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An improved LOD specification for 3D building models

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Abstract

The level of detail (LOD) concept of the OGC standard CityGML 2.0 is intended to differentiate multi-scale representations of semantic 3D city models. The concept is in practice principally used to indicate the geometric detail of a model, primarily of buildings. Despite the popularity and the general acceptance of this categorisation, we argue in this paper that from a geometric point of view the five LODs are insufficient and that their specification is ambiguous.

We solve these shortcomings with a better definition of LODs and their refinement. Hereby we present a refined set of 16 LODs focused on the grade of the exterior geometry of buildings, which provide a stricter specification and allow less modelling freedom. This series is a result of an exhaustive research into currently available 3D city models, production workflows, and capabilities of acquisition techniques. Our specification also includes two hybrid models that reflect common acquisition practices. The new LODs are in line with the LODs of CityGML 2.0, and are intended to supplement, rather than replace the geometric part of the current specification. While in our paper we focus on the geometric aspect of the models, our specification is compatible with different levels of semantic granularity. Furthermore, the improved LODs can be considered format-agnostic.

Among other benefits, the refined specification could be useful for companies for a better definition of their product portfolios, and for researchers to specify data requirements when presenting use cases of 3D city models. We support our refined LODs with experiments, proving their uniqueness by showing that each yields a different result in a 3D spatial operation.

Keywords: Level of detail; 3D city modelling; 3D GIS; 3D building models; CityGML; Scale

Highlights

- CityGML LODs are an industry standard for conveying the grade of 3D city models.
- The 5 LODs are not defined precisely, and they are not sufficient for this purpose.
- We present a refined series of 16 LODs that overcomes these issues.

1 Introduction

The level of detail (LOD) of a 3D city model is one of its most important characteristics. It denotes the adherence of the model to its real-world counterpart, and it has implications on its usability (Biljecki et al., 2014b).

The CityGML 2.0 standard from the Open Geospatial Consortium (2012) defines five LODs. The concept is intended for several thematic classes of objects but it is primarily focused on buildings, and the five described instances increase in their geometric and semantic complexity (Figure 1).

LOD0 is a representation of footprints and optionally roof edge polygons marking the transition from 2D to 3D GIS. LOD1 is a coarse prismatic model usually obtained by extruding an LOD0 model. LOD2 is a model with a simplified roof shape, and where the object's parts can be modelled in multiple semantic classes (e.g. roof, wall). LOD3 is an architecturally detailed model with windows and doors, being considerably more complex than its preceding counterpart. LOD4 completes an LOD3 by including indoor features (Kolbe, 2009). This taxonomy has been developed in the German Special Interest Group 3D (SIG 3D) initiative (Albert et al., 2003), and has been further described in Gröger and Plümer (2012). The five LODs have become widely adopted by the stakeholders in the 3D GIS industry and they now also describe the grade and the design quality of a 3D city model, especially its geometric aspect (i.e. "how much detail should be acquired?"). They have gained importance also in the computer graphics (Verdie et al., 2015; Musialski et al., 2013), and BIM (Tolmer et al., 2013) communities when dealing with 3D building models.

Figure 1: The five LODs of CityGML 2.0. The geometric detail and the semantic complexity increase, ending with the LOD4 containing indoor features.

The LOD concept of CityGML is primarily intended to differentiate the grade of data resulting from different production workflows, and they are driven by semantics as much as geometry. In the industry and research community they were accepted from the outlook on geometric richness, which was partly caused by the lack of applications that require semantics. For instance, we have observed that while the LOD2 from the point of view of CityGML developers represents a model with differentiated semantic surfaces, practitioners primarily refer to models with roof shapes, even when not dealing with data that is semantically structured.

