Accepted Manuscript

Formalisation of the level of detail in 3D city modelling

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This is an Accepted Manuscript of an article published by Elsevier in the journal *Computers, Environment and Urban Systems* in Nov 2014, available online:
http://doi.org/10.1016/j.compenvurbsys.2014.05.004

Cite as:

Biljecki, F., Ledoux, H., Stoter, J., Zhao J. (2014): Formalisation of the level of detail in 3D city modelling. *Computers, Environment and Urban Systems*, vol. 48, pp. 1-15.

Abstract

The level of detail in 3D city modelling, despite its usefulness and importance, is still an ambiguous and undefined term. It is used for the communication of how thoroughly real-world features have been acquired and modelled, as we demonstrate in this paper. Its definitions vary greatly between practitioners, standards and institutions. We fundamentally discuss the concept, and we provide a formal and consistent framework to define discrete and continuous levels of detail (LODs), by determining six metrics that constitute it, and by discussing their quantification and their relations. The resulting LODs are discretisations of functions of metrics that can be specified in an acquisition–modelling specification form that we introduce. The advantages of this approach over existing paradigms are formalisation, consistency, continuity, and finer specification of LODs. As an example of the realisation of the framework, we derive a series of 10 discrete LODs. We give a proposal for the integration of the framework within the OGC standard CityGML (through the Application Domain Extension).

Keywords: Level of detail; 3D city modelling; Scale; CityGML; ADE

Highlights

- Formalisation of the concept of level of detail as the degree of its adherence to its corresponding subset of reality
- Every geo-dataset has a level of detail, which can be specified with 6 metrics
- Level of detail is a concept separated from quality
- The approach is of continuous nature and it enables an arbitrary number of discrete LODs
- The framework has been implemented in CityGML and 10 discrete LODs are made as an example of the realisation

1 Introduction

The concept of level of detail (LOD) is essential in 3D city modelling. It is used to define a series of different representations of real world objects, and to suggest how thoroughly they have been acquired and modelled. Although the background and intention of the concept are intuitively recognised, in 3D city modelling the term LOD has been borrowed from 3D computer graphics and accepted without much discussion. In this paper we argue that the term of LOD in 3D city modelling is currently incoherent, and that it is different from the one in computer graphics. It does not have a significant overlap other than the goal of the selection of a model sufficient for accomplishing a required task while balancing computational, economical and cognitive limitations (Çöltekin & Reichenbacher, 2011; Mao, 2011; Luebke et al., 2003).

While the term is prevalent in several papers in the GIS research community, it is influenced by computer graphics and its meaning often differs. For instance, Meng & Forberg (2007) define LOD as a uniform number of milestones along the scale space when taking the scale space as a linear continuum. For Glander & Döllner (2008) it is a degree of generalisation. Forberg (2007) expresses that it as a common way to enhance the performance of interactive visualisation of polyhedral data. According to Sester (2007) and Goetz (2013) LODs are multi-scale models for different applications. Lemmens (2011) equals it to the term of resolution and states that it is related to how much detail is present in the data and may refer to space, time and semantics.

As explained in Section 2, the LOD in 3D city modelling serves as a specification-related instruction for the acquisition, modelling, generalisation and exchange of spatial data. This is in contrast with computer graphics where models are simplified to their coarser counterparts in a dynamic process. Moreover, LODs of 3D city models do not differ only by the amount of data, richness of *details* and visual properties, but may also define the semantics, and the complexity of buildings and other city objects required for different applications (Gröger & Plümer, 2012). While researchers recognise that there are no universally agreed LODs for 3D buildings and other objects comparably to the 2D topographic maps that have official scale series (Meng & Forberg, 2007), there is still not much work on the formalisation of LOD, i.e. a fundamental discussion that would standardise and unify the different approaches.

The CityGML 2.0 standard of the Open Geospatial Consortium (2012) contains the *de facto* LOD concept of 3D city modelling, developed by a Special Interest Group 3D (SIG3D) initiative (Albert et al., 2003; Gröger et al., 2004, 2005). The specification of LOD for CityGML establishes quality classes for data acquisition, and the model's LOD roughly reflects the model's complexity and accuracy (Kolbe et al., 2005, 2009). However, as it is the case with other standards, the LOD concept of CityGML has deficiencies, and discussions for its improvement are undergoing (Benner et al., 2013; Löwner et al., 2013).

The goal of this paper is to formalise the concept of LOD in 3D city modelling, and to provide a framework for specifying LODs. Lacking a definition, specification, and a universal standard, the current LODs cannot be compared, translated, sorted, and evaluated. This leads to ambiguity in the communication of the acquisition–modelling properties of a 3D city model between users and producers.

We define the LOD of a 3D city model as the degree of its adherence to its corresponding subset of reality. In this paper we decompose the LOD into six metrics that may be defined by continuous functions (Section 3), yielding a continuous LOD approach. In this view, the LODs are discretisations from a series of functions of such metrics (Section 4). We argue that in such case the traditional term LOD might be misleading. However, we do not propose linguistic modifications because we are aware that the current term is deeply ingrained in the GIS community. We show the example of the implementation of the framework resulting in ten discrete LODs. Finally, a proposal for the integration within CityGML is made (Section 5).

2 Analysis of existing concepts and the need for an LOD definition

We have evaluated different 3D city model representations and LOD concepts found in academia, standards, products and guidelines (Section 2.1), and we have made an analysis and summarised their shortcomings in Section 2.2. We have found that these standards are essentially different not only by their specification, but also by their driving metrics, targeted usage, and arrangement of thematic classes and elements. In total, 26 level of detail paradigms comprising 79 mutually exclusive LODs have been evaluated.

2.1 Analysis of the concepts of LODs

CityGML defines five discrete LODs (LOD0–4), which are differentiated mostly by the complexity of the geometries. The LOD0 is a digital terrain model with building footprints, and no volumes are present. Subsequent LODs are improving in terms of the complexity of objects in the geometric and semantic sense. The LOD4 adds interior geometry, but otherwise it retains the same properties as LOD3. The textures can be added to any LOD (i.e. the texture is not part of the LOD specification), and generalisation of the geometry is vaguely described and seldom implemented. The standard includes different thematic classes, e.g. buildings, roads, and vegetation.

The progress of the LODs is not consistent: the first LOD is 2.5D only, while LOD1–3 improve the exterior geometry, and LOD4 adds one level of detail of the interior, that is indeterminate. Therefore, instead of five LODs, with respect the 3D city models and exterior geometry, there are three distinguished LODs with different flavours.

CityGML partly owes its popularity to this simple and straightforward LOD concept. However, we argue that this concept has shortcomings and drawbacks, making it unsustainable as the number of producers, applications, and users grow. Researchers are aware of the deficiencies, and as of the production of this paper, discussions about the improvements of the LOD concept for the next version of CityGML (v. 3.0) are undergoing (Machl, 2013).

National mapping agencies recently started adopting 3D city modelling standards. Examples include the Netherlands (Stoter et al., 2013), whose standard is tied to CityGML, and China (Chinese Ministry of Housing and Urban-Rural Development, 2010) developed from scratch not basing their model on any international standard. The Dutch standard extends CityGML classes and attributes, being more precise in the specifications. It also gives recommendations for the textures. The Chinese standard contains four LODs, and defines which topographic objects should be modelled, and their thresholds (minimum size). The building LODs are defined by accuracy and basic description of the geometry. Also, different models have different requirements for the texture resolution.

In academia, especially in the field of 3D generalisation, there are different specifications of the discrete LODs (Meng & Forberg, 2007). For instance, Thiemann (2003) defines three LODs for settlements and buildings: LOD1 contains aggregated settlement blocks with a uniform height, LOD2 blocks of the individual buildings without roof form, and LOD3 is LOD2 enhanced with a simplified roof form. Schilcher et al. (1998) describes three LODs for individual buildings:

LOD1 is a model popping up of the ground plan to a uniform height, LOD2 is LOD1 enhanced with a standard roof form, and LOD3 is an LOD2 enhanced with photorealistic textures and small surface features.

A few companies offer product portfolios of off-the-shelf 3D city models or for integration in a product (e.g. navigation software). Examples include Blom ASA (2011), Vertex Modelling (2013), NAVTEQ (2011), CyberCity 3D (2013), Sanborn (2013), and TeleAtlas (Vande Velde, 2005). The companies offer a few LODs (in all cases five or less), which are distinguished by the wealth of details and/or textures, and where landmarks have a special status. The semantics and the required accuracy are seldom specified. Further, some companies offer additional adaptation and customisation of their models to fit the needs of their clients, making these LODs rather generic guidelines and frames of a final product later to be agreed by the two parties. However, most of the producers of 3D city models do not advertise their models in form of a series of LODs with a description and usage recommendation for each. Their internal standards serve rather as a general frame, and may differ for each client or project. By direct inquiry, we have obtained the modelling specifications of a few companies. They are essentially different but commonly contain a few LODs where the texture is not a part of an LOD specification.

The popular applications on smartphones for personal navigation, such as Google Maps and Apple Maps, recently started including 3D city models for their 3D visualisation mode. They contain up to two LODs distinguished by the complexity of the geometry and appearance.

We have studied a few tenders for the procurement of 3D city models, and publicly available models maintained by local authorities, such as the ones from the Glasgow City Council (2009), Lusail in Qatar (Hochtief ViCon, 2011), and Australian cities: City of Wollongong (2010), City of Perth (2013), and Adelaide City Council (2009). The tender specifications of 3D city models define one LOD, and are often not detailed: they rather specify the minimum requirements for the deliverables, e.g. minimum accuracy, which features of a building should be included, and a set of library roofs to be used.

For this paper, we have also studied specific cases which cannot be accomplished and fit in a multi-purpose LOD specification as are most of the above paradigms. These include the integration of the interior in a CityGML LOD2 model (Boeters, 2013), mixing LOD for buildings of different types (Glander & Döllner, 2009), and further, mixing CityGML LODs in the same object (different LODs for the wall and roofs) in an application for communicating future urban design with physical 3D models (Novaković, 2011).

2.2 Analysis and critical overview of the current LODs

The overview of the described paradigms for each group is listed in Table 1.

From the paradigms briefly presented in the previous section, it is obvious that the main deficiency of the current LOD approaches is that it is not clear what the LOD is (it is merely clear that it is a conception of the design quality of the 3D city model and the amount of data) and what it comprises. If a series of multiple discrete LODs is available, it is not clear by what it is driven. For

Table 1: Overview of the analysed LOD paradigms per group. All the series of LODs are driven by the fineness of the exterior geometry.

