

SPATIO-SEMANTIC COHERENCE IN THE INTEGRATION OF 3D CITY MODELS

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ABSTRACT:

An increasing number of applications rely on 3D geoinformation. In addition to 3D geometry, these applications particularly require complex semantic information. In the context of spatial data infrastructures the needed data are drawn from distributed sources and often are thematically and spatially fragmented. Straight forward joining of 3D objects would inevitably lead to geometrical inconsistencies such as cracks, permeations, or other inconsistencies. Semantic information can help to reduce the ambiguities for geometric integration, if it is coherently structured with respect to geometry. The paper discusses these problems with special focus on virtual 3D city models and the semantic data model CityGML, an emerging standard for the representation and the exchange of 3D city models based on ISO 191xx standards and GML3. Different data qualities are analyzed with respect to their semantic and spatial structure leading to the distinction of six categories regarding the spatio-semantic coherence of 3D city models. Furthermore, it is shown how spatial data with complex object descriptions support the integration process. The derived categories will help in the future development of automatic integration methods for complex 3D geodata.

1. INTRODUCTION

Virtual 3D city models are applied for an increasing number of tasks related to environmental simulations like noise mapping, training simulators, disaster management, architecture, and city planning (Shiode, 2001; Döllner et al., 2006). In addition to 3D geometry and appearance information, these applications particularly require complex semantic information. However, the needed data are typically drawn from distributed sources and often are thematically and spatially fragmented. Thus, for a given geographic region data differ in quality and modelled semantic aspects. This situation is rather typical in the context of spatial data infrastructures which provide immediate access to numerous geodata sources on the Internet.

Straight forward joining of 3D objects would inevitably lead to geometrical inconsistencies such as cracks, permeations, or inconsistencies in the degree of detail. Prominent examples for these inconsistencies are ‘flying’ or ‘drowning’ buildings, when a Digital Terrain Model (DTM) and 3D building models from different sources are combined. According to Laurini (1998) such inconsistencies belong to layer fragmentation. This term describes errors occurring during merging of datasets covering the same region but containing different feature classes. In contrast, zonal fragmentation deals with errors occurring during merging of datasets containing the same feature class but covering spatially disjoint regions. Here, typical inconsistencies are overlaps or gaps at the borders of, for example, the DTMs of two neighbouring municipalities.

Hence, methods are required for seamless data integration. So far data integration was done by the data provider (mapping agencies, etc.). Consistency of datasets was ensured by

extensive, mostly manual harmonisation. Humans are able to recognize geometry and implicitly associate semantics. This additional knowledge combined with a natural sense for plausibility is applied to solve local inconsistencies. In the context of new technologies like web services (Web Map Service, Web Feature Service; see Groot and McLaughlin, 2000) the user can easily access and combine geospatial data from multiple sources. Consequently data integration cannot be performed by the data providers, but the user has to ensure consistency himself which is a major drawback.

In order to allow for ad-hoc combination of distributed datasets, methods for automatic data integration have to be developed. Since such methods cannot rely on human abilities of sensible interpretation of arbitrary situations, feature semantics have to be provided explicitly. These semantics allow for two different integration approaches, either by using implicitly known rules or by using explicitly given connectors (such as tie points, terrain intersection curves, etc.). The more information is provided by the semantic layer, the less ambiguities remain for geometric integrations. Based on that knowledge, adaptive harmonization processes for diverging contents are enabled. For example a door always requires a surface to step on. Thus, when a building and a terrain are joined, the lower edge of a polygon marked as door requires either a staircase or the terrain to touch that edge. Additionally, semantic information allows inferring limits for geometric adjustments, e.g., street furniture is more likely to be moved than the streets themselves.

In this paper, we analyse the structure of semantic and spatial information of 3D city models as well as their correspondence, referred to as spatio-semantic coherence. As available data

differ in their structural subdivision we describe common cases of spatial and semantic complexity in the context of CityGML, a geospatial data model specifically designed for the representation and exchange of 3D city models. Section 2 gives an overview on city models in general and selected aspects of CityGML. Section 3 explains spatio-semantic coherence and describes the abovementioned cases of different spatial and semantic complexity. Section 4 then discusses benefits for data validation and integration. Section 5 outlines related work and finally section 6 concludes the paper with a short summary and an outlook.