While the five LODs generally provide a categorisation of the overall level of abstraction, content, value, and usability of 3D city models, this classification has several drawbacks and shortcomings as we show in Section 2. Since the specification is crucial among practitioners and researchers for conveying the grade of a 3D city model and its adherence to the real-world, in this paper we present a refined specification to solve such problems. It should be noticed that the topic of refining and improving the current specification of the LODs is currently under consideration in the CityGML community for version 3.0 (Machl, 2013; Löwner and Gröger, 2016), and we hope that our proposal will help the discussions. However, our work is intended to be independent of any particular 3D format, and applicable to any format that can be used to store 3D building models, including ones such as COLLADA and OBJ.

In Figure 2 we give an example of the shortcomings of the current concept, from the point of view of the geometric detail. The figure illustrates two LOD2 models: the model on the left has been acquired with two acquisition techniques, the walls are at their actual location and the roof overhangs are explicitly present. The representation in the middle has been acquired with one technique (aerial photogrammetry) where the walls are derived as projections from the roof outline (the third model will be introduced in another example in the following section). This example illustrates how the CityGML LOD concept is ambiguous and that it falls short in defining the complexity of the models: the two models are of the same LOD (LOD2) according to CityGML while the first one is more laborious to acquire and it may bring better results in a spatial analysis (e.g. more accurate volume (Biljecki et al., 2016)). Hence, practitioners would not consider them to be of equal value and usability. For these reasons we argue in this paper that they should be considered as different LODs, and our specification differentiates such cases.

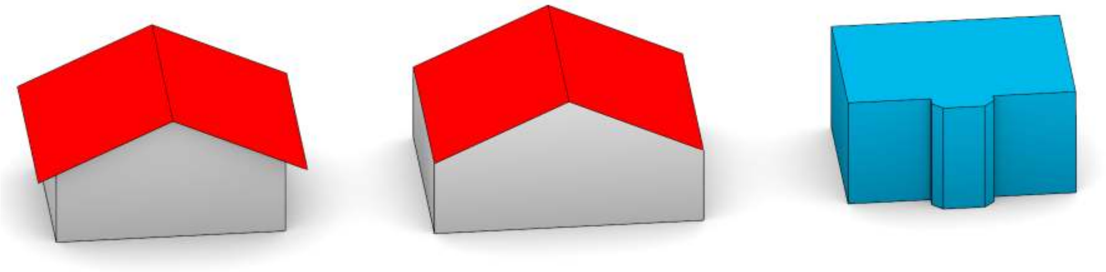

Figure 2: Two variants of LOD2 and an LOD1 model exposing the shortcomings of the CityGML LOD concept, and why the computer graphics principles cannot be fully applied to GIS and 3D city modelling.

This ambiguity is most evident in the production of the models. For instance, in 3D generalisation where researchers produce multiple geometric variants of LODs and discuss the ambiguity, among others see Guercke et al. (2011), Fan and Meng (2012), Stoter et al. (2011), Noskov and Doytsher (2014), and Deng et al. (2016).

Solving the ambiguity is also important considering: (1) the increasing number of acquisition techniques (e.g. the recently investigated being drones (Nex and Remondino, 2013), radar (Zhu and Shahzad, 2014), handheld devices (Rosser et al., 2015; Sirmacek and Lindenbergh, 2014), procedural modelling (Wonka et al., 2003; Müller et al., 2006; Kelly and Wonka, 2011; Müller Arisona et al., 2013; Tsiliakou et al., 2014; Smelik et al., 2014), conversion from BIM and computer graphics models (Donkers et al., 2015; Kumar et al., 2016), and generation from 2D drawings (Gimenez et al., 2015)); (2) the number of data producers and national mapping agencies requesting 3D data is increasing (Stoter et al., 2015), and without a finer specification data producers and users may resort to creating their own specifications (e.g. see the series from Blom ASA (2011)), which might increase the ambiguity; (3) the increase in quantity of data sets with non-homogenous LODs (Fan et al., 2014; Touya and Reimer, 2015; Arroyo Ohori et al., 2015a); and (4) use cases have different requirements when it comes to the complexity and quality of the data. Furthermore, the number of 3D use cases is rapidly increasing (Biljecki et al., 2015b), for instance—solar potential estimation (Freitas et al., 2015), studying the thermal characteristics of the outdoor space (Maragkogiannis et al., 2014), firefighting simulations (Chen et al., 2014), and advances in multi-scale navigation (Hildebrandt and Timm, 2014). Each of these use cases may have different requirements when it comes to the LOD of the models.