Group	No. of LODs	Main driving metric(s)
Standards	4–5	Ext. geometry, texture, semantics
Academia	3	Ext. geometry, texture
Off-the-shelf	4–5	Ext. geometry, texture, type of object
Mobile applications	1–2	Ext. geometry, texture
Internal guidelines	4	Ext. geometry
Municipalities	1–5	Ext. geometry, minimum accuracy
Special cases	1–5	Ext. geometry
All:	1–5	At least ext. geometry

instance, LODs in one standard are driven by the complexity of the geometry and the semantics (CityGML), while in the other by the characteristics of the texture (Blom3D). On the other hand, NAVTEQ's LODs are driven by the type of objects, i.e. the finest LOD only contains better representations of landmarks, while residential buildings remain the same as in the previous LOD. Thus, an LOD does not simply define the wealth of the geometry, but much more: semantics, texture, interior, acquisition techniques, and so on. The formalisation and quantification of such metrics is rarely discussed.

The paradigms all describe one or multiple discrete LODs, which are not linked and are not continuous. In case of multiple LODs, the improvement in the specifications of finer LODs is obvious. However, the functions of the progress are not specified, implying that the specifications are derived rather arbitrarily without connections between LODs, and the refinement of the range into intermediary LODs is not possible. For instance, the quality of LOD2 is not 2 times that of LOD1, and it is not possible to derive an LOD1.7. In the paradigms defined by the producers, the LODs progress in the sense that are adapted according to the acquisition technique. For instance, all features mandated in all but the finest LOD can be acquired with aerial photogrammetry. However, modelling features such as high-quality photorealistic textures, the geometry of awnings and openings rather requires a terrestrial acquisition technique.

Because there is no definition for an LOD, LODs cannot be compared, translated, sorted, and evaluated. Further, some paradigms define properties (semantics, texture, accuracy) that others do not mention. Since the LOD of a 3D city model is one of its most important properties, the industry and the research community suffers from such deficiency, not being able to easily and efficiently communicate the acquisition–modelling requirements of a 3D city model in question (Biljecki et al., 2013).

Considering the thematic classes, the current standards are mostly focused on defining buildings, and with the exception of CityGML, they pay little attention to other classes of city objects. There are, however, independent studies about improving the LOD specification of other thematic classes, e.g. Chen (2013) and Rafiee et al. (2013) do it for trees, Tamminga et al. (2013) for roads.

From the semantic perspective, the paradigms do not offer a full semantic integration, and understate the importance of expressing the semantic requirements. For instance, in CityGML, a chimney is stored as a building installation and does not have its separate semantic class, which might be useful for some applications. In addition, if a chimney has its flue modelled, it is stored together as one building element in a class which is general and assigned to dissimilar types of building elements such as outer stairs.

Standards deal mostly with single objects without a specification for generalisation from a finer to a coarser LOD, and the modelling of aggregated multiple objects is not clear. Fan & Meng (2012) notice that there is not a robust relationship between the elements in different LODs and reusability across multiple LODs are not possible.

Continuing the analysis, the current LODs are not specified exactly, and are rather considered as ranges since at least two different models of the same object can be of the same LOD. For instance, Benner et al. (2013) expose 12 different models which are LOD2 variants in CityGML. This causes ambiguity which is a two-fold problem: due to incomplete LOD specifications it is not possible to precisely build a model of a specific LOD, and it is not possible to precisely evaluate existing models and determine their LOD. Beside stricter specifications, a solution would be to increase the number of discrete LODs to accommodate different variants.

In brief, LOD, as one of the oldest and most important concepts in 3D city modelling, needs clarification, formalisation and improvement, and more research to address the detected issues.

Not much related work has been done on the formalisation of the LOD in the frame of 3D city modelling. Bandrova & Bonchev (2013) suggest defining LOD by distinguishing it from scale and accuracy, and propose six discrete LODs for 3D maps. Löwner et al. (2013) and Benner et al. (2013) develop the separation of the LODs into semantic, exterior, interior, and appearance (sub)LODs for CityGML. Further, they refine the LODs for the interior.

3 Considerations for the improvement of the LOD concept

3.1 Composition of the design characteristics of a 3D city model (metrics)

By analysing the standards presented in Section 2, by discussing with other researchers and practitioners, based on own experience, we have composed a list of 6 metrics (quantifiable *ingredients*) that constitute a 3D city model from the design and specification perspective. These metrics may be applied separately to all data in a spatial extent (or dataset), to a class of city objects (thematic class), and to their elements (features which cannot be semantically further decomposed). The spatio-semantic design characteristics of any model could be unambiguously specified with these six metrics.

1. Presence of city objects and elements The selection of objects and elements that have to be modelled is an obvious metric. However, this concept is hampered by non-standardised nomenclature and semantics, unclear hierarchies of objects and elements, their aggregation relations, and modelling rules (e.g. should a roof be modelled with overhangs or not). In this paper, we discuss how to define this metric and we use common-sense nomenclature. The semantics, modelling rules, and aggregation specifications are out of scope.

The presence of an object or element is a binary property (something should be acquired or not), and it can be simply expressed as a list of real-world features that have to be geometrically mapped. Figure 1 shows an example of three different LODs (A, B, and C) for two city objects: building and vegetation. The coarsest LOD (LOD-A) requires only buildings to be modelled and only as a block model which is shown in grey. So here only one element of the building has to be acquired, in this case defined as a building block. Vegetation and other thematic classes of city objects are not required to be included in this LOD. The LOD-B improves the LOD-A by replacing the block model with the walls, ground plate, and roof structure. The finest LOD in this series, LOD-C, adds the thematic class vegetation, and to buildings it adds elements such as windows and significant roof structures such as dormers. This LOD also contains the walls and the roof structure as in the coarser counterpart.

This metric also covers the aggregation of objects and elements, and we add a structure defining the relations of objects and elements in multi-LOD cases. However, exact aggregation rules are out of scope of this paper.

For simplicity, in this example the elements and objects contained in coarser LODs remain unchanged in finer LODs.

2. Feature complexity Besides listing objects and/or elements that have to be modelled, one important description of an LOD is the complexity or fineness of their geometry with respect to the real-world. This metric defines the geometrical correspondence of the model to the reality, which most of people inadvertently perceive as resolution or (the level of) detail. A straightforward way to realise it is as the minimum length of linear elements in the real-world that will be taken into account in the model.

Continuing on top the previous metric presence, a city object and its elements may be present in two LODs, however, with a different feature complexity. Thus one model may geometrically be closer to the reality. Figure 2 shows an example of a house modelled in two different feature complexities.

This concept is linked to shape complexity, and it can be expressed in various ways (Rossignac, 2005). For instance, it can also be quantified with a fractal dimension (Mandelbrot, 1967). In this paper we simply choose a metric magnitude, i.e. modelling all the details of an element that are bigger than a certain size, such as in the Fig. 2 where the *dents* and “irregularities” of the wall surface are in reality bigger than 30 cm.

Feature complexity is related, but should not be confused with the complexity of the model. For instance, a simple house with flat elements may be modelled with a fine feature complexity, and

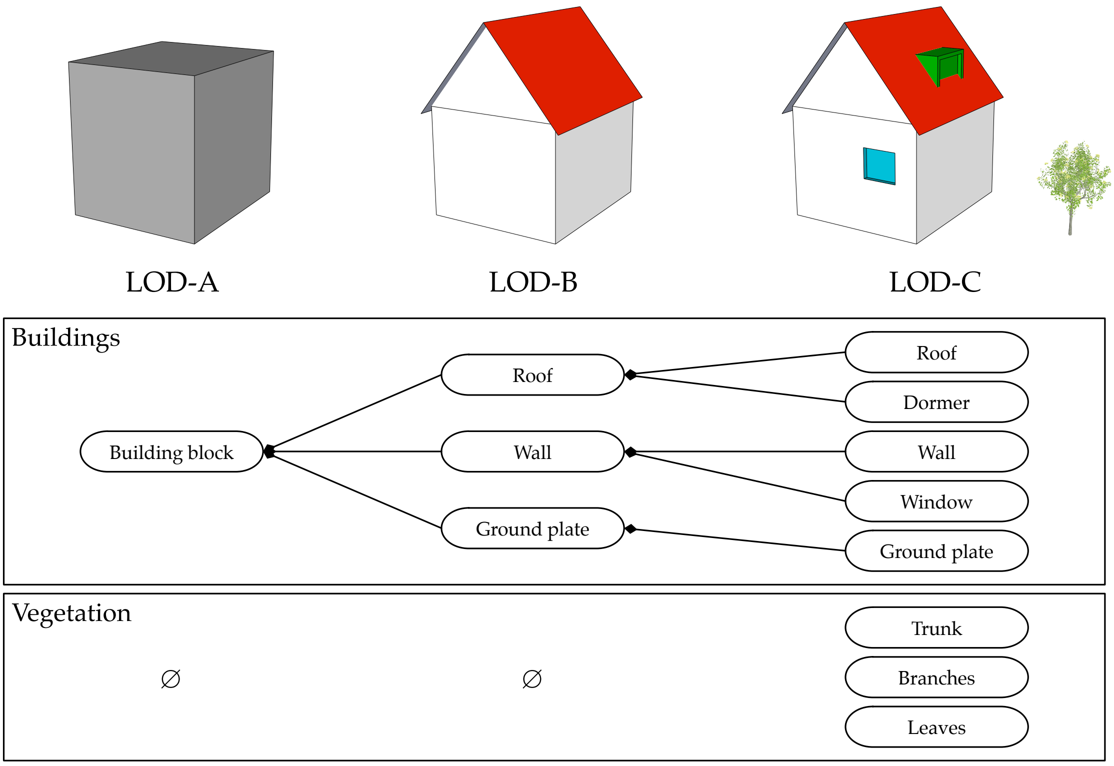

Figure 1: A simplified explanation of the concept of presence of city objects and their elements in three different LODs of a 3D city model. The aggregation relation between elements is expressed in the diagram below the graphical representations. Notice that the element Building block is not found in finer LODs (it is replaced), contrary to the case of walls and roof structure.

