PFG 2016 / 1, 031 – 043
Stuttgart, February 2016

Article

Evaluation Criteria for Recent LoD Proposals for City-GML Buildings

Marc-O. Löwner, Braunschweig & Gerhard Gröger, Bonn

Keywords: Virtual 3D city models, semantical data models, CityGML, Level of Detail, evaluation criteria

Summary: The Level of Detail (LoD) concept is an essential part of the Open Geospatial Consortium standard CityGML and of 3D city models in general. New applications such as indoor navigation and energy performance estimation ask for a revision of the current CityGML 2.0 LoD concept. Currently, new approaches are discussed that need to be evaluated. Here, new evaluation criteria for the assessment of recent Level of Detail concepts in the field of semantical 3D city models are developed. They cover richness of aspects, completeness of the concept, completeness of models in a particular LoD, avoidance of inconsistent models, freedom of interpretation, and feasibility and complexity of transformation from CityGML 2.0 into the proposed concept. These criteria represent an added value because user defined LoD profiles of the new CityGML version 3.0 LoD concept are likely and therefore need to be evaluated. Applying the developed criteria, we evaluate the most current proposals on the further development of the CityGML 2.0 LoD concept.

Zusammenfassung: *Kriterien zur Bewertung aktueller Vorschläge für Gebäude-LoD in CityGML.* Der Detaillierungsgrad (Level of Detail, LoD) stellt ein wesentliches Konzept von CityGML, dem internationalen Standard des Open Geospatial Consortiums für semantische 3D-Stadtmodelle, dar. Neue Anwendungsfelder wie die Innenraumnavigation oder die Energiebedarfsanalyse erfordern allerdings eine Überarbeitung der in City-GML 2.0 definierten Konzepte und haben bereits eine Folge von Verbesserungsvorschlägen nach sich gezogen. Hier werden neue Evaluationskriterien zur Bewertung aktueller LoD-Konzepte von semantischen 3D-Stadtmodellen vorgestellt. Diese Kriterien umfassen die Reichhaltigkeit der Aspekte, die Vollständigkeit des Konzeptes, die Vollständigkeit der Modelle innerhalb eines LoD, die Vermeidung inkonsistenter Modelle, die Interpretationsfreiheit sowie die Möglichkeit und Komplexität der Transformation von CityGML 2.0 in das vorgeschlagene Konzept. Die Definition solcher Kriterien ist wichtig, weil für CityGML 3.0 die Möglichkeit diskutiert wird, Profile der LoD Definition zuzulassen. Mittels der neu entwickelten Kriterien werden die aktuellen Verbesserungsvorschläge des LoD Konzeptes bewertet.

1 Introduction

Virtual 3D city models represent single buildings, city quarters, whole cities and even regions for applications such as noise propagation simulation and mapping (Czerwinski et al. 2007), fine dust distribution modelling (Ghassoun et al. 2015), urban and telecommunication planning (Köninger & Bartel 1998, Knapp & Coors 2008), or real-time simulations for emergency driving training (Randt et al. 2007). Some application areas such as emergency management (Zlatanova & Li 2008) or indoor navigation (Becker et al. 2009) even require information of the building's interior on a city level. These models may vary with regard to geometrical and semantical complexity and to the degree of deviation from the corresponding real world objects. Complexity levels then are the result of specific data acqui-

www.schweizerbart.de
DOI: 10.1127/pfg/2016/0282
1432-8364/16/0282 $ 3.25

sition processes or they may be used to assess the suitability of data for specific applications.

The Open Geospatial Consortium (OGC) *CityGML* standard (Gröger et al. 2012, Gröger & Plümer 2012) for the representation of semantically enriched 3D city models has introduced a Level of Detail (LoD) concept in order to support different applications of 3D city models. It does not only cover the geometrical detail level, but also the semantical one, i.e. the richness of feature types modelled. The current LoD concept of CityGML 2.0 provides five discrete levels of detail. Its definition is widely accepted in the scientific community (e.g. Boguslawski et al. 2011, Quinn et al. 2009, Iwaszczuk & Stilla 2010, Fan et al. 2009, Götzelmann et al. 2009, Guerke et al. 2009). The term "*LoDx model*", $x \in \{0, 1, 2, 3, 4\}$, is frequently used to address the complexity of existing city models and their suitability for specific applications. However, some deficiencies have been identified, which hamper the use of CityGML for important applications. In particular, indoor objects are coupled with the highest LoD in CityGML 2.0, implying highly complex semantics and geometry. Hence, applications requiring only coarse indoor models or indoor models in combination with a coarse exterior are not supported. Further, there are no multiple LoD for indoor objects in CityGML 2.0 (e.g. coarse or highly detailed 3D representations, or 2D footprints) which are required for indoor navigation (Domínguez et al. 2011, Hagedorn et al. 2009). In addition, the explicit representation of windows in an outer wall of a building is only possible in LoD3, which requires an accurate geometrical representation of the building façade. To estimate a building's energy demand, however, explicit information on the area covered by windows is needed, whereas a very coarse representation of the façade's geometry is sufficient (Dalla Costa et al. 2011).

To overcome these deficiencies, modifications or extension of the LoD concept have been proposed (Boeters et al. 2015, Biljecki et al. 2013, Biljecki et al. 2014, Benner et al. 2013, Löwner et al. 2013, Nagel 2014). Until today, none of these proposals or possible combinations of their single aspects have been evaluated to be the best LoD concept for 3D city models in a comparative approach. Assessment criteria for the comparison of LoD approaches which are relevant for 3D city model collectors, providers and users are still missing.