In this paper we improve the geometric aspect of the LOD specification of 3D building models. We provide an extended and more informative series of 16 LODs that are compatible with the existing CityGML LODs. The refined taxonomy is a result of a research into currently available 3D city models and an investigation of the acquisition workflows. We review related work on this topic (Section 3), and for each LOD we give requirements and show an example (Section 4).

We have generated a sample data set in 16 LODs and run them through a few GIS operations to show that each LOD is unique from a geometric point of view and may bring different results in a spatial analysis (Section 5).

In this paper we focus on the exterior of buildings (i.e. their exterior shell in LOD0–3). The refinement of the indoor and semantics aspect of the specification can be considered as orthogonal topics to this one. These topics are being tackled by other researchers who decompose it into different levels of abstraction and integrate them into expanded LOD1, LOD2 and LOD3 models (for examples see the work of Boeters et al. (2015) and Löwner et al. (2013)). While the semantic LOD and indoor LOD are out of scope of our paper, present work on these topics is compatible with our work because such specification can be supplemented to ours. For instance, each of the newly refined LODs can be assigned a semantic LOD depending on the achieved spatio-semantic coherence.

2 Shortcomings of the current concept and difficulties with designing a specification

The LOD concept used in CityGML 2.0 has been borrowed from computer graphics in which multiple representations of polygon meshes are differentiated by their number of faces, and their simplification is performed by algorithms that reduce the number of faces while attempting to retain visual fidelity (Luebke et al., 2003; Clark, 1976). While the early purpose of the LOD in 3D GIS was to improve visualisation performance (e.g. see Coors and Flick (1998)), visualisation is now only one of the applications of 3D city models (Biljecki et al., 2015b). Nowadays, LOD also implies the usability of the model and its adherence to the real-world feature. When simplifying the 3D geometries (generalising), different approaches are used, since the goal is to also retain various geometric and semantic aspects that are not relevant for visualisation, and to preserve the structure of the simplified building (Xie et al., 2012). However, it should be noted that in computer graphics the rationale implies choosing the optimal LOD among multiple LODs, while in GIS practitioners almost always deal with a single model at a certain LOD. Therefore, for the large part the LOD concept is used *prior* to acquisition of a 3D model (e.g. to detail the procurement of data, delivered in a single LOD), while in computer graphics they are on-the-fly derived from a finer model.

Despite the historic relation, the design of an LOD specification in GIS is hampered by the fact that the LOD concept in 3D GIS is inherently different from the one in computer graphics (Biljecki et al., 2014b). We clarify this with two further arguments related to Figure 2. First, this example exposes that the two models on the left have the same polygon count, the foremost metric in computer graphics to distinguish two representations. Second, besides the aforementioned LOD2 models, the model on the right is a geometry extruded from a fine footprint of the same building. This LOD1 model has a higher face count than the LOD2 models. While the number of the primitives generally gives a good impression about the geometric complexity of a 3D city model, it cannot be considered as an unambiguous differentiator as it is the case in computer graphics. (The only exception to this in GIS and in 3D city modelling is terrain because of its usually triangular representation: lower LOD means less triangles (De Berg and Dobrindt, 1998; Suárez et al., 2015).)

Consequently, unlike in computer graphics, the LODs in 3D GIS cannot be ordered: the LOD1 model, intrinsically considered inferior to an LOD2, may be accounted as more valuable than an LOD2 for certain scenarios when a finer footprint is more useful than the acquired roof shape. An example of such use case is the computation of the net internal area of a building, useful for energy estimations, real estate valuation, and population counts (Kaden and Kolbe, 2014; Nouvel et al., 2015; Boeters et al., 2015; Lwin and Murayama, 2009). Hence it does not strictly hold that LOD$(i+1) >$ LOD i, i.e. the LODs are rather nominal, instead their ordinality rather depends on the use case and other aspects (Biljecki et al., 2014b).