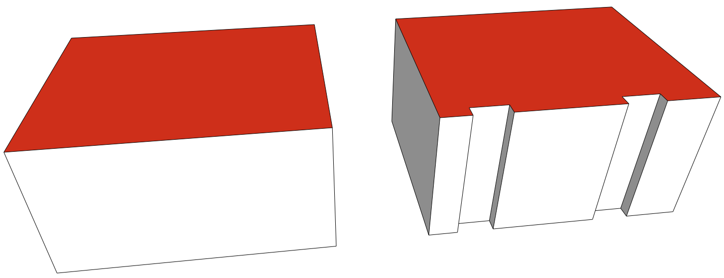

Figure 2: Two buildings modelled in different feature complexity. The wall surface (white) and top surface (red) in the finer LOD (right) are modelled more precisely due to the finer feature complexity requirement.

while the resulting model would closely correspond to the real-world, it may still look simple and coarse.

Further, in addition to elements, this metric may be applied to city objects. In such case it specifies the minimum size that an object has to have in order to be acquired, a metric currently used in CityGML.

3. Dimensionality While 3D city models imply the use of 3D volumetric geometries, primitives of lower dimensions can be used as well. Examples are 2D footprints of buildings which are used in the LOD0 of CityGML. Roads may be represented as (1D) lines, and trees as (0D) points, which may be satisfying for a number of applications. We consider dimensionality of the geometry of an object different from the concept of feature complexity, and as a separate metric. The dimensionality can be defined for elements as well. For instance, a 3D building may contain windows modelled as polygons, and chimneys as points on the roof surface.

4. Appearance (texture) Regardless of the application, appearance properties of a 3D city model may considerably improve its realistic impression, and its acquisition is often tedious and expensive. Further, the appearance may complement the presence of the elements which are not geometrically and semantically acquired. For instance, while windows of a building may not be geometrically present in a model which is textured, they are available for visual inspection and rough measurements.

5. Spatio-semantic coherence The semantic richness of a 3D city model has been an important concept of CityGML from the very beginning. Semantic information is critical for a number of applications, and it is one of the important features that separate the discipline of 3D city modelling from 3D graphic or virtual reality models.

The spatio-semantic coherence describes the granularity of the semantics in a model and its correspondence to the geometry, since it is possible to have different LODs of the semantics for the same geometry (and other metrics). For instance, while a tree may have its canopy and branches modelled, in one case they may be assigned the same semantics (e.g. tree), while in another each element could have its proper semantics (1:1 mapping).

Stadler & Kolbe (2007) recognise six general cases of spatio-semantic coherence. In the finest case, the semantic model and the geometry are given as a complex aggregation where both components correlate on the same levels of the hierarchy. Following their work, we have decided to consider that as the finest value of the metric spatio-semantic coherence.

6. Attribute data Each component of a 3D model (a dataset, a city object, and their elements) can be assigned one or more attributes, for instance, year of construction, and use of the object, access to the roof, material of a wall, address, and type of a road. However, the list cannot be easily compiled because it is dependent on the application.

3.2 Points of discussion related to the metrics

Coverage and applicability of metrics A metric may be expressed from a discrete or continuous function. For instance, the presence of elements is discrete (cf. Fig. 1), while the resolution of the texture may be continuous (e.g. a value ranging from 50 to 10 cm/px). Table 2 shows such property for each metric, and the applicability of metrics per dataset or spatial extent (multiple objects covering all thematic classes), city object, and their elements. For instance, presence is a metric that can be defined for both an object (e.g. bridge) and an element (e.g. cables).

Table 2: Property of the metrics (discrete and continuous), and applicability of the definition of the values of metrics per dataset (or spatial extent), classes of city objects, and their elements.

	Metric	Property	Extent	City object	Element
1.	Presence	Discrete		•	•
2.	Feature complexity	Continuous	•	•	•
3.	Dimensionality	Discrete			•
4.	Appearance	Continuous	•	•	•
5.	Semantics	Discrete	•	•	•
6.	Attributes	Discrete	•	•	•

The role of spatial accuracy with respect to the LOD Spatial accuracy, and other data quality elements defined by the standard ISO 19157 (ISO, 2013), are independent from the LOD. That means that two datasets of the same area may have the same LOD but different spatial accuracy. For instance, Oude Elberink & Vosselman (2011) highlight that specifying the LOD does not mean that the geometric accuracy of the model has been determined.

In some cases features may be considered of a fine LOD, however, their geometry and other data may considerably deviate from the real-world. This is in line with the framework presented in this paper, i.e. LOD is seen as a product specification of a 3D model, and it is different from the data quality concepts such as spatial accuracy or completeness. However, on top of the LOD specification, practitioners may define recommendations or requirements of spatial accuracy for an LOD.

Partial specifications Notice that when defining an LOD it is not required to specify all the metrics. For instance, in the production of 3D city models represented as digital surface models (DSM), it is not possible to specify the presence of objects and elements to be collected. Producers rather specify the feature complexity as a loose equivalent to resolution, and do not have much control over the collection of different types of objects and elements (e.g. vehicles may also be present in the model).

Generic (library) features In order to improve the efficiency of modelling, storage, query and visualisation, it is not uncommon to simply acquire a footprint or a point representing a feature, and then to include a finer model of the model from a library for visual representation. Coors (2001, 2003) distinguish this as a query data model (feature geometry) and a presentation model (view), each having its LOD, the latter possibly having multiple LODs depending on the visualisation requirements. This is common in tender documents where it can be specified to use features from a library (e.g. for common types of roofs, cf. Kada (2007)) instead of modelling each feature.

The framework presented in this paper takes into account such concept. For each representation its LOD can be specified. However, the correspondence of the models and their real-world situation, is a matter of spatial data quality elements.

3.3 Interior of the model

CityGML supports only one LOD for the interior which is not particularly defined and requires a fine exterior geometry and semantics (LOD3). Researchers identify this problem and propose multiple LODs for the interior (Hagedorn et al., 2009; Kemec et al., 2012).

The interior is one of the key concepts when defining the specification of a 3D city model, however, it is not listed as a metric since we consider that the interior geometry is a different concept that should be separated from the exterior geometry, and all the presented metrics could be applied to it. For instance, depending on the application, we may consider a model with fine exterior geometry and texture, but with no interior, still as a high-LOD model.

With this view we first decompose a city object to the exterior and interior, and use the metrics separately to each. We consider the interior of the model a separate concept from the exterior for the following reasons: (1) the applications using only exterior geometry are by far outnumbering the indoor applications which are fundamentally different and have different users; (2) the vast majority of 3D city models do not contain any interior (Morton et al., 2012); (3) with the recent introduction of indoor standards the interior geometry developments seem to be dissociated from the "orthodox" 3D city modelling field (Li & Lee, 2010); and (4) the acquisition and modelling techniques for the interior are different, e.g. see (Sternberg et al., 2013).

4 Proposal of a formalised LOD framework

We define the LOD of a 3D city model as the degree of its spatio-semantic adherence to its corresponding subset of reality. The values through which the adherence is assessed are the metrics introduced in the Section 3.1. When an LOD is decomposed into these quantifiable components, a straightforward comparison of two or more LODs is possible. Each such different combination of the values of metrics is a different LOD, and a small difference results in a change in the LOD, making this framework continuous.

Here we introduce two concepts: series of LODs and continuity. The series of LODs are a sensible combination of metrics such that their progress is overall. Viewing this concept in a continuous world, LODs are discretisations of progressive and monotonic functions of the values of metrics, i.e. each discrete LOD i is a collection of the values of n metrics M, which are the result of the discretisation of functions of metrics:

$$\text{LOD } i = \begin{bmatrix} \mathrm{M}_1 & \mathrm{M}_2 & \dots & \mathrm{M}_n \end{bmatrix} = \begin{bmatrix} f_1(i) & f_2(i) & \dots & f_n(i) \end{bmatrix}, i \in \mathbb{R}, n \in \mathbb{Z}$$

In the following two sections we show how to specify the functions of the metrics, how to define a series of LODs, and give an example of the realisation of the framework. We also introduce a specification format for discrete LODs.

4.1 Specifying the metrics

4.1.1 UML model of the specification

A UML diagram (Figure 3), based on the discussion in Sections 3.1 and 3.3 and on Table 2, is created to support the specification of the metrics for an LOD. Each 3D city model consists of a selection of one or multiple city object types (thematic classes) in a spatial extent, with general properties (`GeneralMetric`) that apply to the hierarchy, such as the feature complexity for all types of city objects and semantic requirements. Each city object that has to be modelled can be defined by metrics such as attributes and again feature complexity. As argued in Section 3.3, an object should be separated into exterior and interior, however, the latter is constrained with the exterior. The focus of the specification is on objects' elements (features that make up a city object), which acquisition–modelling specification is defined by the presented 6 metrics.

The city objects can be specified further than the typical classes in CityGML. For instance, instead of defining a class for buildings, two classes such as residential buildings and landmarks may be defined, and different acquisition–modelling specifications can be applied to each. This is in line with 3D city models that are used for navigation purposes. Equally important, it is possible to define city objects based on other criteria such as their size, e.g. trees taller than 2 metres can be defined as a city object class of tall trees that should be modelled with higher specification requirements than shorter trees.

Aggregation is supported within this framework as well. A CityObject may be aggregated to another CityObject. The same applies to elements. Furthermore, the framework permits us to mix LODs (e.g. roof and walls at different LODs).

4.1.2 Specifying the functions of the metrics

Some of the the presented metrics (see Table 2) are quantifiable and of continuous nature, hence their values may be expressed in functions.

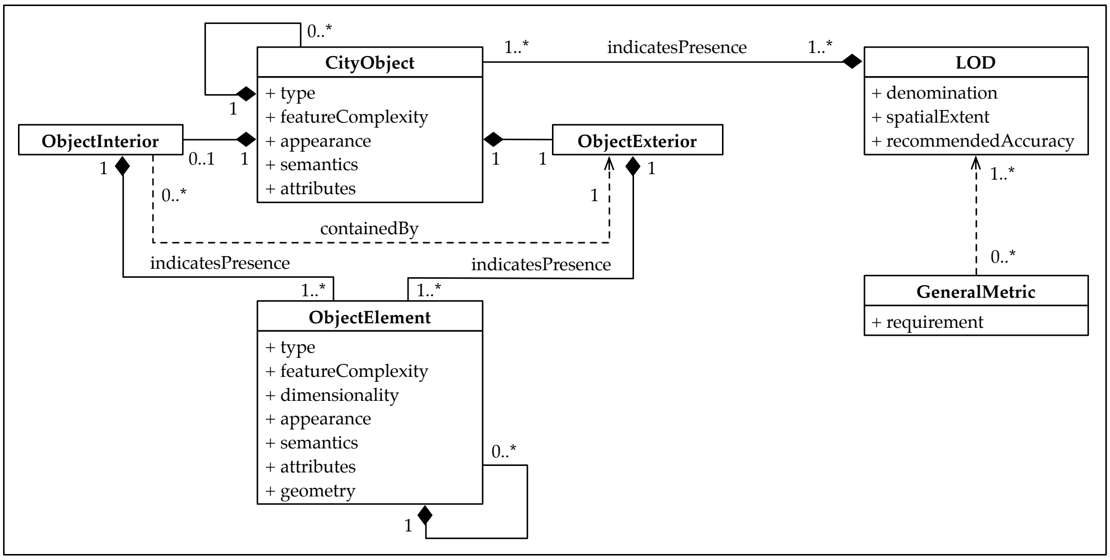

Figure 3: The UML diagram of our LOD specification.