2. 3D CITY MODELS AND CITYGML

Virtual 3D city models are digital representations of the Earth's surface and related objects belonging to urban areas. They enable a wide variety of applications which in turn create a demand for detailed 3D city models. Such models need to reflect the complexity of city objects and their interrelations. Data covering various aspects are readily available from multiple sources. For effective use, these datasets need to be integrated into application specific models.

Visualisation, for example, requires high quality graphical representations, which ought to be as realistic as possible. For this purpose geometry along with appearance information is sufficient. In contrast, engineering applications like noise mapping or disaster management (Kolbe et al., 2005) aim at the execution of complex queries and analyses based on detailed semantic information. For example, in noise mapping additional acoustic data such as paving and noise insulation of walls allow the calculation of high resolution noise pollution maps (Czerwinski et al., 2006).

Depending on the application domain, semantics are needed to perform proper analyses. To enable collaboration in heterogeneous environments, standardised data exchange methods for city models comprising both spatial and semantic information are required. CityGML addresses this problem.

2.1 CityGML

CityGML is an open data model and XML-based format for the storage and exchange of virtual 3D city models. It is realised as an application schema for GML3, the extendible

international standard for spatial data exchange issued by the Open Geospatial Consortium (OGC). The main idea is to achieve a common definition of the basic feature classes, attributes, and relations in the sense of an ontology for 3D city models with respect to geometric, topological, semantic, and appearance properties (Gröger et al., 2006). This is important for cost-effective sustainable maintenance, allowing the reuse of the same dataset in different application domains.

The modelling principle is based on a feature class taxonomy and a decomposition both on the semantic and spatial side (from the whole city over the city objects like buildings down to smaller components like a balcony). These decompositions result in two hierarchical structures which will be described in the following (see also Kolbe and Gröger, 2003).

The **semantic model** of CityGML consists of class definitions for the most important features within virtual 3D city models, including buildings, DTMs, water bodies, transportation, vegetation, and city furniture. Figure 1 shows a small part of the semantic model used to describe buildings. All classes shown are derived from the basic class 'Feature', defined in ISO 19109 and GML3 for the representation of spatial objects and their aggregations. Features comprise spatial as well as non-spatial attributes which are mapped to GML3 feature properties with corresponding data types (ISO/FDIS 19109, 2005).

The following observations can be made from figure 1:

- A building can be recursively composed of building parts.
- A building can be bounded by several types of surfaces (walls, roof) which may have openings like windows and doors.
- A building can have outer building installations.
- Both the semantic and geometry model allow for aggregations on several levels.

Spatial properties of CityGML features are represented by objects of GML3's **geometry model**, which is based on the standard ISO 19107 "Spatial Schema" (Herring, 2001), representing 3D geometry according to the well-known Boundary Representation (B-Rep, Foley et al., 1995). CityGML actually uses only a subset of the GML3 geometry package.

