base="xs:string">
      <xs:enumeration value="correlation"/>
      <xs:enumeration value="dependency"/>
      <xs:enumeration value="aggregation"/>
    </xs:restriction>
  </xs:simpleType>
  <!-- =================================================================================== -->
  <xs:simpleType name="InterSpaceTopologyRelationType">
    <xs:restriction base="xs:string">
      <xs:enumeration value="equals"/>
      <xs:enumeration value="contains"/>
      <xs:enumeration value="overlap"/>
      <xs:enumeration value="inside"/>
    </xs:restriction>
  </xs:simpleType>
  <!-- =================================================================================== -->
</xs:schema>
```

Listing 1: Normative XML Schema Definition of the Multilayered Space-Event Model

Annex B
(informative)

Example XML instance document

This annex illustrates the structure of an XML instance document following to the normative XML Schema definition of the Multilayered Space-Event Model as introduced in Annex A. It picks up the example for the application of the Multilayered Space-Event Model given in chapter 8.6 and shows how to encode the separate space layers as well as the resulting Multilayered Graph containing both the intra-space adjacency graphs and the inter-space connections. In order to keep the example clear, only two of the space layers being discussed and modeled in chapter 8.6 are mapped to a corresponding XML instance document. All remaining layers can be easily added and encoded following the explanations in this annex.

The following fig. 29 shows the setting used in the following example. On the left of fig. 29, the partitioning of topographic space into navigable cells suitable for the locomotion type "driving" (e.g. wheel chair users and mobile robots) as well as two coverage areas of WiFi access points in primal space is shown. The right part of fig. 29 illustrates the resulting Multilayered Graph for these two space layers in dual space. Please refer to chapter 8.6 for further descriptions.

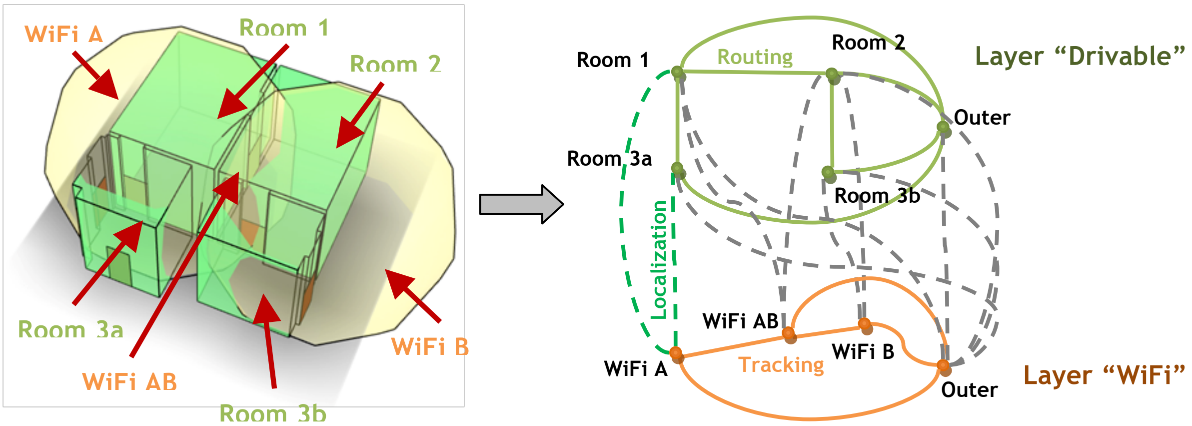


Fig. 29: Example selected context of navigation "Drivable" and "WiFi" as introduced and discussed in chapter 8.6.

The following listing 2 illustrates the general skeleton of XML instance documents representing a concrete setting of the Multilayered Space-Event Model. The root element <MultiLayeredGraph> is a feature collection which maps the Multilayered Graph of the conceptual data model. The elements of this feature collection can be separated into two feature types: 1) <SpaceLayer> elements providing a description of each space layer according to the structured space model (cf. chapter 8.1), and 2) <InterSpaceConnection> elements denoting the inter-space connectivity between the <SpaceLayer>s.