In Figure 4 we give an example of the function of the metric feature complexity for a dataset (general metric), that applies to all objects and elements, unless specified otherwise. For all metrics, first an arbitrary interval range of LODs (e.g. from 0 to 10) is assigned. In the construction of the functions we must determine a range of values and their function, i.e. in this case the feature complexity ranges from 6 m to 0.1 m in an exponential function. In this way, it is possible to discretise the function and obtain the value of the feature complexity at one or more specific points in order to define a series of LODs, e.g. the LOD 4.88 specifies the feature complexity at 0.81 m.

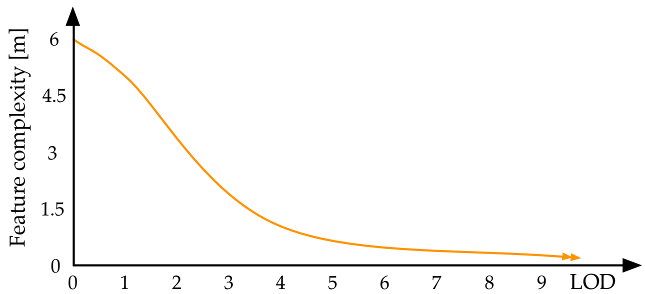

Figure 4: Example of the function of the metric feature complexity. This is one of the functions that define the series of LODs.

The discrete metrics, especially the presence of objects and elements require a different approach. Our goal is to define in a integrated approach: (1) how to denote the presence of objects and elements in a series of LODs; (2) how to specify the depth of spatio-semantic coherence; and (3) how to define the aggregation of objects and elements; and finally (4) how to specify the required attributes. Similarly to the continuous functions, these functions specify the values of the metrics at discrete steps.

In order to express the metric presence, first we have to define an inventory of city objects and their elements that are relevant for 3D city modelling. While CityGML is a good start, such doesn't exist. For this reason we have analysed the standard ISO 6707-1:2004 Building and civil engineering – Vocabulary – Part 1: General terms (ISO, 2004) which is extensive in the inventory of elements that compose a building. With this standard we have virtually all elements that are relevant for 3D city modelling in a well defined list, and beyond that since the standard is quite detailed. This example shows an example how to base the list and semantics of elements, in this case for a building. Afterwards, it is required to select the scope of the selection of the relevant elements since 3D city modelling has no clear boundaries. For instance, in a coarse LOD buildings could be aggregated in building blocks (of a few adjacent buildings), and further in a neighbourhood block. For many stakeholders and applications this might be out of scope. On the other side of the LOD axis, each element could be decomposed into very detailed elements. As an example, a wall could be decomposed into bricks and mortar, and each could be individually modelled. This may also be out of the scope of 3D city modelling.

After setting the scope, based on the described with a few additions we have made an inventory of elements of a building, and their aggregation hierarchy across a series of LODs from 0 to 9. An excerpt example of the elements per discrete LODs are shown in Figure 5. Since a building can be composed of more elements than it can be fit in a simple diagram, this example is limited. The designation in the brackets refers to the definition in ISO 6707-1. Such inventory may also apply to the LODs typical in Building Information Modelling (BIM), and small-scale objects, which also means that this LOD concept, if viewed broadly, can be extended to both areas and their ranges of LODs.

Second, the metric spatio-semantic coherence fits such hierarchy, but is defined separately from the metric presence. The specification can define the metric equal or lower than the presence. For example, while awning and fence of a balcony may be modelled (in this particular example LOD9 with respect to the presence) the semantics of both elements may be balcony. That is, the presence of elements has the value 9, but the semantics the value 6. For a full spatio-semantic coherence, their LODs should correspond.

Third, the aggregation is specified by introducing new city objects and elements such as aggregated balconies, i.e. balconies which are close enough to each other get aggregated in one object. This is done by creating new objects and elements in the hierarchy and prefixing them with "Agg_". For instance, the hierarchy specifies that the balconies are required to be modelled in LOD6 and finer, but LOD4 specifies that it enables the aggregation of balconies. Similar is with the buildings in LOD1 and aggregated buildings in LOD0. The aggregation rules can be attached to their relations (e.g. aggregate balconies if their distance is less than 3 metres), and are out of scope of this paper.

Finally, the required attributes may be defined for each LOD. For instance, in one LOD a building may not require any attribute, but in a finer LOD it may require an attribute such as year of construction. This can be realised by specifying such requirement in the hierarchy at a respective

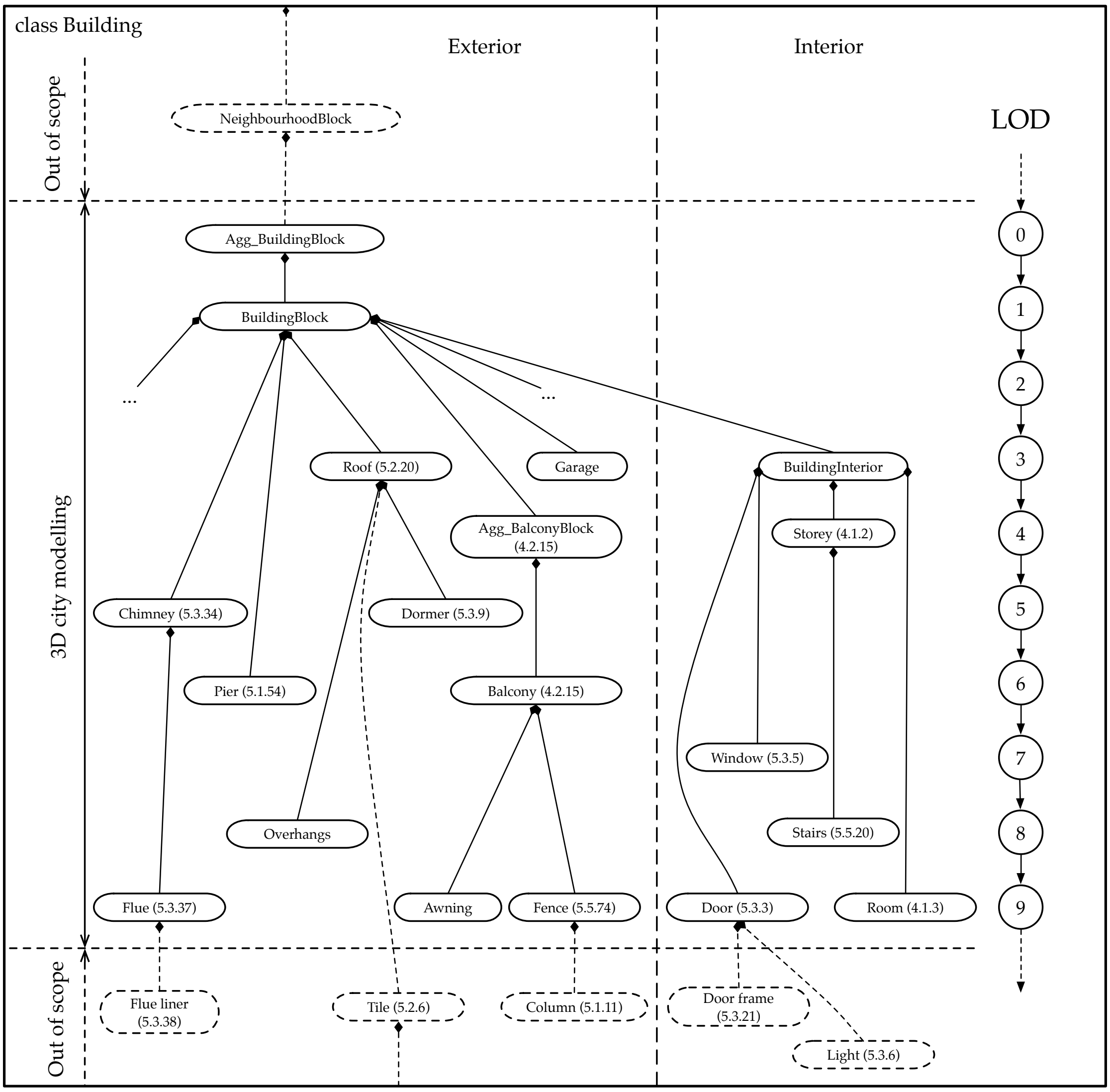

Figure 5: An example of the object building and its elements, in the scope of 3D city modelling, in a hierarchical form in order to support the metrics of presence (with aggregation), semantics, and attributes for a series of LODs. The right axis shows the LOD values. Referenced names are from ISO 6707-1.

discrete point. This is not given in the figure due to the limited space, but it is shown later in the example of a specification of a discrete LOD (Tab. 3).

4.2 Defining a consistent series of levels of detail

Sensible combinations of different and improving metrics values are what we consider a consistent series of LODs. Figure 6 gives a clarification where the left graph shows the CityGML's five LODs decomposed into the two leading metrics: exterior geometry and interior geometry. While we do not consider these two as metrics, in CityGML they can be seen as metrics (Section 2.1). The progress of the LODs is directed towards each metric at a time, meaning that the progress is not overall, but also that their relation does not exist. Other standards are similar. The right graph shows our approach, simplified with two arbitrary metrics (e.g. texture and feature complexity). Any combination of the values of these two metrics can be an LOD, and any combination of the functions of metrics could represent a series of LODs. While this enables an infinite number of permutations and supports any combination of metrics, it would yield numerous senseless combinations (e.g. acquiring a high texture elements with a low feature complexity, and vice-versa), and a series with no clear logic (e.g. a finer LOD having a lower feature complexity than a lower LOD).