Currently, there is a discussion in the CityGML community whether the fixed and standardized geometrical representation for a particular LoD, e.g. *LoD1Solid* or *LoD2MultiSurface* for buildings, should be replaced by a more flexible and generic model where each *CityObject* can be represented by any geometry type. According to this framework, restricting *profiles* may be defined for particular *CityObjects* including one official profile in the CityGML Specification. Thus, evaluation criteria become even more important.

Here, the assessment criteria *richness of aspects*, *completeness of the concept*, *completeness of models in a particular LoD*, *avoidance of inconsistent models*, as well as *feasibility and complexity of transformation from CityGML 2.0* for the evaluation of LoD concepts are introduced and applied to the most recent approaches. The term 'aspect' denotes a component of the data model that is relevant for the LoD concept, for example geometry, semantics, appearance, or topology. However, since no formal definitions are given, we see this contribution as a beginning of a discussion about requirements on LoD concepts.

In section 2 we give an overview on recent LoD concepts for semantical 3D city models focussing mainly on the CityGML Building model. The criteria, which are the base of the comparison, are introduced in section 3. The evaluation and comparison of the approaches introduced in section 2 is presented in section 4. We will end with conclusions and an outlook.

2 Recent Level of Detail Concepts for Semantical Building Models

This section gives an overview over three recent LoD concepts for semantical 3D building models that are related to the further development of CityGML. For a detailed description of the CityGML 2.0 LoD concept reference is made to Löwner et al. (2013), Gröger et al. (2012), and Gröger & Plümer (2012). A more general overview of LoD concepts for semantic 3D city models can be found in BENNER et al. (2013).

2.1 *The Benner Approach*

The Benner approach (named after its main contributor JOACHIM BENNER) is directly related to the further development of the CityGML standard (BENNER et al. 2013, LÖWNER et al. 2013). It exhibits two modifications: First, there is an explicit separation between a geometrical and a semantical LoD. Second, the current LoD4 has been mapped to four LoD for the interior. Hence, a building is partitioned into an exterior and an interior, both with one or more explicit LoD of geometrical and semantical aspects.

For geometry, the Benner approach supports four different representations (LoD0 to LoD3) for all top-level features of the CityGML building model, whether they represent the building's exterior shell (*Building*, *BuildingPart*, …) or interior components (*Room*, …). BENNER et al. (2013) identify the semantical structuring and classification as an important criterion for virtual 3D city models. They define four different *Semantical Levels* (S0 – S3) for the *Building* model's top level features. As for the Geometrical LoD, the Semantical Levels of exterior shell and rooms may be different. If a building refers to more than one room, all corresponding *Room* features must have the same Semantical Level.

Since this extended concept allows for building models representing the exterior building shell as well as interior rooms in different geometrical and semantical LoD with only some restrictions on acceptable combinations, new labels have been defined that extend the existing CityGML 2.0 labels. They are a combination of geometrical and semantical labels where the latter is put in brackets, e.g. LoD2.1(S2.0) for a building with an exterior shell in LoD2 together with interior Objects in LoD1 where *Building*, *BoundarySurfaces* and *BuildingInstallations* for the exterior and *Rooms* for the interior are semantically classified.

2.2 *The Biljecki Approach*

The Biljecki approach (BILJECKI et al. 2013) does not only focus on CityGML, but also on proprietary approaches for 3D city models that are developed by commercial companies. An LoD is defined as a quality measure with regard to a specific application. This measure is related to a variety of aspects including richness of feature types, attribute richness, complexity of geometrical details, appearance quality, and positional accuracy. Separate hierarchies for geometry and semantics are proposed, which have to be defined by users. Further, it is proposed to define constraints for each LoD, which assure its consistency. An example is a constraint that prevents interior geometries without exterior ones.

A modification of this approach with a similar set of six aspects is presented in BILJECKI et al. (2014). These aspects are applied to the exterior and the interior of features. They span a space of six dimensions, and an LoD is defined as a vector of six values or ranges of values. Only *consistent series* of LoD0, …, LoD*n* are considered, which have to be monotonic in each aspect. This means that from one LoD(*i*) to the next LoD(*i*+1) in the sequence, the values of the six aspects increase or remain unchanged, but never decrease. Hence, there is a total order on the LoD in a series that than allows for the comparison of two LoD. As an example for the implementation of the framework, a series LoD0 to LoD9 is defined. The main aspects are *existence of features*, *geometrical correspondence between model and reality*, and *resolution of the appearance*. These 10 LoD are roughly a refinement of the LoD0 to LoD4 in CityGML 2.0. The concept is implemented as an extension of CityGML (formally, an Application Domain Extension).

2.3 *The Nagel Approach*

The Nagel approach (named after CLAUS NAGEL who was the first to propose this concept) is built on practical experience and directly related to the further development of CityGML 2.0 (LÖWNER et al. 2015, NAGEL 2014). It needs just two definitions. First, every city object has a spatial representation in every LoD that refines its spatial representation in higher LoD. That means secondly, that there is no restriction on the usage of any feature type in an LoD. Thus, even feature types that have been limited to CityGML 2.0 LoD4, e.g. a *CeilingSurface,* can be used in any lower LoD. In this approach, LoD0 stands for planar representations and LoD1 for prismatic blocks model representations of a feature. Further, LoD2 models represent a generalised shape of a *CityObject* whereas LoD3 represents it in its highest geometrical complexity.