```
<?xml version="1.0" encoding="UTF-8"?>
<MultiLayeredGraph xmlns="http://www.igg.tu-berlin.de/MLSM/0.1.0" xmlns:gml="http://www.opengis.net/gml"
  xmlns:xlink="http://www.w3.org/1999/xlink" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="http://www.igg.tu-berlin.de/MLSM/0.1.0 MLSM_v0.1.0.xsd">

  <!-- Part 1: Description of Space Layers -->
  <spaceLayerMember>
    <!—E.g., Topograhy Space -->
    <SpaceLayer> … </SpaceLayer>
  </spaceLayerMember>


  <spaceLayerMember>
    <!—E.g., Sensor Space -->
```

```
    <SpaceLayer> … </SpaceLayer>
  </spaceLayerMember>

  <!-- Part 2: Description of inter-space connectivity between the Space Layers -->
  <interSpaceConnectionMember>
    <InterSpaceConnection> … </InterSpaceConnection>
  </interSpaceConnectionMember>

</MultiLayeredGraph>
```

Listing 2: Skeleton of XML instance documents according to the Multilayered Space-Event Model.

SpaceLayer element

The general layout of a <SpaceLayer> element is shown in listing 3. The listing is an excerpt of the description of the topographic space as sketched in fig. 29 which represents navigable areas for driving subjects and objects.

```
    <SpaceLayer>
      <gml:name>Building Topography Layer (Drivable)</gml:name>
      <class>topographic</class>

      <!-- Spaces in primal space (geometry and topology) -->
      <space>
        <Space gml:id="TL_Space_Room1">
          <externalReference>
            <informationSystem>file://CityGML_Builing.gml</informationSystem>
            <externalObject>
              <uri>#Room1</uri>
            </externalObject>
          </externalReference>
          <topoSolid>
            <gml:TopoSolid>
              <gml:directedFace xlink:href="#TL_Face_Door1"/>
              <gml:directedFace xlink:href="#TL_Face_Door2"/>
              <gml:directedFace xlink:href="#TL_Face_InteriorWall1"/>
              …
              <gml:solidProperty xlink:href="file://CityGML_Builing.gml#Room1_solid_geometry"/>
            </gml:TopoSolid>
          </topoSolid>
        </Space>
      </space>

      <space>
        <Space gml:id="TL_Space_Room2"> … </Space>
      </space>

      …

      <!-- SpaceBoundaries in primal space (topology and geometry) -->
      <spaceBoundary>
        <SpaceBoundary gml:id="TL_SpaceBoundary_Door1">
          <externalReference>
            <informationSystem>file://CityGML_Builing.gml</informationSystem>
            <externalObject>
              <uri>#Door1</uri>
            </externalObject>
          </externalReference>
          <topoFace>
            <gml:Face gml:id="TL_Face_Door1">
              <gml:directedEdge> … </gml:directedEdge>
              <gml:directedTopoSolid> … </gml:directedTopoSolid>
              <gml:surfaceProperty xlink:href="CityGML_Builing.gml#Door1_surface_geometry"/>
            </gml:Face>
          </topoFace>
        </SpaceBoundary>
      </spaceBoundary>

      <spaceBoundary>
```



```xml
      <SpaceBoundary gml:id="TL_SpaceBoundary_Door2"> … </SpaceBoundary>
    </spaceBoundary>

    …

    <!-- Intralayer adjacency graph -->
    <!-- States resulting from Poincare Dualityapplied to Spaces -->
    <state>
      <State gml:id="TL_State_Room1">
        <topoNode>
          <gml:Node gml:id="TL_Node_Room1">
            <gml:pointProperty>
              <gml:Point>
                <gml:pos> … </gml:pos>
              </gml:Point>
            </gml:pointProperty>
          </gml:Node>
        </topoNode>
      </State>
    </state>

    <state>
      <State gml:id="TL_State_Room2"> … </State>
    </state>

    <state>
      <State gml:id="TL_State_Outer"> ... </State>
    </state>

    …

    <!-- Transitions resulting from Poincare Dualityapplied to SpaceBoundaries -->
    <transition>
      <Transition gml:id="TL_Transition_Door1">
        <topoEdge>
          <gml:Edge>
            <gml:directedNode xlink:href="#TL_Node_Room1"/>
            <gml:directedNode xlink:href="#TL_Node_Room2"/>
            <gml:curveProperty>
              <gml:LineString>
                <gml:posList> … </gml:posList>
              </gml:LineString>
            </gml:curveProperty>
          </gml:Edge>
        </topoEdge>
        <state xlink:href="#TL_State_Room1"/>
        <state xlink:href="#TL_State_Room2"/>
      </Transition>
    </transition>

    <transition>
      <Transition gml:id="TL_Transition_Door2"> … </Transition>
    </transition>