However, we consider that only a subset of such combinations may be a consistent series of LODs, where the progress of each metric is well defined in a monotonic and progressive function, and comparable (two examples are shown here as a green line and an orange curve). Any combination lying on such line is considered as a discrete LOD of a particular (continuous) series, and in this figure such combinations are denoted in green and orange, respectively.

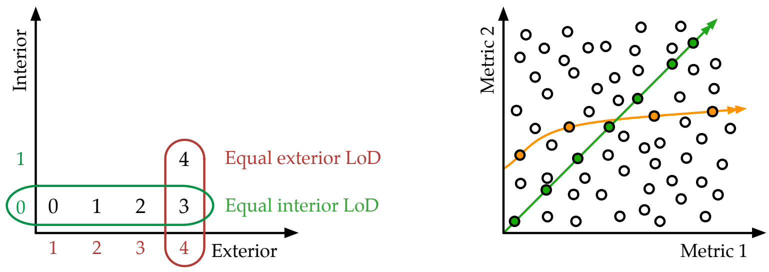

Figure 6: Simplified example of the construction of an LOD function from metrics. The left graph shows the theory on CityGML, an approach applicable to most of current standards, while the right graph shows our view of the consistent series of LODs.

4.3 Specifying a discrete LOD of a 3D city model

In order to express the specification of a discrete LOD, a straightforward specification format (for acquisition and modelling guidelines) should be available. However, we have realised that in 3D city modelling such specification does not exist, therefore we propose our own, in tabular form. An example of the specification of a discrete LOD (e.g. named LOD i) is given in Table 3.

First of all, the general metrics which apply to all city objects and elements (unless specified otherwise for each) are given in the beginning: the feature complexity is 0.4 m. The semantics should

Table 3: The example of the specification of a discrete LOD derived as a discretisation from a series of functions of metrics, with three city object types and their elements. For simplicity, the number of objects and elements is limited.

	3D City Model LOD specification				**LOD i**			
General metrics	Feature complexity				0.4 m			
	Appearance resolution				0.3 m/px			
	Semantics				Yes, full spatio-semantic coherence			
City objects and elements	**Object**	**Feat. C.**	**Attributes**	**Elements**	**Feat. C.**	**Dim.**	**Appearance**	**Attributes**
	Buildings		+ Occupancy + EnergyRating	Wall		2		+ Material
				Roof	0.2 m	3		*None*
				Roof.Dormer	0.2 m	3		*None*
				Chimney	0.2 m	3		*None*
				Balcony		3		*None*
				Pier		3		*None*
				Opening		2		*None*
				Interior				
				Storey		3	*None*	+ Use
	Roads		+ RoadUse	Traffic area- Cars		2	Black	+ SpeedLimit
				Traffic area- Bicycles		2	Red	*None*
	Street lights	1 m	+ PowerConsumption	Pole		3	*None*	*None*

be fully specified (each object and element which cannot be semantically further decomposed should have its semantic class).

The second part contains the list of city objects and their elements that should be acquired (the names of the classes are according to the previous section), with the realisation of the rest of the metrics in vertical columns. If a value left out it means it is inherited from the general metric or the metric of the object. This list indicates presence by itself—if an object or element is not there, it should simply not be modelled.

In this example, buildings should be acquired with attributes of the occupancy and energy rating. The elements of the building that should be acquired are the walls, roofs with dormers, chimneys, balconies, piers and openings. The interior is given separately: only the storeys should be acquired with the attribute of their use. In this example the roof, dormer, and chimney are required to be modelled with a finer feature complexity (0.2 m) which overrides the general guidelines for the dataset.

Other types of city objects that should be modelled are roads, and street lights. Their specifications are self-explanatory following the logic for the specifications of the buildings. The street lights do not require any appearance, while the roads are coloured with a single colour. If a street light is smaller than one metre, then, it should not be modelled.

This table answers two relevant questions when modelling: which objects and elements to acquire and how, and we believe that it represents a concise way to represent an acquisition–modelling specification of a discrete LOD of a 3D city model.

4.4 Example of the realisation of the framework with ten discrete LODs

In this section we give an example of the realisation of the proposal resulting in a series of 10 general discrete LODs (evenly separated in the function of the scale-space), which are intended for general use, and include the interior and the metrics presented in this paper. After the construction of the functions of the values of the metrics, for the discretisation we have chosen ten LODs since it is a number high enough to result in significant differences between the LODs, but low enough so that the differences are not too subtle and negligible.

Due to the limited space, it is not possible to give all the functions of the metrics (explained in Section 4.1.2) and comprehensive specifications of each resulting discrete LOD (in which each discrete LOD could have its table with all the objects and elements; cf. Table 3). However, we made this example in line with the hierarchy shown in Figure 5 and the function of the metric feature complexity shown in Figure 4, with a concise explanation and visual examples of the models. Moreover, one of the LODs (LOD7) corresponds to the specification given in the Table 3.

While constructing the series of LODs we have considered the following: (1) it should be possible to acquire the range of lower LODs with only one acquisition technique (i.e. LODs [0,5] can be acquired with airborne techniques—thus only one method is required, while subsequent LODs require complementing it with terrestrial techniques); (2) the improvement with respect to all the metrics is overall and consistent; and (3) city objects other than buildings should be clearly specified as well in order to overcome the shortcomings of the current LOD paradigms when it comes to the specification of other thematic classes.

The descriptive list follows, while an example of the visual representations of the ten discrete LODs is shown in Figure 7 and Figure 8. The setting shows a large house near a small forest, a river, and a road. The left side of each figure shows the exterior of the model, while the right side shows its interior.

LOD0 Aggregated blocks of adjacent buildings of significant size (10 m). The building on the right with which the principal house is aggregated is not shown in subsequent LODs for aesthetic reasons.

LOD1 Buildings whose feature complexity is higher than 10 m are modelled. Vegetation is available as a surface only for larger areas, while only larger water surfaces such as canals, river, and lakes are acquired. Roads are modelled as lines.

LOD2 Buildings blocks are adjusted with respect to deviations larger than 4 metres of the block geometry such as passages, and roofs of unusual shape (e.g. divided in two where one part is more than 4 metres higher than the other). Roads are modelled as surfaces.

LOD3 Buildings have a basic roof shape and larger additions such as garages. Larger vegetation areas are extruded to their average height, while smaller vegetation areas are modelled as a separate thematic class (as surfaces). The feature complexity of the model is 2 m. The basic interior of buildings is introduced (one volume of the interior).

LOD4 Buildings are still basic, with added balconies and terraces and other parts. Feature complexity is 1 m, and close elements can be aggregated together, such as the balconies in this example. The city furniture of larger footprint (linear element larger than 1 m) is modelled as a basic 3D block. Smaller vegetation areas become a block of the average height of the vegetation. The road gets distinct traffic areas. The interior of the building has storeys.

LOD5 The roof of a building contains larger structures such as dormers and chimneys. Smaller parts of the building, e.g. entrance installation with the awning and stairs, are modelled as blocks.

LOD6 Other smaller building elements, larger than 50 cm, are modelled as blocks, i.e. entrance stairs and balconies become distinct objects. The interior is extended for the space of the dormers. All objects are coloured with a single (dominant) colour of a shape.

LOD7 Buildings have openings which are larger than 0.4 m modelled as 2D shapes, and balconies have a finer geometry. The texture is acquired at resolution of 30 cm/pixel. Solitary vegetation objects (trees) are acquired, as other city furniture elements such as lamp posts. The interior also gets corresponding openings.

LOD8 The feature complexity is 30 cm. Roofs have overhanging parts, smaller openings that have not been included in the previous LOD (width lower than 50 cm). Those are included in the interior as well. The interior also gets the connections between storeys, such as stairs.

LOD9 The feature complexity is very fine (10 cm). Hence, the openings of the building are modelled in 3D, while balconies get fences, awnings, and a privacy wall, and the lamp posts are more advanced. Roofs are added the remaining details according to the feature complexity (e.g. drainage). The resolution of the appearance is 20 cm/px. The interior becomes more advanced: it contains rooms and their connections (door openings).

This example shows one possible distribution of a continuous LOD series constructed from a combination of metrics and their functions, and discretisation into ten evenly-separated LODs. Since the functions of the metrics are determined, and the LOD values are on an interval scale, it is possible to generate further discretisations and refinements of LODs, e.g. LOD 7.43, enabling continuous LODs similar to computer graphics.

4.5 Terminology

The classic and well-established term "level of detail" implies a degree of generalisation or amount of features of a 3D city model, hence it is not correct with respect to the definition given in this paper, but also current concepts. The term *detail* is loosely equivalent to the presence and complexity of the objects and their elements, which makes LOD an incomplete term. While more appropriate terms that would accompany this definition would be terms such as *level of quality* (Döllner & Buchholz, 2005), *level of abstraction* (Glander & Döllner, 2009), or *level of completeness* (Tempfli & Pilouk, 1996), the conventional term of LOD is so well established in the GIS community that we do not propose any change here.