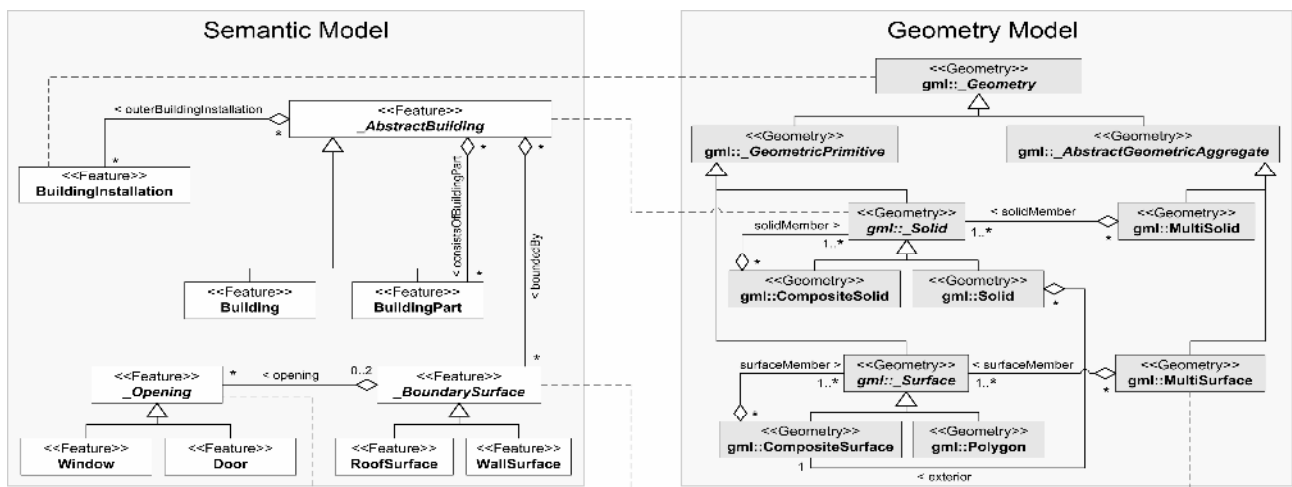


Figure 1. UML class diagram (Booch et al., 1997) of CityGML's semantic and geometry model (left: excerpt from the building model, right: excerpt from ISO 19107 Spatial schema). Both structures allow for aggregations on several levels.

The geometry model of GML3 consists of primitives. For each dimension, they may be combined to form (among others) aggregate or composite geometries, meeting different connectivity requirements. Whereas aggregate geometries are arbitrary collections of primitives, composite geometries only represent primitives topologically connected along their boundaries.

In CityGML, topology can be represented explicitly. Every part of space may be modelled only once and then referenced by all features which include the same geometry. Thereby redundancy can be avoided and explicit topological relations between parts are maintained.

Furthermore, the concept of Levels of Detail (LoD) is supported. In one dataset, the same object may be represented in up to 5 discrete and well-defined LoDs simultaneously, ranging from pure DTMs to architectural models with interior structures. This is achieved by feature classes being only valid for a specific range of LoDs. For example the building feature class is valid for LoDs 1 to 4 whereas the boundary surface feature class is valid for LoDs 2 to 4 only.

Thus, CityGML is capable of representing 3D city models at various degrees of complexity with respect to geometry as well as semantics. This allows flexible use of CityGML as exchange format both in terms of representable data and applications.

3. SPATIO-SEMANTIC COHERENCE

When following the line of the ISO 191xx standards family in dealing with geospatial information, then there is a dual structure comprising geometry and semantics. As described above, in CityGML this situation is realized by the two aggregation hierarchies of feature and geometry types. By linking corresponding objects (represented by dashed lines in figures 1 and 2 to 6), coherence in modelling of semantics and geometry shall be assured. In the following the meaning of this term will be examined in more detail.

In general, coherence denotes the quality or state of cohering, namely a logical, orderly, and aesthetically consistent relationship of parts (www.thefreedictionary.com). According to this definition, coherence in the geospatial context describes consistent relationships of spatial and semantic entities. Those relations are realised in the form of associations, which can only be established in case of structural similarity. So, in other words, if semantic and geometric aggregations show the same structure, they will be considered coherent. Only then, semantic and spatial

information can be used in conjunction, bearing two obvious benefits:

- Geometrical objects “know” what they are.
- Semantic entities “know” where they are and what are their spatial extents.

In a mathematical sense, structural similarity between spatial and semantic decompositions is described by a homomorphism between the two structures. Basically, the more aggregation relations from concrete model instances can be mapped from the geometry hierarchy to the semantics hierarchy (and vice-versa), the higher is the degree of coherence. The derivation of a specific quantitative measure based on this principle is subject of ongoing work.

In the following, we will examine and distinguish different cases of 3D city models with respect to their underlying semantic and spatial complexity. Spatial complexity does not refer to the number of geometric primitives. It rather denotes the structural subdivision of geometry into meaningful parts, defining hierarchical as well as topological relations. Analogously, semantic complexity stands for the structural subdivision of semantic information. Figures 2 to 6 depict a building composed of walls, windows, door, roof, and stairs. The pictures on the left side show the visual appearance (which is the same for all examples), the trees in the middle and on the right side represent the semantic and spatial structures used to describe the building. The dashed lines mark relations between corresponding entities in both structures.

Case 1: Only geometry, no semantics. The first case (see figure 2) describes typical models based on 3D graphics formats like VRML, X3D, KML, U3D or legacy CAD geometry formats. These 3D models comprise a more or less structured geometry, often organized in scene graphs (cf. Foley et al, 1995). They are characteristic outputs of 3D modelling tools used in computer graphics and CAD. As they do not comprise semantic object information – in many cases not even an object ID is supported – there is no coherence.