In order to improve flexibility, a distinction is made between volumetric geographic features and *BoundarySurfaces*. An *AbstractBuilding*, for instance, is then modelled with zero to two instances of a *GM_MultiSurface* in LoD0, representing the footprint or the edges of a roof. For the representation in LoD1 to LoD3 it is modelled as a *GM_MultiSurface* or as a *GM_Solid*, respectively. An *AbstractBoundarySurface*, which might be possible in all four LoD is represented by a *GM_MultiCurve* in LoD0 and zero to one *GM_MultiSurfaces* in LoD1 to LoD3. Here, the curve representation stands for the footprint as a spatial abstraction of that wall surface.

The proposed concept stands out with its clear and short definition. By allowing all feature types being modelled in LoD0 to LoD3 an explicit LoD for interior features becomes obsolete.

3 Definition of Criteria for the Comparison of recent LoD Concepts

In order to compare the LoD concepts, six criteria are introduced: *richness of aspects*, *completeness of the concept*, *completeness of models in a particular LoD*, *avoidance of inconsistent models*, *freedom of interpretation*, and *feasibility and complexity of transformation from CityGML 2.0*.

Richness of aspects

A Level of Detail concept for semantical 3D city models may define more than just the aspect of geometrical similarity of the model and the real world feature. In contrast to computer graphics, it also may cover the semantical LoD, i.e. the richness of feature types such as wall surfaces, installations, or building parts represented in the model. In addition, other aspects of a model can be considered, e.g. its appearance, attribute data and so forth. However, a useful LoD concept should cover more than just geometry or, at least should be extensible to other aspects like semantic or appearance. An increasing complexity of the concept itself and the labelling of instance documents are inextricably linked to this criterion.

Completeness of the concept

Completeness of the concept is the degree to which the concept allows for the representation of data. A concept is complete if all datasets can be represented. The more restrictions apply, the lesser is the completeness. Even models which may be considered as inconsistent might lead to a higher degree of completeness. An example is a 3D dataset with coarse interior objects (blocks model rooms) with highly detailed outer shell penetrated by the room geometries. Such a model is well suited for energy applications, where a rough estimation of the indoor volume is sufficient, but detailed roof structures with dormers are required for solar panel placement planning. In addition, this criterion plays a role for legacy data. Such datasets often violate consistency rules of data models or LoD concepts, e.g. thresholds for geometrical accuracy, topological inconsistencies, or missing semantical classifications, but might be valuable since there are no other datasets available.

Since inconsistent models may increase the completeness of the concept, this criterion is inverse to the criterion 'avoidance of inconsistent models'.

This criterion is crucial for users of 3D city models, which have to check whether the data needed for an intended application can be represented by a particular LoD concept. Likewise, for data collectors it is important to check whether captured data can be represented.

Completeness of models in a particular LoD

This criterion is the degree to which completeness of instant models in a single LoD is forced by the concept. A model is complete in a particular LoD if the concept states that all objects or their parts specified in the particular LoD and existent in the real world are represented in the dataset. One precondition for completeness is the LoD being defined for principal objects, e.g. buildings, primarily for those, which have to represented completely. The LoD of the subordinated features (boundary surfaces, installations, etc.) is determined by the LoD of the principal objects. For example, if a concept provides boundary surfaces and installations in LoD2 and defines that a 'LoD2 building' has an complete outer shell and is completely bounded by boundary surfaces, the LoD2 model of this concept is complete. Likewise, if an 'LoD3 building' requires a complete outer shell with boundary surfaces and openings as feature types, it is complete. If the LoD is defined for each feature type separately, there are no dependencies and, thus, the completeness of models in an LoD is low. This concept would allow representing a single opening or single furniture without any buildings or rooms.

This criterion refers to the rules of an LoD concept and to the degree to which the concept demands completeness. Hence, this criterion can be evaluated by inspecting the concept. It is another issue outside the scope of this discussion whether a particular dataset is complete with regard to an LoD specification (an issue of quality principles evaluation procedures, c.f. ISO 19157:2013). This completeness typically can be assured based on reference data only.

This criterion is of interest for applications which require complete models, for example to assess the energy loss of a building, which rely on models where each opening (door or window) is represented as a feature in the building model.

Avoidance of inconsistent models

This criterion determines whether the LoD specification contains a sufficient explicit or implicit set of integrity rules to assure that the model instances are meaningful. The risk to produce inconsistent models can be avoided by declaring an appropriate LoD concept for virtual 3D buildings. Weak definitions may lead to inconsistent model instances even if the modeller follows all rules and restrictions defined. Inconsistency may occur on the geometrical level if interior structures penetrate the exterior shell due to different interior and exterior LoD. Semantically, inconsistency may occur if more semantical information is allowed to be attached to a coarse and undifferentiated geometry. Therefore, this assessment criterion results also from the completeness of concept.

Freedom of interpretation

An LoD concept may restrict the freedom of interpretation of the modeller. Therefore, it should be clearly defined and avoid ambiguity to result in comparable results when applying modelling rules. Clarity of definition is particularly of interest for the relationship between vendor and customer. Both parties should agree whether a concrete instance model is suited for a specific application and whether the model contains all the data to fulfil the user's demands. Further, a precisely defined Level of Detail concept aiming at improving description of the dataset can lead to a faster and more robust development of application software, e.g. with respect to support switching between different LoD. This also entails a comprehensible and unambiguous labelling of different LoD. Informative value of the label is an essential element when restricting the freedom of interpretation. Thus, the expression of a clearly defined LoD concept leads to unambiguous instance models.