    …

  </SpaceLayer>
```

Listing 3: General layout of a <SpaceLayer> element describing a single space layer according to the structured space model (cf. chapter 8.1).

A <SpaceLayer> is a container for further feature elements which are used to systematically describe the space layer in primal and dual space on the one hand and geometry and topology on the other hand. A first type of sub-elements is <Space> which represents a real world object and one cell in primal space. In this example we assume that the interior built environment is modeled according to CityGML and stored in an external file. As shown in listing 3, <Space>s may denote references to thematic objects in external data sources such as files or databases. For example, the first <Space> element representing *Room1* in listing 3 references an existing CityGML Room object. The geometry and topology in primal space of the cell represented by <Space> is specified using GML3 elements. Again, references to existing geometries in external data sources are allowed. In this example, the geometry for *Room1* is also taken from the external CityGML file using the XLink mechanism provided by GML3. Of course, external references are not mandatory and all information may instead be given inline.

In addition to <Space>, the <SpaceBoundary> sub-elements of <SpaceLayer> are used to semantically describe the boundary faces of each cell and to represent both their geometry and topology in primal space. For example, the first <SpaceBoundary> element in listing 3 represents the *Door1* between *Room1* and *Room2* and, thus, a shared face where both rooms touch. Similar to the <Space> elements, <SpaceBounday> may denote a reference to an external data source which contains the semantic real world object. In this example, *Door1* is again defined in the external CityGML file which is referenced in listing 3. The same CityGML file is further referenced for the geometry description of the door. Both geometry and topology are modeled based on GML3 elements. Please note, that the <gml:Face> representations of <SurfaceBoundary>s can, of course, be reused to create a <gml:TopoSolid> representation for the <Space>s. For example, the <gml:TopoSolid> of the first <Space> in listing 3 (*Room1*) is referencing the <gml:Face> of the first <SpaceBoundary> element (*Door1*) using GML3's XLink mechanism.

In addition to the primal space representation, the sub-elements <State> and <Transition> of <SpaceLayer> are used for the dual representation of the space layer both in topology and geometry space. A <State> results from applying the Poincaré Duality to a cell in primal space and, thus, represents a node in dual space. Accordingly, a <Transition> is the result from mapping a <SpaceBoundary> from primal space to dual space and, thus, represents as an edge. The topological representation of <State> as <gml:Node> and <Transition> as <gml:Edge> is used to establish the intra-layer adjacency graph. Furthermore, this graph can be embedded into 3D Euclidean Space through an additional geometric representation. The latter one allows for describing trajectories and geometric route networks.

The following listing 4 shows the <SpaceLayer> element for representing the WiFi Sensor Layer. Please note, that this listing is again just an excerpt and lacks the full topological and geometric representation of the cells for brevity reasons.

```
<SpaceLayer>
  <gml:name>WiFi Sensor Layer</gml:name>
  <class>sensor</class>

  <space>
    <Space gml:id="SL_Space_WiFi_A"> … </Space>
  </space>

  <space>
    <Space gml:id="SL_Space_WiFi_AB"> … </Space>
  </space>

  <space>
    <Space gml:id="SL_Space_WiFi_B"> … </Space>
  </space>

  <state>
    <State gml:id="SL_State_Wifi_A">
      <topoNode>
        <gml:Node gml:id="SL_Node_WiFi_A"></gml:Node>
      </topoNode>
      …
    </State>
  </state>

  <state>
    <State gml:id="SL_State_Wifi_AB">
      <topoNode>
        <gml:Node gml:id="SL_Node_WiFi_AB"></gml:Node>
      </topoNode>
      …
    </State>
  </state>
```



```
      <state>
        <State gml:id="SL_State_Wifi_B">
          <topoNode>
            <gml:Node gml:id="SL_Node_WiFi_B"></gml:Node>
          </topoNode>
          …
        </State>
      </state>

      <state>
        <State gml:id="SL_State_Wifi_Outer">
          <topoNode>
            <gml:Node gml:id="SL_Node_WiFi_Outer"></gml:Node>
          </topoNode>
          …
        </State>
      </state>

      <transition>
        <Transition>
          <topoEdge>
            <gml:Edge>
              <gml:directedNode xlink:href="#SL_Node_WiFi_A"/>
              <gml:directedNode xlink:href="#SL_Node_WiFi_AB"/>
            </gml:Edge>
          </topoEdge>
          …
        </Transition>
      </transition>