Case 2: Only semantics, but no geometry. This case is rather unusual and describes a situation in which it is known, that the city model consists of specific geospatial features of known types, but where geometry is unknown or not available. This type of data may be derived from economic or accounting data or may emanate from a facility management system. It would be useful for the generation of hypotheses in the task of automatic urban object reconstruction from aerial and terrestrial laser and image data (see Fischer et al., 1998, Brenner, 2003).



Figure 2. Unstructured geometry without semantic object information (Case 1).

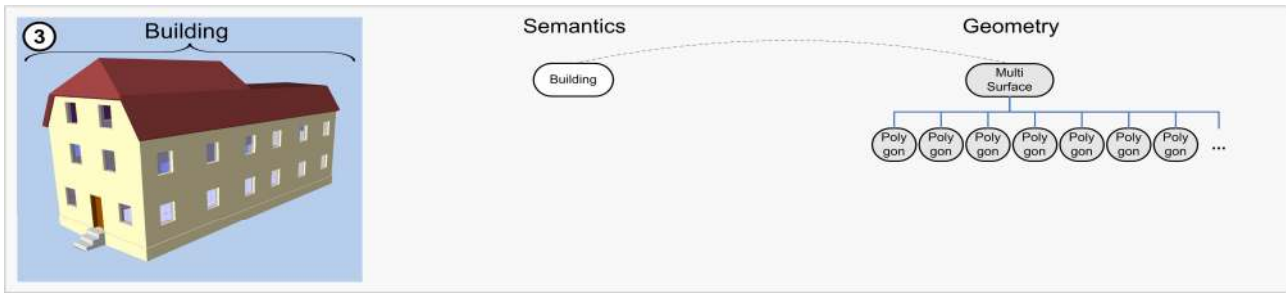


Figure 3. Simple object with unstructured geometry (Case 3).

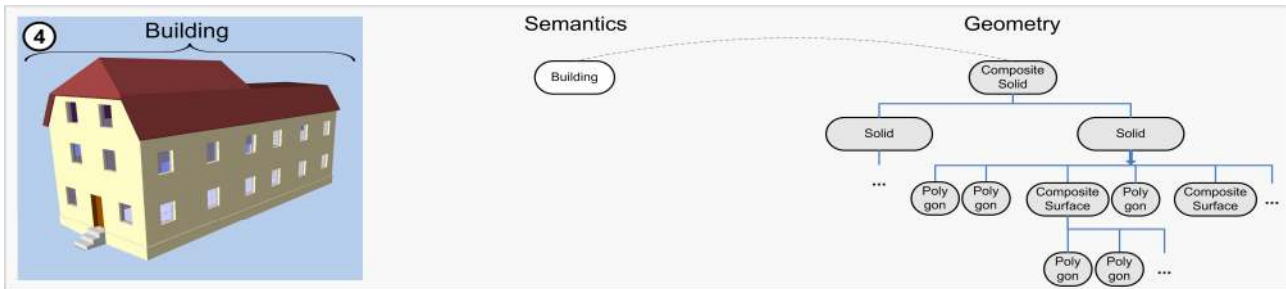


Figure 4. Simple object with complex structured geometry (Case 4).

Case 3: Simple objects with unstructured geometry (figure 3). Objects are represented by geographic features. Each feature has a spatial attribute consisting of an unstructured collection of 3D surfaces and possibly a number of scalar, non-spatial attributes. This model has to be rated highly coherent, if the morphology described by the geometry is simple, and little coherent if the unstructured geometry describes a complex shape (e.g. a detailed building complex). Typical implementations are models represented by so-called Multipatch-Shapefiles (cf. ESRI 1998).

Case 4: Simple objects with structured geometry (figure 4). In this case, geometry is not only detailed but also structured with respect to spatial decomposition. However, when it comes to semantics, no more than the existence of a building is indicated. So, relations cannot be established between sub-geometries and the missing semantic components resulting in a low degree of coherence. These kinds of models can be created with photogrammetric object extraction tools (cf. Gülich and Müller, 2001) or by automated reconstruction of geometric primitives from unstructured geometry like laser scanner point clouds or triangulations (cf. Marshall et al., 2001).