For collectors and providers of data, however, an ambiguously defined model has the advantage of less effort to build up a 3D city model. In addition, legacy models might fit better to an ambiguously defined model. Hence, the scope of such models is significantly wider.

Feasibility and complexity of transformation from CityGML 2.0

Since 2008 many companies, federal surveying agencies and municipalities, responsible for the representation and provision of their 3D city models use CityGML, worldwide. Hence, the required effort to transform these models to a newer version of CityGML with a modified LoD concept (if this transformation is feasible at all) is an important criterion. If models conforming to the new LoD concept are syntactically and semantically compatible with

CityGML 2.0, the complexity is zero. If there is a simple one-to-one mapping between the names of the elements in the model, the complexity is very low. The complexity is high if complex structural or geometrical transformations or classification processes are required to transfer datasets to the new concept.

This criterion is related to the freedom of interpretation. If it is higher in the source than in the target concept, mapping requires the often complex classification of the vague one. For example, if geometry details of the source concept are vaguely defined but mandatory in the target concept, the geometry has to be classified (for example, as LoD1, 2 or 3 geometries) in order to assign the level in the target concept.

4 Comparison of four recent LoD Concepts

Based on the criteria introduced in section 3, we now evaluate the discussed LoD approaches and compare them. An overview of the evaluation results is given in Tab. 1. The order of evaluation is the same for all criteria: 1) CityGML 2.0, 2) Benner approach, 3) Biljecki approach, (example LoD0 – LoD9 instancing the Biljecki framework will be examined additionally), and, 4) Nagel approach.

4.1 *Richness of Aspects*

The CityGML 2.0 LoD concept enables the representation of a *CityObject* in different geometrical LoD and provides a refined semantical description with ascending LoD. However, geometric and semantic complexity of a building model is strictly coupled. In LoD0 and LoD1 no further decomposition of a *Building* or *BuildingPart* into other feature classes or semantic classification is possible. LoD2 represents the prototypic roof shape of a building, thematic ground, wall and roof surfaces as well as installations, such as balconies and dormers. LoD3 as the most detailed level for the outer shape allows for the semantical representation of openings. LoD4 adds interior structures like rooms, furniture, interior installations. While a certain LoD enforces a specific geometric representation, the increase of semantic complexity is only optional. Therefore, it cannot be stated that a semantical LoD is entirely independent.

Regarding geometry, the Benner approach supports four different representations for all top-level features of the CityGML building model regardless whether they represent the building's exterior shell (*Building*, *BuildingPart*, etc.) or interior components. Next to the aspect of geometry Benner et al. (2013) define four different *Semantical Levels* (S0 – S3) for

Tab. 1: Overview of the evaluation of LoD concepts according to the criteria developed in section 3. Ratings range from '– –' (not fulfilled at all) to '++' (completely fulfilled). '/' means that the criterion is not applicable.

	CityGML 2.0	Benner	Biljecki (framework)	Biljecki (LoD0 – 9)	Nagel
Richness of aspects	±	+	+ +	+	–
Completeness of the concept	±	+	±	±	+ +
Completeness of Models in an LoD	±	+ +	+ +	+ +	– –
Avoidance of inconsistent models	+ +	– –	+ +	+ +	– –
Freedom of interpretation	+ +	±	– –	– –	+ +
Feasibility and complexity of transformation from CityGML 2.0	/	+	– –	– –	+ +

the *Building* model's top level features. As for the Geometrical LoD, the Semantical Levels of exterior shell and rooms may be different. If a building refers to more than one room, all corresponding *Room* features must have the same Semantical Level.

In comparison to the CityGML 2.0 LoD concept the Benner approach reveals a higher richness of aspects including a graduation of interior details, the independent representation of different semantical LoD for exterior and interior and an independent semantical Level of Detail for both, the interior and exterior building.

The Biljecki approach defines a very rich LoD concept involving six aspects, which consider semantics (features, attributes), geometry (accuracy, dimensionality), appearance and the relation between geometry and semantics. The exterior and the interior of features are considered separately. Combinations of these aspects are restricted by the concept of series of LoD, which forces an increase of the values of the particular aspects if the LoD number increases. The proposed implementation of the approach (LoD0 – LoD9) uses only a subset of the aspects of the general framework (feature complexity, dimensionality, and appearance). Nevertheless, the richness of both concepts is significantly higher than the richness of all other proposals.

The Nagel approach allows all *CityObjects* to be modelled in every LoD, geometrically. Consequently, an extra LoD for interior feature types, the CityGML 2.0 LoD4, becomes unnecessary. These results in four LoD from LoD0 for surface representations of real-world features, e.g. the ground surface of a building, to LoD3 for the most detailed representation of modelled features. For instance a boundary surface, which can only be modelled from LoD2 in the CityGML 2.0 LoD concept, can be represented as a curve in LoD0 that represents the 'surface of a wall' in the real word. Therefore, the Nagel approach is more flexible than the CityGML 2.0 LoD concept.

No semantical LoD is introduced by the Nagel approach. However, since the CityGML 2.0 LoD concept restricts the usage of some feature types in lower LoD, e.g. a boundary surface in LoD0, it is argued, that the Nagel approach allows for semantically richer models, at least in lower LoD. A floor plan may be considered as an example. Because all feature types can be used to represent the 2D representation of a story, i.e. *IntBuildingInstallation*, *InteriorWallSurface*, *Door*, *Window*, etc. the floor plan is semantically rich and can be queried for wall surfaces, doors, columns, and so forth.