      <transition>
        <Transition>
          <topoEdge>
            <gml:Edge>
              <gml:directedNode xlink:href="#SL_Node_WiFi_AB"/>
              <gml:directedNode xlink:href="#SL_Node_WiFi_B"/>
            </gml:Edge>
          </topoEdge>
          …
        </Transition>
      </transition>

      <transition>
        <Transition>
          <topoEdge>
            <gml:Edge>
              <gml:directedNode xlink:href="#SL_Node_WiFi_A"/>
              <gml:directedNode xlink:href="#SL_Node_WiFi_Outer"/>
            </gml:Edge>
          </topoEdge>
          …
        </Transition>
      </transition>

      <transition>
        <Transition>
          <topoEdge>
            <gml:Edge>
              <gml:directedNode xlink:href="#SL_Node_WiFi_B"/>
              <gml:directedNode xlink:href="#SL_Node_WiFi_Outer"/>
            </gml:Edge>
          </topoEdge>
          …
        </Transition>
      </transition>

    </SpaceLayer>
```

Listing 4: Excerpt of the <SpaceLayer> element describing the WiFi Sensor Layer as illustrated in fig. 29.

InterSpaceConnection element

The <SpaceLayer> element already fully describes a single space layer of the Multilayered Space-Event Model both in primal and dual space. The connections between the layers are represented by the <InterSpaceConnection> element. As described in chapter 8, the nodes in dual space of two space layers are connected through an inter-space edge iff the corresponding cells in primal space overlap. By this means, the dual graph representations of all layers are combined to the Mutlilayered Graph.

The following excerpt in listing 5 shows the <InterSpaceConnection> element which denotes the overlap of *Room1* and *WiFi coverage area A* in primal space and, thus, establishes the corresponding edge between the nodes in dual space.

```
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room1"/>
    <state xlink:href="#SL_Space_WiFi_A"/>
    <topoEdge>
      <gml:Edge>
        <gml:directedNode xlink:href="#TL_Node_Room1"/>
        <gml:directedNode xlink:href="#SL_Node_WiFi_A"/>
      </gml:Edge>
    </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
```

Listing 5: Example for a single <InterSpaceConnection> element establishing an edge between two nodes of two different space layers in dual space.

As shown in listing 5, the <InterSpaceConnection> may reference the semantic <State> elements which are linked between the two space layers. Additionally, it establishes a mandatory <gml:Egde> between their <gml:Node> representations in dual topology space. In this example, the XLink mechanism of GML3 is used to reference the corresponding elements within the <Space> element of the two <SpaceLayer>s. Please note, that an <InterSpaceConnection> only represents the link between two layers. The attribute <topoRelation> can be used to express the type of topological relation between the primal cells of both layers. For example, a subspace layer is restricted to the relations “contains”, “inside”, and “equals”.

All <InterSpaceConnection>s for the example depicted in fig. 29 are shown in the following listing 6. Please note, that listing 6 is an excerpt and lacks the full topological representation of the <InterSpaceConnection>s for brevity reasons.

```
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room1"/>
    <state xlink:href="#SL_Space_WiFi_A"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room1"/>
    <state xlink:href="#SL_Space_WiFi_AB"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room1"/>
    <state xlink:href="#SL_Space_WiFi_Outer"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
```



```xml
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room2"/>
    <state xlink:href="#SL_Space_WiFi_B"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room2"/>
    <state xlink:href="#SL_Space_WiFi_AB"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room2"/>
    <state xlink:href="#SL_Space_WiFi_Outer"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room3a"/>
    <state xlink:href="#SL_Space_WiFi_A"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room3a"/>
    <state xlink:href="#SL_Space_WiFi_Outer"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room3b"/>
    <state xlink:href="#SL_Space_WiFi_B"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Room3b"/>
    <state xlink:href="#SL_Space_WiFi_Outer"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
<interSpaceConnectionMember>
  <InterSpaceConnection>
    <state xlink:href="#TL_State_Outer"/>
    <state xlink:href="#SL_Space_WiFi_Outer"/>
    <topoEdge> ... </topoEdge>
    <topoRelation>overlap</topoRelation>
  </InterSpaceConnection>
</interSpaceConnectionMember>
```

Listing 6: <InterSpaceConnection> elements denoting the connections between the two space layers shown in fig. 29.

Finally, the two illustrated <SpaceLayer> elements of the Topography Space and the WiFi Sensor Space (listings 3 and 4) together with the <InterSpaceConnection> elements shown in listing 6 should be inserted in the skeleton described by listing 2 in order to get a full and valid XML instance document of the example shown in fig. 29.

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