Case 5: Complex objects with unstructured geometry (figure 5). Semantics are detailed, which means that the thematic decomposition of the building is known. Since geometry is detailed, yet unstructured, relations between

semantics and geometry again cannot be established on different aggregation levels. Thus, coherence is given only to the degree that it is known that the aggregated building object in total is spatially represented by a set of 3D surfaces. Such models might be the result of a simple derivation from 3D Building Information Models (BIM) like the Industry Foundation Classes (IFC, Adachi et al., 2003; see section 5 for further information about IFC) or facility management systems. The complex spatial structure, which often is being represented using Constructive Solid Geometry (CSG, see Foley et al., 1995), is transformed to a collection of 3D boundary surfaces (B-Rep).

Case 6: Complex objects with structured geometry. Both the semantic model and the geometry is given as a complex aggregation. If all semantic components correlate to geometric components on the same level of the hierarchy, the structure is considered as being fully coherent (figure 6). These models reveal the highest degree of structural quality as they are both semantically and geometrically rich, and above are structurally isomorphic. Such models can be derived by sophisticated analyses and transformations from Building Information Models like IFC. In (Benner et al., 2005) it was shown how to map the semantics and CSG geometry of the IFC model to a spatio-semantic coherent B-Rep representation in CityGML. Also methods for the automatic extraction of buildings aim at this level of quality (Fischer et al., 1998, Brenner, 2003).

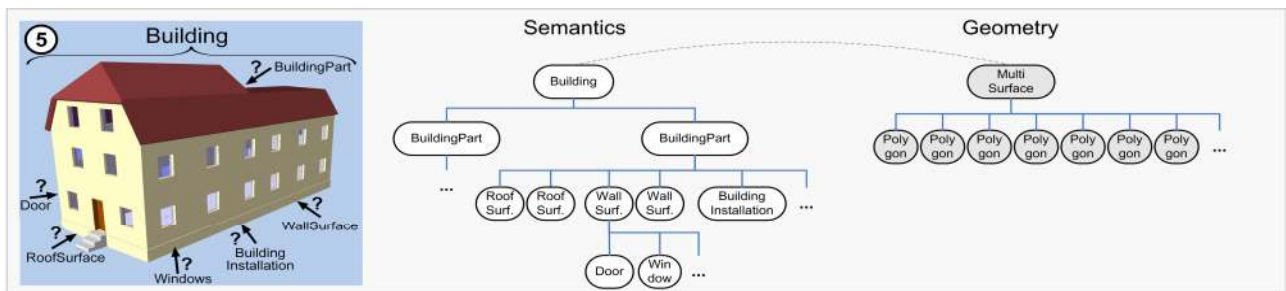


Figure 5. Object with complex semantic structure and detailed, but unstructured and uncorrelated geometry (Case 5).

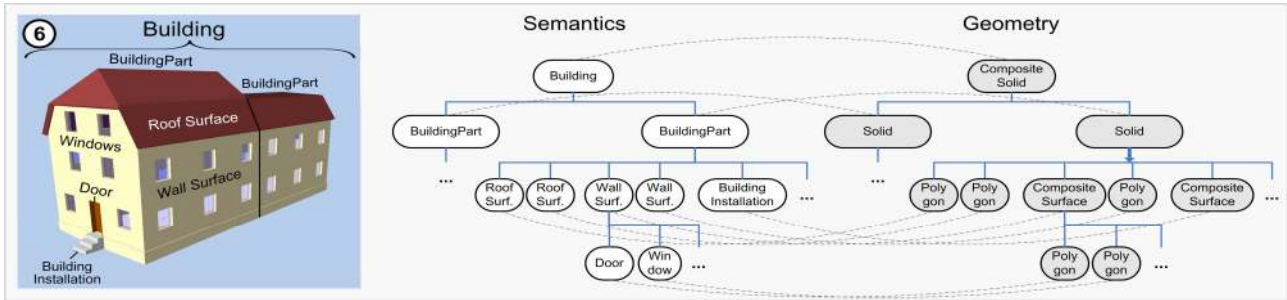


Figure 6. Complex object with fully coherent spatio-semantic structure (Case 6).

In order to facilitate the representation of city models with different data qualities, CityGML supports cases 2 to 6. Case 1 is not directly covered, because CityGML is based on the feature model of ISO 19109 and therefore always needs to assign geometries to (at least simple) semantic objects. Thus, models could initially be represented in an unstructured and incoherent way and may be step-wise refined by manual and automated qualification processes within the same modelling framework.