4.2 *Completeness of the LoD Concept*

The completeness of the LoD concept is low for CityGML 2.0, since there are a lot of restrictions between the two aspects of geometry and semantics. First, indoor objects can only be represented in the most detailed LoD. Coarse room representations, which are relevant for energy applications, for example, are out of scope of the concept. Second, semantical richness and complexity of the geometry are coupled. Not all combinations of geometrical and semantical complexity are supported. Hence, datasets which are suitable or required for some applications cannot be represented by CityGML. For example, openings cannot be represented in combination with coarser outer shell of a building. Also rooms cannot be combined with such a coarse outer representation. On the other hand, incomplete instance models in an LoD (see next criterion) can be represented by CityGML 2.0, for example a single opening without any building or wall. Hence, the completeness of the LoD concept is high for such 'incomplete' instance models.

In the Benner approach rooms can be represented in any geometrical detail level, and combinations of indoor objects and the outer building shell are possible. A geometrical detail level can be combined with an arbitrary semantical level, due to the separation into geometrical and semantical LoD. Only a few restrictions remain such that boundary surfaces, openings and building installations cannot be geometrically represented in LoD0 or LoD1.

In the Biljecki approach, the exterior and the interior are separated. Hence, each combination of indoor and outdoor LoD can be represented. However, the completeness is restricted by the monotonicity condition, stating that the value of an aspect cannot decrease in a higher LoD. Hence, geometry and semantics are coupled, as it is the case in CityGML 2.0. The concept is more restricted than the Benner approach, which allows for combinations of geometric and semantical aspects, despite the restrictions mentioned.

The concrete implementation of the Biljecki concept by defining LoD1 to LoD9 is significantly more restricted than the general framework, since exterior and interior are coupled. Coarse indoor objects cannot be represented with a fine exterior. Hence, the completeness is comparable to the completeness of the CityGML 2.0 LoD concept.

The Nagel approach is based on geometry only and has no restrictions at all. Hence, the completeness of the LoD concept is maximal.

With regard to new application areas which initially were the motivation for a modified LoD concept, both, the Nagel and the Benner approach meet the requirements. The Nagel approach is not restricted at all while in the Benner approach, the two aspects geometry and semantics are independent and can be arbitrarily combined. In the general Biljecki approach, the combination of aspects is restricted by the monotonicity condition. Since exterior and interior are separated, more applications are supported. In the concrete implementation, however, interior and exterior are coupled. Hence, neither energy applications (coarse interior / fine grained exterior) nor indoor applications (2D interior objects) are possible.

4.3 *Completeness of Models in a particular LoD*

In CityGML 2.0, a LoD is defined for principal objects such as buildings and it is implied that the corresponding models are complete in that LoD. However, this is stated only narratively in the specification, but is not defined in the mandatory part: neither the UML diagram, nor the XML schemas or the conformance requirements state this explicitly. Hence, the completeness of models in a particular LoD is low.

In the Benner approach, an LoD is also defined for principal objects. The geometrical as well as the semantical label explicitly state the content of such an object. This holds for the geometry and for the semantical content. The latter is explicitly defined by a list of feature types which have to be present in the model. Hence, the models are complete with regard to these labels.

The general framework of Biljecki provides an aspect 'Feature Complexity', which is explicitly defined as 'fineness of geometry with respect to the real world'. As a straightforward way to denote this, the minimal length of objects is mentioned; if this condition is fulfilled, the object has to be represented in the model. Hence, the models are complete, at least for objects which are larger than this minimal dimension. Since the concrete implementation of the framework contains the aspect 'Feature Complexity', it is complete as well.

The Nagel approach defines LoD for each feature separately and independently. If a building feature, for example, is labelled as LoD3, no statement on the occurrence of subordinate feature types are made. Hence, completeness of models in a particular LoD is low.

4.4 *Avoidance of Inconsistent Models*

The CityGML 2.0 LoD concept for buildings is very straight-lined because the LoD attribute is obliquely devoted to the building object itself. As a result, higher detailed buildings consist of an optional superset of features describing the building of the particular lower Level of Detail. In addition, the list of features that represent a building in a specific LoD is defined, thus preventing the assignment of more semantical information to a coarse and undifferentiated geometry. Further, the highest geometrical representation for both, the exterior shell and the interior is required in LoD4 so that interior structures cannot penetrate the exterior shell. Thus, a violation of semantics and geometry is virtually impossible.

The Benner approach determines the complete LoD of a building by the combination of Geometric LoD and Semantical LoD. Therefore they define feasible combinations. Geometric LoD0 models can only be combined with Semantical Level 0, while geometric LoD1, LoD2 and LoD3 models are allowed to represent four variants with increasing semantical complexity. These restrictions result in 13 feasible combinations of Geometrical LoD and Semantical LoD for the building exterior and interior and make inconsistent models of geometric and semantic combination impossible.

The Benner approach distinguishes between exterior and an interior Level of Details. Thus, geometrical problems might occur if the LoD of the geometrical detail level of the exterior and the interior are not identical. For instance, if rooms have a detailed geometry, but the exterior is coarse, fitting problems are likely to happen. Either the room geometry penetrates the exterior shell, or empty spaces inside the building are not covered by rooms. Vice versa, if rooms have a coarse geometry, but the exterior shell is fine-grained, the room geometry might penetrate the exterior shell (rf. Fig. 15 in Benner et al. 2013).