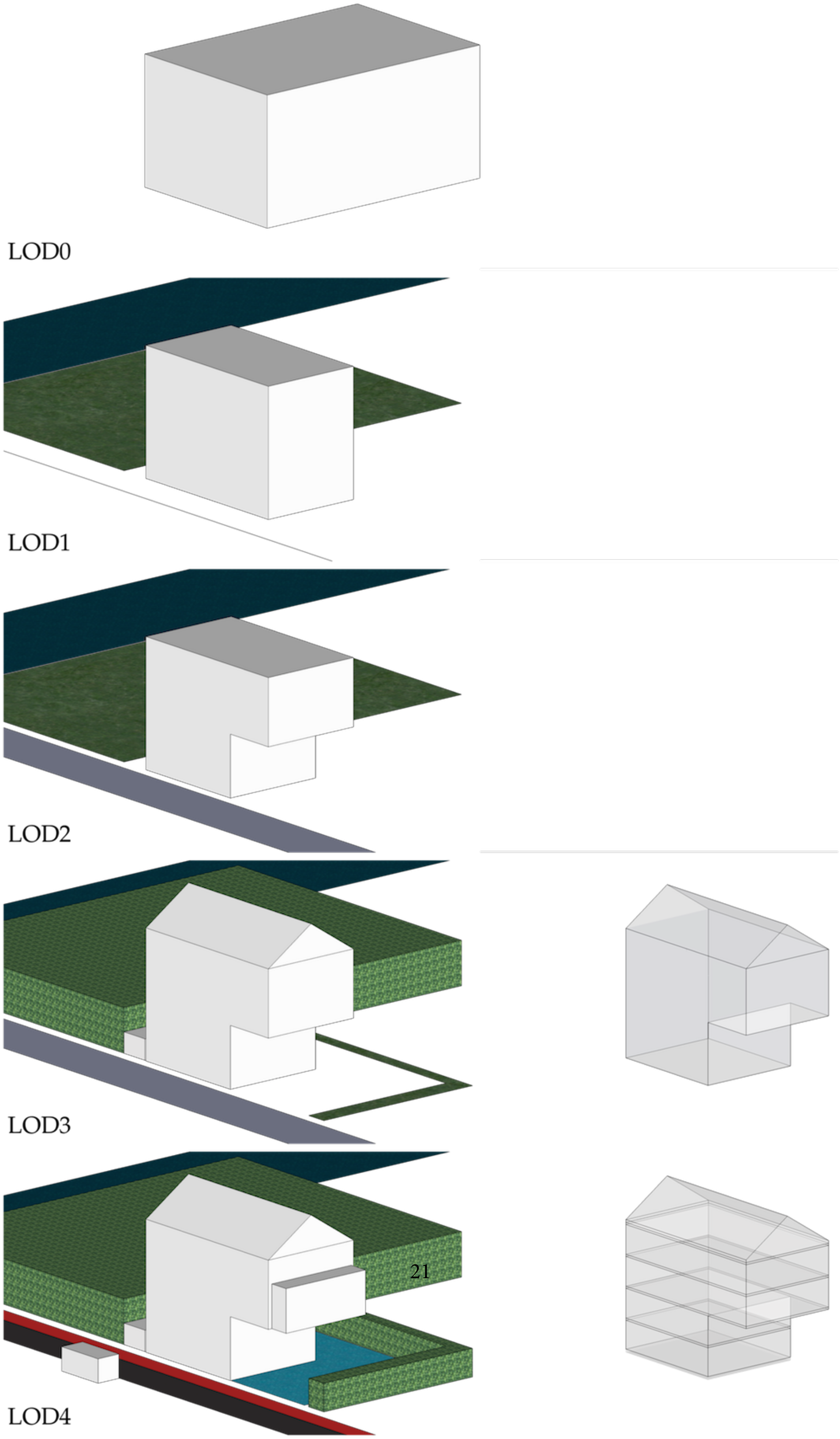

Figure 7: Visual representation of the discrete LODs 0–4.

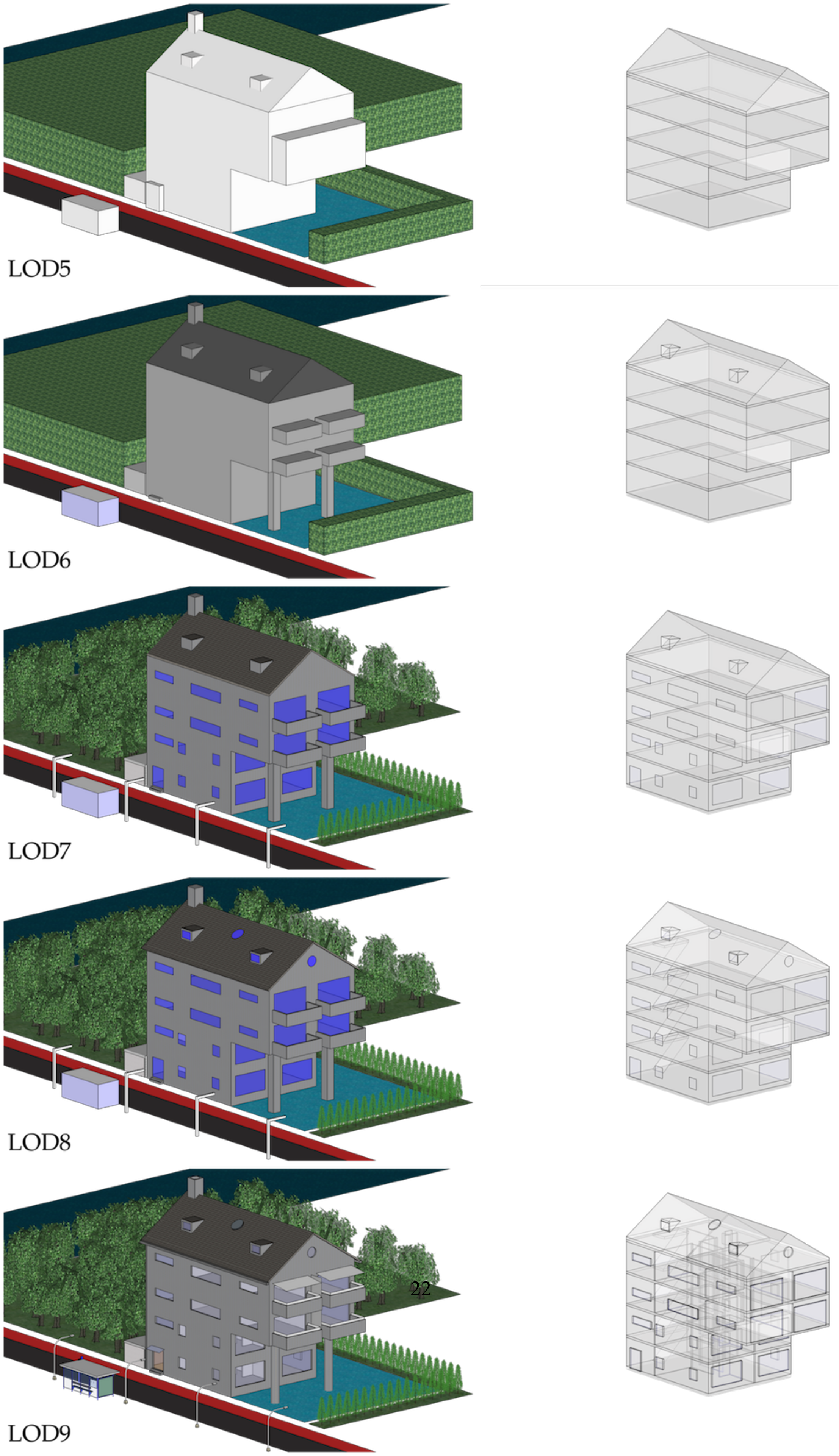

Figure 8: Visual representation of the discrete LODs 5–9.

5 Realisation of our proposed framework in CityGML

We have implemented our framework in CityGML since it is currently the most relevant standard for 3D city modelling, and it is undergoing discussions for the extension of the LOD concept for the upcoming version (Machl, 2013). There are three main points to translate to CityGML: (1) how to map the presented extended and nested semantic classes; (2) how to integrate the specification of the metrics of a discrete LOD; and (3) how to integrate the geometry of non-CityGML discrete LODs.

However, there are some limitations in CityGML with respect to our solution: (1) the classes in CityGML are limited (e.g. there is no separate class for balconies, it belongs to `BuildingInstallation`), so there is not always 1:1 mapping to classes and semantics, (2) nesting such as a `BuildingInstallation` is an element of another `BuildingInstallation` is not supported, (3) the definition of the geometry in CityGML is restricted to the proprietary LODs.

We have integrated our framework as an Application Domain Extension (ADE) in UML based on the guidelines from Van den Brink et al. (2012, 2013). While an ADE is primarily specified in order to adapt CityGML to the requirements of specific application domains (Çağdaş, 2013), it proven to be a good solution for the integration of this framework.

5.1 UML models of the ADE integration

As an example of the UML integration we have integrated the specification for the discrete LOD presented in the Table 3. Figure 9 shows the UML integration of the concept presented in this paper into CityGML, limited to the classes in the example. All additions in the ADE have been prefixed with "`newlod`".

Mapping the classes CityGML is limited when mapping classes of objects and their elements. For instance, a garage and a balcony of a building both belong to `BuildingInstallation`, and there is no semantic distinction between the two. Further, each cannot be further decomposed and nested (e.g. garage roof being part of a garage). We have solved this by extending our classes as subclasses of CityGML classes according to the hierarchy presented in Figure 5.

Specifying the metrics Each of the presented metrics should be specified in the UML. First of all, the presence of the objects and elements is denoted by the presence of UML classes. Second, the general metrics that are applicable to all objects and elements are integrated as a CityGML `GenericAttribute`. For the rest of the metrics, new attributes were defined for each object and element, e.g. `newlod_FC` for the feature complexity.

Geometry of the LOD The geometry of the discrete LOD is modelled as a geometry property of the UML elements, and it is specified with the data type `newlod_LODgeometry` (bottom left of the diagram).