From the descriptions above it becomes clear that besides the spatial and semantic complexity also the coherence of the two structures is an important quality aspect of 3D city models. In order to measure the degree of coherence we have to consider that it reflects the degree of similarity of both the semantic and spatial subdivisions, depending on the number of correspondences that can be identified. This number has to be normalised by the number of entities, because simple structured data can be as coherent as complex structured data.

If spatial and semantic complexity are mapped together with the degree of coherence (each on one axis), they span a **coherence space**. All feature instances can be located within that space with respect to their concrete spatial and semantic characteristics. Since full coherence is achievable only along the line of equal spatial and semantic complexity, the resulting **surface of maximum possible coherence** is shaped like an arch. Figure 7 illustrates interdependencies between geometry, semantics and their coherence. The dashed line at the back represents an open interval as coherence is not defined for either no semantics or no geometry. The labels 1 to 6 represent the locations of the cases 1 to 6 discussed above.

Please note that in all of the aforementioned cases (except for case 2) the visual appearance of the model may be identical when being rendered. This shows that even if models look similar they may substantially differ wrt. their structural quality – or vice versa: one cannot conclude important aspects of data quality by just visual inspection. Although not surprising from a theoretical point of view, it is worth mentioning in the context of 3D city models, because it has a significant impact on the possible applications for specific city model instances and their inherent support of data integration.

4. BENEFITS OF SPATIO-SEMANTIC COHERENCE

In the following we examine the role of spatio-semantic coherence in the validation of 3D city models on the one hand and its support for the integration of distributed datasets in order to establish spatial interoperability on the other hand.

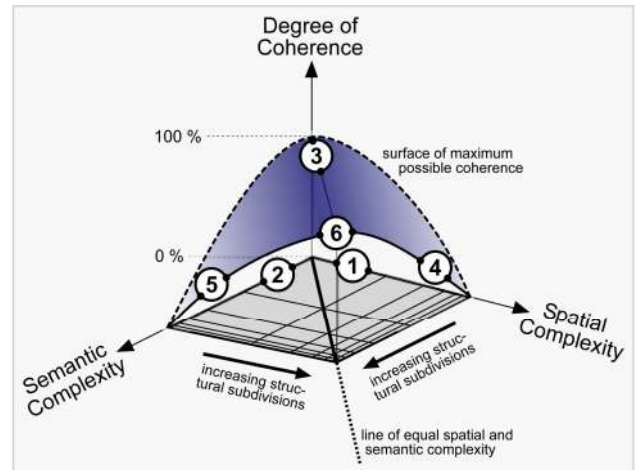


Figure 7. Possible degree of spatio-semantic coherence depending on spatial and semantic complexity. The numbers refer to the cases 1 to 6.

4.1 Data validation

Data validation means consistency checking of existing data. The set of consistency rules is mainly determined by the underlying data model. In case of a purely geometric model, data validation would be limited to checking spatial constraints defined for geometry classes such as composites that have to be connected along their boundaries. If the model covers both geometry and semantics in a coherent way, more detailed consistency rules can be specified. For example, semantic information associated with geometric entities typically define topological constraints between different feature types such as “contains”, “touches”, etc. (cf. Clementini and Di Felice, 1996). Taking rooms as an example, they have to be disjoint and fully lie inside their surrounding building shell. Also the terrain should topologically connect to the lower edge or surface of the doors or the entrance stairs of buildings.

4.2 Data integration

In this paper we focus on the integration of CityGML data from distributed sources, i.e. we assume that all datasets are modelled according to one common data model. The problem of data integration is therefore not to overcome semantic differences between the datasets, but to spatially harmonize fragmented data (layer and zonal fragmentation according to Laurini, 1998) in order to establish a geometrically, topologically, and semantically consistent 3D scene.

In the following, the relevance of spatio-semantic coherence for data integration is explained using three scenarios:

- If there are **no semantics** (case 1 from above) or the semantic structures are not correlated with geometric structures, integration can be carried out purely on the basis of geometric shape. This means that harmonization cannot rely on tie points or other connecting features to correlate feature geometries. Figure 8 shows the combination of three datasets with unknown semantics which cannot be automatically integrated. From the visual impression (despite using arbitrary colours) it is obvious to the reader, that the object geometries describe a building, a path and terrain. However, this information is not available to an automated integration process, as it is not explicitly represented and also typically cannot be concluded from the data. Thus, an integration process would not be able to attach the path to the door of the building and the building could not be “dropped onto the ground”, because it is not known that the shapes represent buildings, paths, and the terrain.