In the general framework of Biljecki, there is a strict separation between indoor and outdoor objects. Hence, inconsistent models might also happen here. However, it is stated in Biljecki et al. (2014) that 'the interior is constrained with the exterior'. However, it is not completely clear what this exactly means and whether those inconsistencies are prevented. In the concrete implementation LoD0 to LoD9 of the Biljecki framework, the geometry detail increases for indoor and outdoor in a similar way and are comparable to the CityGML 2.0 concept. Hence, violations between indoor and outdoor objects are not possible.

The Nagel approach defines LoD not for an entire building, but for every particular *CityObject* with no restriction on how a composed building should be modelled using *CityObjects* in different LoD. Thus, this proposal might lead to inconsistent models as already identified for the Benner approach. Moreover, the label for a certain LoD does not belong to an entire building any longer, but to its composing feature types.

4.5 *Freedom of Interpretation*

The CityGML 2.0 specification provides definitions of the particular LoD in terms of geometry and semantics that are very vague with respect to geometrical complexity. Semantics of an LoD is defined in terms of feature classes for buildings and its parts, but only a maximal set of such feature types is provided. Hence, the semantical richness is optional.

In addition to a geometrical representation, an LoD3 model might have boundary surfaces, openings, and installations, which again might have boundary surfaces. However, it is not strictly required that such features are present in an LoD3 building representation. Therefore, all of the following models would be qualified as LoD3: building geometry only, building geometry and thematic surfaces, thematic surfaces only, building geometry, thematic surfaces and openings as well as thematic surfaces and openings. Since *BuildingParts* and *BuildingInstallations* are other optional feature types, which both can be combined with these five options, the number of different LoD3 models is at least 20. Here, only semantical variability is considered. If additionally geometrical aspects are taken into account, this number increases significantly.

Consider a simple blocks model with thematic boundary surfaces and openings as an example for a problematic LoD classification. The question is how to classify such a model. Classification as LoD1 or LoD2 is impossible, since these schemata do not provide openings. Technically, it is possible to qualify such a model as LoD3. Admittedly, this violates the definition of LoD3, which 'denotes architectural models with detailed wall and roof structures' (Gröger et al. 2012). To sum up, it can be said that freedom of interpretation is high for the CityGML 2.0 approach.

The Benner approach defines a compact nomenclature incorporating exterior and interior Geometrical and Semantical Levels, which specializes the CityGML 2.0 LoD indicators and results in a substantially higher informative value of the label. It indicates the geometrical modeling style and the semantic modeling depth of a *Building* or *BuildingPart*, consistently extending the CityGML LoD notation. Ambiguities are almost impossible and the freedom of interpretation is low.

The aspects in the Biljecki approach are defined very precisely. The criterion 'Presence of city objects and elements' defines the feature types which have to be present in a particular LoD. The 'Feature Complexity' allows specifing concrete minimal dimensions of features, and 'Attribute data' a concrete list of attributes. Hence, the freedom of interpretation is low. This also holds true for the concrete implementation of the framework. For each LoD (0 to 9), concrete values for the feature complexity such as minimal size of objects is given, e.g. 10 m in LoD0 for building blocks or 10 cm in LoD9.

In the Nagel approach, only one criterion, the detail level of geometry, is used. However, this criterion is not defined precisely, but only intuitively by giving figures as examples. Hence, the freedom of interpretation is supposed to be high.

4.6 *Feasibility and Complexity of Transformation from CityGML 2.0*

The Benner and the Nagel approach have in common that LoD4 has been replaced by LoD3 for interior and exterior objects. The additional LoD4 outer geometry has deliberately been introduced into CityGML in order to provide the possibility to adapt the outer shell to the interior objects, in particular to fit the openings of rooms. Although the LoD4 outer geometry may differ from the LoD3 outer geometry, only one representation (LoD3) is provided by both, the Benner and the Nagel approach. Hence, there might be a loss of information when transforming CityGML 2.0 datasets containing LoD3 and LoD4 into either concepts.

A general problem when transforming datasets from CityGML 2.0 is the vagueness of definitions with respect to geometry. Even if it contradicts the common understanding of LoD3, a coarse block can be used as a LoD3 representation without breaking syntactical rules or conformance requirements of the CityGML 2.0 concept.

Apart from the aforementioned problems, the mapping from CityGML 2.0 into the Benner approach can be easily performed. LoD0 is mapped to LoD0(S0) while LoD1 is mapped to LoD1(S1). Further, LoD2 is mapped to LoD2(S2), if the conditions of LoD2 (semantics) are completely fulfilled. If the semantic conditions of S1 respectively S0 are fulfilled, LoD2 is mapped to LoD2(S1) or LoD2(S0), respectively. LoD3 is mapped to LoD3(S3), if the conditions of LoD3 are completely fulfilled. If openings are not represented, it is mapped to LoD3(S2). If *BoundarySurfaces* are not represented, it is mapped to LoD3(S1). Finally, LoD4 is mapped to LoD3.3(S3.3), if the conditions of LoD4 are completely fulfilled. However, it is mapped to LoD3.x(S3.y), if the conditions for semantical completeness are fulfilled only partially. The value for x has already been defined in the mapping for LoD3, whereas y is set to 2 if openings are not represented completely, y is set to 1 if in addition the interior building installations and the building furniture are missing. Finally, y is set to 0 if boundary surfaces are not present. The fulfillment of the semantical conditions can easily be checked by scanning the dataset.