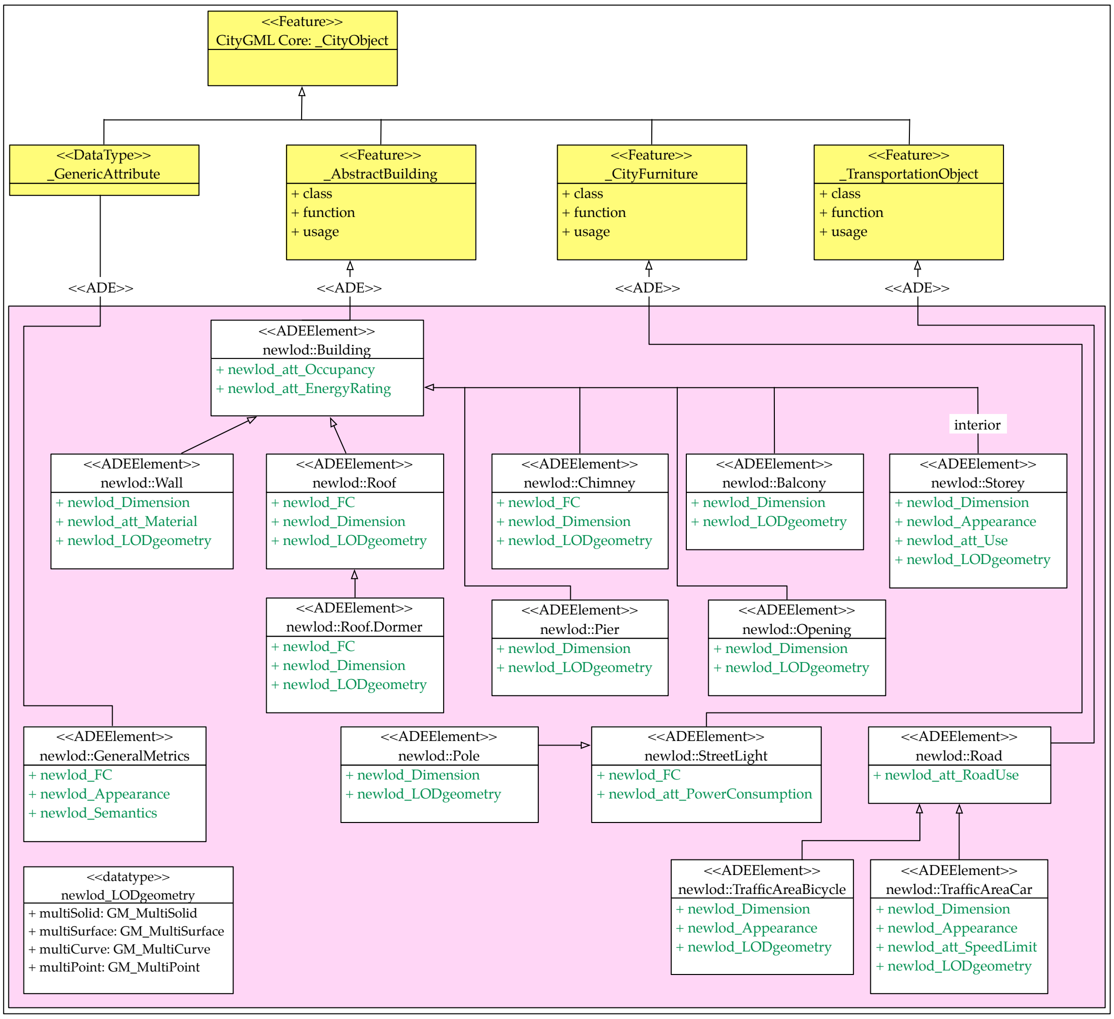

Figure 9: UML model of the implementation of the concept in CityGML through the Application Domain Extension. The CityGML classes are in yellow, while the extended part is in the pink area. This is a reduced example since not all classes can be fit in this diagram.

Integration of multiple discrete LODs and classes The above simplified example shows the integration of one LOD in CityGML. Multiple LODs are also possible, where the selection of classes may be different for each LOD, and the geometry of the same class may differ. In such case, the integration is as follows:

- The attributes are extended for each LOD. For instance, for two LODs A and B, the attribute `newlod_FC` becomes `newlodA_FC` and `newlodB_FC`, since they may differ in the LODs, depending on the function of metrics.
- All city objects and their elements that are present in the UML should be present. In case

of multiple LODs, their presence in each LOD is then denoted with a new binary attribute `newlod_Presence`, i.e. in this particular example: `newlodA_Presence` and `newlodB_Presence`.

- For each class the geometry per LOD is stored separately: `newlodA_LODgeometry` and `newlodB_LODgeometry`.

The ADE approach enables the full integration of our concept into CityGML. As future work, we plan to integrate the LOD functions thus enabling continuous LODs in CityGML.

6 Conclusion and future work

In this paper we have given a comprehensive LOD analysis with a list of most shortcomings of current paradigms, and we have discussed the concept of LOD in 3D city modelling thoroughly.

We have defined and formalised the concept, and we have established a harmonised LOD framework which is applicable to any format in 3D city modelling, not just CityGML. We see the LOD as the degree of correspondence between the model and the real-world object, being driven by the geometry, appearance, semantics and other related metrics which can be quantified, with separated exterior and interior concept. Such approach enables a consistent specification of the data, and facilitates the translation between the standards and the comparison of their LODs by decomposing them into quantified metrics, since LODs are discretisations of continuous functions of the metrics.

Our concept has several advantages over other concepts: (1) we create a thorough 3D city model base specification (with UML) used for expressing properties of 3D city models that can be used in the industry; (2) we show how to create continuous LOD series and their discretisations enabling a higher number of LODs which are also consistent; (3) we recognise the importance of semantics and extend and refine the semantic classes; (4) we decompose the city objects into more city objects based on their properties; (5) we give emphasis to the aggregation of objects and elements; and (6) allow mixing conventional LODs in the same city object by defining the requirements per each element rather than the city object. We have also shown that it is possible to implement the concept in CityGML, improving its deficiencies when it comes to LOD.

The presented concepts are extensible and adaptive for different thematic classes, city objects and their elements. The LODs may also be defined for smaller, and on the other side, large scales, enabling the applicability in BIM or very detailed virtual reality or architectural models, meaning that this framework is not restricted to 3D city modelling.

Our example of the realisation of the framework results in 10 discrete LODs, and shows that this framework enables finer distributions of LODs than presently available series. The progress of LODs in this particular example is with respect to all the metrics, and is more consistent compared to the present solutions.

In future work we plan to design a new series of LODs suited for general use and publish their specifications, work on the specification of application customised LODs for a specific use-case (e.g. estimation of noise pollution, and estimation of solar potential), research the continuous LODs, and integrate the 3D space and LOD in a hyper-dimensional (4D) model for more consistency (van Oosterom & Stoter, 2010; Stoter et al., 2012).

Acknowledgements

We wish to thank the reviewers for their constructive comments which helped us to improve the manuscript. The discussions and useful advices of fellow researchers in the 3D city modelling community are gratefully acknowledged. Thanks are also due to companies and institutions that provided us with the information about their internal practices, and to Peter James Morton for the access to his comprehensive database of 3D city models. This research is supported by (1) the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs (project code: 11300); and by (2) the National Natural Science Foundation of China (No. 41201379).

References

Adelaide City Council (2009). *Development information guide of the Adelaide 3D City Model: Frequently asked questions for architects, designers and developers.* URL: `http://www.adelaidecitycouncil.com/assets/3d_model_development_information_guide.pdf`.

Albert, J., Bachmann, M., & Hellmeier, A. (2003). *Zielgruppen und Anwendungen für Digitale Stadtmodelle und Digitale Geländemodell. Erhebungen im Rahmen der Arbeitsgruppe „Anwendungen und Zielgruppen“ der SIG3D im Rahmen der Initiative GDI-NRW*. Technical Report SIG3D. URL: `http://www.ikg.uni-bonn.de/fileadmin/sig3d/pdf/Tabelle_Anwendungen_Zielgruppen.pdf`.

Bandrova, T., & Bonchev, S. (2013). 3D Maps – Scale, Accuracy, Level of Detail. In *Proceedings of the 26th International Cartographic Conference* (p. 16). Dresden, Germany.

Benner, J., Geiger, A., Gröger, G., Häfele, K.-H., & Löwner, M.-O. (2013). Enhanced LOD concepts for virtual 3D city models. In U. Isikdag (Ed.), *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Proceedings of the ISPRS 8th 3D GeoInfo Conference & WG II/2 Workshop* (pp. 51–61). Istanbul, Turkey.

Biljecki, F., Zhao, J., Stoter, J., & Ledoux, H. (2013). Revisiting the concept of level of detail in 3D city modelling. In U. Isikdag (Ed.), *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Proceedings of the ISPRS 8th 3D GeoInfo Conference & WG II/2 Workshop* (pp. 63–74). Istanbul, Turkey.

Blom ASA (2011). *Blom3D™ Whitepaper for Blom partners, clients and developers*. Technical Report 1.0 BLOM ASA Oslo, Norway. URL: `http://blomasa.com/ftp/products/bis/Blom3D%20Whitepaper.pdf`.

Boeters, R. (2013). *Automatic enhancement of CityGML LoD2 models with interiors and its usability for net internal area determination*. Master's thesis Section GIS Technology, Delft University of Technology. URL: http://www.gdmc.nl/publications/2013/Automatic_enhancement_CityGML.pdf.

van den Brink, L., Stoter, J., & Zlatanova, S. (2012). Modeling an application domain extension of CityGML in UML. In J. Pouliot, S. Daniel, F. Hubert, & A. Zamyadi (Eds.), *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Proceedings of the 7th International 3D GeoInfo Conference* (pp. 11–14). Québec, Canada.

van den Brink, L., Stoter, J., & Zlatanova, S. (2013). UML-Based Approach to Developing a CityGML Application Domain Extension. *Transactions in GIS*, *17*, 920–942.

Çağdaş, V. (2013). An Application Domain Extension to CityGML for immovable property taxation: A Turkish case study. *International Journal of Applied Earth Observation and Geoinformation*, *21*, 545–555.

Chen, M. (2013). *Comparison of 3D Tree Parameters*. Master's thesis Wageningen University Wageningen, the Netherlands. URL: http://edepot.wur.nl/274391.

Chinese Ministry of Housing and Urban-Rural Development (2010). *Technical specification for three dimensional city modeling*. PRC Industry Standard 82765. China Building Industry Press. URL: http://www.china-building.com.cn/Detail/13842.html.

City of Perth (2013). Planning and development application. 3D model specification. URL: http://www.perth.wa.gov.au/sites/default/files/3D_Model_Specification_for_DA_submissions-V4.pdf.

City of Wollongong (2010). City Centre 3D Model Specifications. URL: http://www.wollongong.nsw.gov.au/customerserviceonline/factsheet/Factsheets/City%20Centre%203D%20Model%20Specifications.pdf.

Çöltekin, A., & Reichenbacher, T. (2011). High Quality Geographic Services and Bandwidth Limitations. *Future Internet*, *3*, 379–396.

Coors, V. (2001). 3D-GIS in Networking Environments. In *Proceedings of the International Workshop on 3D Cadastres. Registration of properties in strata* (pp. 159–168). Delft, the Netherlands.

Coors, V. (2003). 3D-GIS in networking environments. *Computers, Environment and Urban Systems*, *27*, 345–357.

CyberCity 3D (2013). 3D Modeling. URL: http://www.cybercity3d.com/index.php?option=com_content&view=article&id=97&Itemid=13.

Döllner, J., & Buchholz, H. (2005). Continuous level-of-detail modeling of buildings in 3D city models. In C. Shahabi, & O. Boucelma (Eds.), *GIS '05 Proceedings of the 13th annual ACM international workshop on Geographic information systems* (pp. 173–181). Bremen, Germany.

Fan, H., & Meng, L. (2012). A three-step approach of simplifying 3D buildings modeled by CityGML. *International Journal of Geographical Information Science*, *26*, 1091–1107.

Forberg, A. (2007). Generalization of 3D building data based on a scale-space approach. *ISPRS Journal of Photogrammetry and Remote Sensing*, *62*, 104–111.