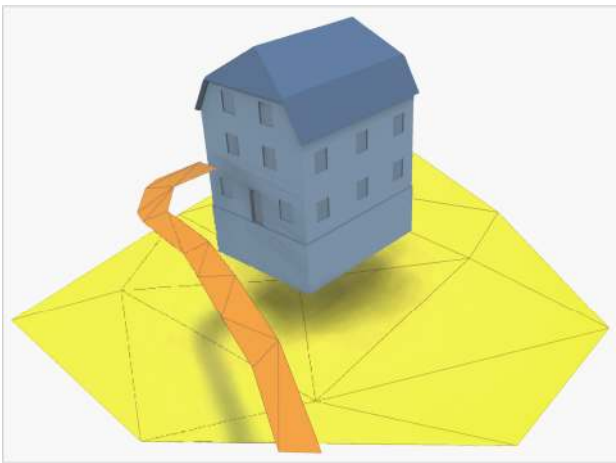


Figure 8. Combination of three datasets (geometries of a building, terrain, footpath) with no explicitly represented semantics. It is not clear (for an automated procedure) which parts of the objects' geometries must be fitted (and how).

- By knowing at least the involved **feature types** (cases 3 to 5), simple strategies for integration may be carried out. In contrast to the abovementioned situation having no semantics, here the building, path, and terrain can be matched to each other. Depending on the feature class and its significance, the degree of tolerable adjustments could be defined. These tolerance values typically rely on underlying methods of data capture and their accuracy, hence data quality. For example a less accurate terrain model would be more likely adjusted to the building's ground surface than the building to the terrain. However, the limited spatio-semantic coherence would possibly not reveal that the building is composed of different storeys, including the cellar. This means that the building could not be combined with the terrain in such a way that the cellar lies below the surface and the other storeys above. Also the path could be mapped onto the ground but most likely could not be “pulled” to the doorstep, as the information about the exact location of the door is not explicit.

- In case of **coherent structural modelling** (case 6), all semantic information can be exploited in the process of harmonization. Detailed semantics then help to identify objects by their properties or define tie points for adjustments. Many important interrelations involve the terrain by features either touching or intersecting it at known positions. Figure 9 shows the same features as figure 8 but this time integrated by the usage of semantic information. Knowing the location of the building's door, the terrain was aligned with the door's lower edge, i.e. the doorstep. The path was also translated to that position and embedded into the terrain.



Figure 9. Consistent integration of the datasets shown in figure 8 is facilitated by detailed semantic information coherently structured with geometry and topology.

From the discussed cases it becomes clear that semantic information is highly beneficial – but only if its relation to geometry is known, which is true for coherent models. Only then, semantics can be employed for:

- making use of known interrelations (in the real world) between specific feature classes;
- defining tolerance and threshold values for the adjustment of various feature classes;
- the identification of corresponding objects; and
- finding tie points (or higher dimensional connecting elements like curves or surfaces) to minimise the ambiguities of adjustments.

The definition of specific integration rules for the combination of different feature types is ongoing work. The development of a quantitative and objective quality measure to rate the degree of consistency of an integrated 3D scene is a topic of future research. However, structural complexity of semantics and geometry together with the degree of spatio-semantic coherence is regarded to be of utmost importance for this task.

5. RELATED WORK

In section 3 we shortly mentioned other data models and exchange formats that are often used for the representation of 3D city models. We will revisit some of them in the following two paragraphs with special focus on spatio-semantic coherence.

3D computer graphics formats like X3D (ISO 19775, 2005) or U3D (ECMA-363, 2005) model the geometric structure only (along with its appearance and limited topology). They do not provide specific support for the representation of semantic information. However, Pittarello and De Faveri (2006) proposed two approaches to augment X3D by semantic infor-

mation. Generally, they suggest to represent complex spatial real world objects as multi-level aggregation hierarchies. The first approach is based on tagging X3D geometries with semantic information (properties and relations) in their metadata fields, leaving some problems to represent objects without geometries. The second approach employs the Resource Description Framework (RDF, 2004) and introduces the three different spatial aggregation concepts ‘containedBy’, ‘sharedBy’, and ‘boundedBy’ which are used to define zonal models. Although these aggregation types impose implicit topological constraints, these are not discussed. Since semantic and spatial information is encoded in two separate hierarchies, coherence would be also an issue there, but is not examined.