The Biljecki approach provides strict, precisely defined requirements for the geometry. In order to check whether for instance a CityGML 2.0 LoD3 model satisfies the minimal dimension of the corresponding LoD of Biljecki, it is not sufficient to consider the datasets only. Instead, the corresponding real world objects have to be inspected, which is very elaborate and expensive. For the transformation into the concept of Biljecki, first the aspects on which the LoD concept is based on have to be compared. The geometry aspect of CityGML corresponds most likely to the 'Feature Complexity'. Whether semantics is modelled or not in a particular LoD is covered by the 'Presence of CityObjects and Elements' aspect. Hence, the CityGML 2.0 aspects are a subset of the Biljecki aspects and, in general, datasets can be transformed. However, the problem of vague geometry definition in CityGML 2.0 versus a very precise definition of the Biljecki approach remains. Due to this, the transformation is very elaborate.

For the example LoD 0 to 9, the mapping is as follows: For LoD0, there is no counterpart; at least not for buildings (there are no areal representations for buildings). LoD1 corresponds to LoD1, LoD2 to LoD3 (since there is no interior in LoD2, the interior representation in LoD3 is empty). LoD3 is represented as LoD8 (again without interior) and finally LoD4 is represented as LoD9.

The transformation of CityGML 2.0 models according to the Nagel approach is straightforward: The LoD of each feature can be derived immediately from its geometry properties. Only a simple syntactical transformation is required. Hence, it is the LoD concept with the smallest transformation complexity.

5 Summary and Discussion

This paper evaluates and compares different proposal for the revision of the CityGML 2.0 LoD concept. Therefore, new evaluation criteria are developed reflecting the needs that are relevant for stakeholders of 3D city models. These criteria cover such questions as: Can all 3D city building models be represented by the concept? To which degree are inconsistent models prohibited, as they nevertheless might be adequate for some applications? Can user rely on models to be complete in terms of all parts defined in that LoD (likely to be a high burden for data collectors)? Are all aspects, which might be relevant for users, e.g. geometry, semantics, and appearance reflected by the concept? How flexible and vague are the definitions? Vaguely defined concepts widen the scope of models and alleviate data collection. Strictly defined concepts are more reliable for users. Is it feasible to transform current models into the new concept and what are the transformation costs? However, the evaluation procedure can not formally be defined, since we consider concepts and their rules and specifications. The evaluation whether or to which degree a concept fulfils a specific criterion is performed by discursively inspecting the specifications of the concepts.

Four current and relevant proposals from academia and the commercial sector as well as the CityGML 2.0 concept are discussed and compared in relation to these criteria. The degree to which the criteria are fulfilled is very heterogeneous among the approaches. The Nagel approach is very flexible without any constraints, but allows for models with few properties users can rely on. The Benner approach indicates the semantic content of models in a reliable way, and is nearly as flexible as the Nagel approach. Far more precise and mandatory is the Biljecki approach, which, however, has some of the restrictions of the current CityGML 2.0 model. The costs for transforming CityGML 2.0 models to this concept are high.

It is expected that the evaluation presented here will be very valuable for the definition of the LoD profiles of the new LoD concept of CityGML 3.0. The group which will develop the official LoD profile can profit from the result, as well as users which will define own LoD profiles, in order to accommodate for their applications of 3D city models. This approach is innovative, since up to now, evaluation criteria for LoD concepts have not been developed and no systematic evaluation and comparison of current LoD approaches were possible.

References

Becker, T., Nagel, C. & Kolbe, T.H., 2009: A Multilayered Space-Event Model for Navigation in Indoor Spaces. – Lee, J. & Zlatanova, S. (eds.): 3D Geo-Information Sciences, Lecture Notes in Geoinformation and Cartography: 61–77, Springer, Berlin, Heidelberg.

Benner, J., Geiger, A., Gröger, G., Häfele, K.H. & Löwner, M.O., 2013: Enhanced LoD Concepts for Virtual 3D City Models. – ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences **II-2/W1:** 51–61.

Biljecki, F., Zhao, J., Stoter, J. & Ledoux, H., 2013: Revisiting the concept of level of detail in 3D City Modelling. – ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences **II-2/W1:** 63–74.

Biljecki, F., Ledoux, H., Stoter, J. & Zhao, J., 2014: Formalisation of the level of detail in 3D city modeling. – Computers, Environment and Urban Systems **48:** 1–15.

Boeters, R., Arroyo Ohori, K., Biljecki, F. & Zlatanova, S., 2015: Automatically enhancing CityGML LoD2 models with a corresponding indoor geometry. – International Journal of Geographical information Science **29** (12): 2248–2268; http://doi.org/10.1080/13658816.2015.1072201.

Boguslawski, P., Gold, C. & Ledoux, H., 2011: Modeling and analyzing 3D buildings with a primal/dual data structure. – ISPRS Journal of Photogrammetry and Remote Sensing **66** (2): 188–197.

Czerwinski, A., Sandmann, S., Stöcker-Meier, E. & Plümer, L., 2007: Sustainable SDI for EU noise mapping in NRW – best practice for INSPIRE. – International Journal for Spatial Data Infrastructure Research **2** (1): 90–111.

Dalla Costa, S., Roccatello, E. & Rumor, M., 2011: A CityGML 3D Geodatabase for Buildings Energy Efficiency. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **XXXVIII-4/C21:** 19–24.