Glander, T., & Döllner, J. (2008). Automated cell based generalization of virtual 3D city models with dynamic landmark highlighting. In *Proceedings of the 11th ICA Workshop on Generalization and Multiple Representation* (pp. 1–14). Montpellier, France.

Glander, T., & Döllner, J. (2009). Abstract representations for interactive visualization of virtual 3D city models. *Computers, Environment and Urban Systems*, *33*, 375–387.

Glasgow City Council (2009). Urban model Specification. Glasgow City Council. Development and Regeneration Services. URL: `http://www.glasgow.gov.uk/CHttpHandler.ashx?id=2078&p=0`.

Goetz, M. (2013). Towards generating highly detailed 3D CityGML models from OpenStreetMap. *International Journal of Geographical Information Science*, *27*, 845–865.

Gröger, G., Benner, J., Dörschlag, D., Drees, R., Gruber, U., Leinemann, K., & Löwner, M.-O. (2005). Das interoperable 3D-Stadtmodell der SIG 3D. *Zeitschrift für Geodäsie, Geoinformation und Landmanagement*, *130*, 343–353.

Gröger, G., Kolbe, T. H., Drees, R., Kohlhaas, A., Müller, H., Knospe, F., Gruber, U., & Krause, U. (2004). *Das interoperable 3D-Stadtmodell der SIG 3D der GDI NRW*. Technical Report Initiative Geodaten Infrastruktur NRW. URL: `http://www.ikg.uni-bonn.de/fileadmin/sig3d/pdf/Handout_04_05_10.pdf`.

Gröger, G., & Plümer, L. (2012). CityGML – Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, *71*, 12–33.

Hagedorn, B., Trapp, M., Glander, T., & Döllner, J. (2009). Towards an Indoor Level-of-Detail Model for Route Visualization. In *10th International Conference on Mobile Data Management: Systems, Services and Middleware* (pp. 692–697). Taipei, Taiwan: IEEE.

Hochtief ViCon (2011). *Lusail City. 3D Model Specifications High Rise Buildings*. Technical Report Hochtief ViCon Lusail City, Qatar. URL: `http://www.lusail.com/English/The-Visitor-Center/lusailstarterpack/Documents/Section%205/Digital%203D%20Model%20Specifications.pdf`.

ISO (2004). ISO 6707-1:2004(E): Building and civil engineering – Vocabulary. International Organisation for Standardisation (TC 59/SC 2).

ISO (2013). ISO 19157:2013 – Geographic information – Data quality. International Organisation for Standardisation (TC 211).

Kada, M. (2007). Scale-dependent simplification of 3D building models based on cell decomposition and primitive instancing. In *Lecture Notes in Computer Science. Proceedings of the 8th International Conference on Spatial Information Theory (COSIT 2007)* (pp. 222–237). Melbourne, Australia: Springer-Verlag.

Kemec, S., Zlatanova, S., & Duzgun, S. (2012). A new LoD definition hierarchy for 3D city models used for natural disaster risk communication tool. In T. Bandrova, C. König, & G. Zhelezov (Eds.), *Proceedings of the 4th International Conference on Cartography and GIS* (pp. 95–104). Albena, Bulgaria.

Kolbe, T. H., Gröger, G., & Plümer, L. (2005). CityGML: Interoperable Access to 3D City Models. In P. van Oosterom, S. Zlatanova, & E. Fendel (Eds.), *Geo-information for Disaster Management. Proceedings of the First International Symposium on Geo-Information for Disaster Management – GI4DM* (pp. 883–899). Delft, the Netherlands: Springer Verlag, March.

Kolbe, T. H., Nagel, C., & Stadler, A. (2009). CityGML–OGC Standard for Photogrammetry. In D. Fritsch (Ed.), *Proceedings of the 52nd Photogrammetric Week '09* (pp. 265–277). Stuttgart, Germany.

Lemmens, M. (2011). Quality of Geo-information. In *Geo-information. Technologies, Applications and the Environment* (pp. 211–227). Dordrecht: Springer Netherlands.

Li, K.-J., & Lee, J. (2010). Indoor Spatial Awareness Initiative and Standard for Indoor Spatial Data. In *Proceedings of the IROS 2010 Workshop on Standardization for Service Robots: Current Status and Future Directions* (p. 5). Taipei, Taiwan.

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. In B. Murgante, S. Misra, M. Carlini, C. M. Torre, H.-Q. Nguyen, D. Taniar, B. O. Apduhan, & O. Gervasi (Eds.), *Lecture Notes in Computer Science. Proceedings of the 13th International Conference Computational Science and Its Applications – ICCSA 2013* (pp. 466–480). Ho Chi Minh City, Vietnam.

Luebke, D., Reddy, M., Cohen, J. D., Varshney, A., Watson, B., & Huebner, R. (2003). *Level of detail for 3D graphics*. Morgan Kaufmann Pub.

Machl, T. (2013). Minutes of the International OGC, SIG 3D and TUM Workshop on Requirements for CityGML 3.0. In *International OGC, SIG 3D and TUM Workshop on Requirements for CityGML 3.0* (pp. 1–28). Munich, Germany: Technische Universität Munchen. URL: `http://en.wiki.modeling.sig3d.org/images/upload/Minutes_of_the_CityGML_Workshop_June_2013_at_TUM.pdf`.

Mandelbrot, B. (1967). How long is the coast of Britain? Statistical Self-Similarity and Fractional Dimension. *Science*, *156*, 636–638.

Mao, B. (2011). *Visualisation and Generalisation of 3D City Models*. Ph.D. thesis KTH Royal Institute of Technology. URL: `http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-24345`.

Meng, L., & Forberg, A. (2007). 3D building generalisation. In W. Mackaness, A. Ruas, & T. Sarjakoski (Eds.), *Challenges in the portrayal of geographic information: Issues of Generalisation and Multi Scale Representation* (pp. 211–232). Amsterdam, the Netherlands: Elsevier Science.

Morton, P. J., Horne, M., Dalton, R. C., & Thompson, E. M. (2012). Virtual City Models: Avoidance of Obsolescence. In H. Achten, J. Pavlicek, J. Hulin, & J. Matejdan (Eds.), *Digital Physicality - Proceedings of the 30th eCAADe Conference* (pp. 213–224). Prague, Czech Republic.

NAVTEQ (2011). *3D Landmarks - A product guide for developers*.

Novaković, I. (2011). 3D Model of Zagreb. *GIM International*, *25*, 25–29.

van Oosterom, P., & Stoter, J. (2010). 5D Data Modelling: Full Integration of 2D/3D Space, Time and Scale Dimensions. In S. I. Fabrikant, T. Reichenbacher, M. van Kreveld, & M. Schlieder (Eds.), *Proceedings of the Sixth International Conference GIScience 2010* (pp. 311–324). Zürich, Switzerland.

Open Geospatial Consortium (2012). OGC City Geography Markup Language (CityGML) Encoding Standard.

Oude Elberink, S., & Vosselman, G. (2011). Quality analysis on 3D building models reconstructed from airborne laser scanning data. *ISPRS Journal of Photogrammetry and Remote Sensing*, *66*, 157–165.

Rafiee, A., Dias, E., & Koomen, E. (2013). Between Green and Grey: Towards a New Green Volume Indicator for Cities. In S. Geertman, J. Stillwell, & F. Toppen (Eds.), *Proceedings of the 13th International Conference on Computers in Urban Planning and Urban Management (CUPUM)* (pp. 1–18). Utrecht, the Netherlands.

Rossignac, J. (2005). Shape complexity. *The Visual Computer*, *21*, 985–996.

Sanborn (2013). 3D Cities™. Sanborn. URL: `http://www.sanborn.com/sites/default/files/files/SANBORN_3DCitiesv4.0.pdf`.

Schilcher, M., Roschlaub, R., & Guo, Z. (1998). Vom 2D-GIS zum 3D-Stadtmodell durch Kombination von GIS-, CAD- und Animationstechniken. In *Tagungsband ACS '98, Fachseminar Geoinformationssysteme* (p. 12). Frankfurt, Germany.

Sester, M. (2007). 3D Visualization and Generalization. In D. Fritsch (Ed.), *Proceedings of the 51st Photogrammetric Week '07* (pp. 285–295). Stuttgart, Germany.

Stadler, A., & Kolbe, T. H. (2007). Spatio-semantic coherence in the integration of 3D city models. In A. Stein (Ed.), *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Proceedings of the WG II/7 5th International Symposium Spatial Data Quality 2007 with the theme: Modelling qualities in space and time* (p. 8). Enschede, the Netherlands.

Sternberg, H., Keller, F., & Willemsen, T. (2013). Precise indoor mapping as a basis for coarse indoor navigation. *Journal of Applied Geodesy*, *7*, 231–246.

Stoter, J., Ledoux, H., Meijers, M., Arroyo Ohori, K., & van Oosterom, P. (2012). 5D Modeling – applications and advantages. In *Geospatial World Forum* (p. 9). Amsterdam.

Stoter, J., Ledoux, H., Reuvers, M., van den Brink, L., Klooster, R., Janssen, P., Beetz, J., Penninga, F., & Vosselman, G. (2013). Establishing and implementing a national 3D Standard in The Netherlands. *Photogrammetrie - Fernerkundung - Geoinformation*, *2013*, 381–392.

Tamminga, G., van den Brink, L., van Lint, H., Stoter, J., & Hoogendoorn, S. (2013). Towards GIS compliant data structures for traffic and transportation models. In *Transportation Research Board 92nd Annual Meeting 2013. Transportation Data Interoperability: Recent Research (Session 283)* (p. 18). Washington, D.C., USA.

Tempfli, K., & Pilouk, M. (1996). Practicable photogrammetry for 3D-GIS. In K. Kraus, & P. Waldhäusl (Eds.), *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences. Proceedings of the XVIIIrd ISPRS Congress. Technical Commission IV* (pp. 859–867). Vienna, Austria.

Thiemann, F. (2003). 3D-Gebäude-Generalisierung. In W. G. Koch (Ed.), *Theorie 2003 - Vorträge der Dresdner Sommerschule für Kartographie* (pp. 52–61). Dresden, Germany.

Vande Velde, L. (2005). Tele Atlas 3D navigable maps. In G. Gröger, & T. H. Kolbe (Eds.), *EuroSDR International Workshop on Next Generation 3D City Models* (pp. 47–50).

Vertex Modelling (2013). Wide Area Models. URL: `http://www.vertexmodelling.co.uk/site/about/wide-area-models/`.