Building Information Models (BIM) are increasingly often represented and exchanged using the Industry Foundation Classes (IFC; see Adachi et al., 2003), an ISO standard describing a product model and data exchange standard for the built-up environment developed by the International Alliance for Interoperability (IAI). IFC objects model constructive elements like beams, walls etc. Like in GML, IFC geometries are spatial properties of semantic objects. The overall geometric structure of complex objects implicitly follows from the semantic aggregation. Aggregation is not explicitly repeated on the geometry side. It is, however, possible to have complex structured geometries attached to semantically simple objects (e. g. IFC_Proxy) as it was discussed above in case 4. This means that spatio-semantic coherence is also not automatically ensured in IFC and should be evaluated to describe data quality more precisely.

The identification and measuring of similarities within one ontology or between different ontologies has been investigated by many authors. In the case of two ontologies, a high degree of coherence between the ontological structures is generally seen as an essential prerequisite (or indication) for semantic interoperability (see Maedche and Staab, 2002; Fonseca et al., 2006). Yet we have not found other work on measuring the coherence of semantic and spatial structures with respect to the same data model. For measuring especially the similarity of aggregation hierarchies different concepts have been proposed by (Surma, 1997) and (Fonseca et al., 2006), but generally the whole field of tree and relational matching is relevant here.

With respect to data integration two tasks can be distinguished: the first is to identify corresponding objects or tie points of features from different datasets. The second task is then to geodetically homogenize the 2.5D and 3D geometries. For the homogenization of 3D geometries, Kampshoff (2005) suggests using the deterministic model of the topology of the Euclidean space where the connection between the true map and observed maps is treated as a homeomorphism. His model allows to estimate the unknown parameters (coordinates) in the system of the true map and to simultaneously consider geometrical constraints, the linear trend, the nonlinear signal and the random noise. Another approach has been suggested by Koch (2005). He employs semantic information in order to integrate different types of features that are part of the earth’s surface, i.e. roads, rivers, and lakes with the digital terrain model. Each feature type brings its own set of constraints allowing to express the specific spatial invariants of the respective real world objects (e.g. the water surface of a lake always has to lie lower than the surrounding terrain – except for outgoing rivers).

6. CONCLUSIONS

Virtual 3D city models are typically acquired and refined step-wise and therefore coherence cannot be assumed at any time. In order to support data integration as well as spatio-semantic queries and analyses, structurally consistent models are to be achieved in terms of geometry, semantics and their correspondence. Structural consistency is one aspect of data quality which usually receives less attention than data accuracy. Yet measures like spatio-semantic coherence are of particular relevance in the context of geospatial modelling.

We have given a short introduction to CityGML, where special focus was laid on the dual aggregation hierarchies of semantic feature types and geometric decompositions. The data model actually allows for the representation of 3D city models in different qualities wrt. to their explicit semantic and geometric structure. The possible scenarios were distinguished into six categories (cases 1-6) of specific data quality. Besides the structural complexity of semantics and geometry, the coherence of these structures was identified as an important aspect of data quality. These three measures were used to define the coherence space, in which every concrete dataset may be located (and rated). Furthermore, it was shown which categories are covered by other existing 3D modelling standards from the fields of computer graphics, CAD, CAAD, BIM, and GIS. Finally, the important role of spatio-semantic coherence in the integration of distributed datasets was explicated.

Since coherence of relational structures can be mathematically described by a homomorphism between the structures, a quantitative measure shall be derived in the future. Starting point will be the closer examination of investigations on tree similarity and relational matching. The measure then will be evaluated in relation to the six cases specified in section 3. Depending on the case and the degree of coherence, we aim at tailoring the integration methods to specific combinations of feature classes.

Furthermore, evaluation of coherence could also be done on the data model level. If aggregation relations in the semantic model would be marked explicitly as spatial aggregations (as proposed by Pittarello and De Faveri, 2006), it would be possible to check whether the aggregation structure would contradict the aggregation structure defined in the geometry model (e.g. of ISO 19107). Also it would become possible to determine the maximum degree of coherence that instances of complex object models in concrete datasets could reach.

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