Domínguez, B., García, Á. & Feito, F.R., 2011: Semantic and topological representation of building indoors: an overview. – The Joint ISPRS Workshop on 3D City Modelling & Applications and the 6th 3D GeoInfo Conference, Wuhan, China.

Fan, H., Meng, L. & Jahnke, M., 2009: Generalization of 3D Buildings Modelled by CityGML. – Sester, M. et al. (eds.): Advances in GIScience. – 12th AGILE Conference, Lecture Notes in Geoinformation and Cartography: 387–405, Springer, Berlin, Heidelberg.

Ghassoun, Y., Löwner, M.O. & Weber, S., 2015: Exploring the Benefits of 3D city Models in the Field of Urban Particles Distribution Modelling – a Comparison of Model Results. – Breunig, M. et al. (eds.): 3D Geoinformation Science, the Selected Papers of the 3D GeoInfo 2014. – Lecture Notes in Geoinformation and Cartography: 193–205, Springer.

Götzelmann, T., Guerke, R., Brenner, C. & Sester, M., 2009: Terrain-Dependent Aggregation of 3D City Models. – ISPRS-Workshop on quality, scale and analysis aspects of city models. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **XXXVIII-2/W11**, Lund, Sweden.

Gröger, G., Kolbe, T.H., Nagel, C. & Häfele, K.H. (eds.), 2012: OGC City Geography Markup Language (CityGML), Encoding Standard, Version 2.0.0., Open Geospatial Consortium. – OGC Doc. No. 12-019, Open Geospatial Consortium, 2012.

Gröger, G. & Plümer, L., 2012: CityGML – Interoperable semantic 3D City Models. – ISPRS Journal of Photogrammetry and Remote Sensing **71:** 12–33.

Guerke, R., Brenner, C. & Sester, M., 2009: Generalization of 3D City Models as a Service. – ISPRS-Workshop on quality, scale and analysis aspects of city models, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, **XXXVIII-2/W11**, Lund, Sweden.

Hagedorn, B., Trapp, M., Glander, T. & Döllner, J., 2009: Towards an Indoor Level-of-Detail Model for Route Visualization. – MDM '09, Tenth International Conference on Mobile Data Management: Systems, Services and Middleware: 692–697, IEEE Computer Society, Piscataway, NJ, USA.

Iwaszczuk, D. & Stilla, U., 2010: A Concept for the Assignment of Textures to Partially occluded Faces of 3D City Models stored in CityGML. – Kolbe, T.H. et al. (eds.): 5th ISPRS International 3D GeoInfo Conference, Germany. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **XXXVIII-4/W15:** 57–62, Berlin.

Knapp, S. & Coors, V., 2008: The use of eParticipation in public participation: The VEPs example. – Coors, V. et al. (eds.): Urban and regional data management. – Urban Data Management Society Symposium 2007 (UDMS Annual 2007), BALKEMA-proceedings and monographs in engineering, water and earth sciences: 93–104, Taylor & Francis, London, UK.

Köninger, A. & Bartel, S., 1998: 3D-GIS for Urban Purposes. – Geoinformatica **2** (2): 79–103.

Löwner, M.O., Benner, J., Gröger, G. & Häfele, K.H., 2013: New Concepts for Structuring 3D City models – an extended Level of Detail concept for CityGML Buildings. – Murgante, B. et al. (eds.): 13th International Conference on Computational Science and Its Applications, Part **III, LNCS 7973:** 466–480, Springer, Berlin.

Löwner, M.O., Benner, J. & Gröger, G., 2015: Aktuelle Trends in der Entwicklung von CityGML3.0. – Seyfert, E. et al. (eds.): Geoinformationen öffnen das Tor zur Welt, 34. Wissenschaftlich-Technische Jahrestagung der DGPF, Tagungsband **23**, Hamburg.

Nagel, C., 2014: Proposal for a revision of the CityGML LOD concept. – Presentation at the 5th Meeting of OGC Working Package 3 for the revision of the LoD concept for CityGML 3.0, 20. 10. 2014, Bonn; https://github.com/opengeospatial/CityGML-3.0/blob/master/WP%2003%20Resources/Meetings/1st/WP03_2014_07_09_Nagel_Proposal_for_a_Revision-of-the-LOD-Concept.pdf (1.11.2015).

Quinn, J.A., Smart, P.D. & Jones, C.B., 2009: 3D city registration and enrichment. – ISPRS-Workshop on quality, scale and analysis aspects of city models. – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences **XXXVIII-2/W11**, Lund, Sweden.

Randt, B., Bildstein, F. & Kolbe, T.H., 2007: Use of Virtual 3D Landscapes for Emergency Driver Training. – 2007 IMAGE Conference, Scottsdale, AZ, USA.

Zlatanova, S. & Li, J. (eds.), 2008: Geospatial information technology for emergency response. – ISPRS book series, Taylor & Francis, London, UK.

Addresses of the Authors

Prof. Dr.-Ing. Marc-Oliver Löwner, Institute of Geodesy and Photogrammetry, Technische Universität Braunschweig, Pockelsstraße 3, 38106 Braunschweig, Germany, e-mail: m-o.loewner@tu-bs.de

Priv.-Doz. Dr. rer. nat. Gerhard Gröger, CPA Software GmbH, Auf dem Seidenberg 3a, 53721 Siegburg, Germany, e-mail: groeger@uni-bonn.de

Manuskript eingereicht: August 2014
Angenommen: Oktober 2015