Focusing on the CityGML 2.0 LOD concept, it might come to a surprise that this ubiquitous standard does not provide a strict specification for the five LODs. It gives short narrative descriptions, with a table (see Tab. 3 in Open Geospatial Consortium (2012)) that is considered as a recommendation, and not a requirement. The description actually specifies the *upper limit* of each LOD, and not the minimal restriction for each, i.e. it restricts what can be a part of each representation. For instance, LOD2 cannot contain openings, but it is not stated that LOD3 must contain openings.

Hence, besides an insufficient number of LODs and their condensed grouping, the main drawback of the concept in the current version of CityGML is that it does not mandate what features and how detailed they should be acquired, and therefore it leaves ambiguity and freedom for the implementation. For instance, it is not stated whether dormers and other larger roof details should be acquired in LOD2. This may lead to misunderstandings between stakeholders, and errors in the utilisation of the models. For example, in solar potential estimations, which are most frequently carried out with LOD2 models (Biljecki et al., 2015a), it is important to have roof superstructures since they cast shadows and they may reduce the area available for the installation of photovoltaic panels. Hence there may be substantial differences between analyses carried out with LOD2 models with and without roof superstructures. For this reason there is a need to differentiate between variants of LODs, and it is therefore important to provide a more expressive specification which diminishes errors caused by an ambiguous LOD specification.

CityGML provides several conformance rules to test the validity of CityGML data, and there are other efforts such as Gröger and Coors (2011), Wagner et al. (2012), and Coors and Wagner (2015) to provide extended modelling guides and rules. However, these do not cover the geometric detail of the models. This drawback results in many valid variants to be considered of the same LOD.

The size (e.g. length or footprint) of real-world features and their parts (e.g. a balcony of a building) that have to be acquired is designated as one of the main differentiators of the LODs. However, this cannot be used as the general guideline to further specify LODs. For example, if an LOD2 requires that certain building parts bigger than a threshold should be acquired, this cannot be applied to windows, because they are not intended to be acquired in LOD2, irrespective of their size. A second example are overhangs (such as in Fig. 2). They may be required by a stakeholder. However, in size they are smaller than other features which may not be required at all (e.g. dormers), hence each group of related features should be treated separately. Finally, nowadays a significant amount of models are constructed with a combination of different data sources. The LOD concept does not consider the LOD of combined data, where some parts of buildings may be acquired in a finer or coarser detail than other parts.

These shortcomings could be solved together by providing a general list of features that should be acquired and the minimum size for each. However, CityGML does not provide such. We provide these in our specification described in Section 4.

3 Related work

The general LOD notion was examined in our earlier work (Biljecki et al., 2014b). The concept is decomposed into six metrics: list of features, their geometric complexity, dimensionality, appearance, spatio-semantic coherence, and attributes. We take into account the first three metrics when defining the geometric aspect of the LOD.

Stoter et al. (2011) recognise that CityGML lacks precise LOD definitions and allows ambiguity, and in a later research, Stoter et al. (2014) argue that the specification should be further defined by practitioners, depending on the intended application of the 3D city model to be acquired. We agree with this reasoning, and think that our approach may help practitioners to do so in a standardised and justified way, while still leaving a significant degree of freedom to accommodate specific requirements of use cases.

Due to the ambiguity and the differences of models that CityGML considers to be of the same LOD, He et al. (2012, 2013) refer to the CityGML LODs as LOD groups, and further define inter-level LODs within the LOD1 group that vary in their geometric complexity. Besuievsky et al. (2014) have a similar approach for LOD3 buildings where they create three variants of LOD3 buildings that are distinguished by the size and type of features to be acquired. We have considered their granular LODs when designing our refined specification.

Borrmann et al. (2014) provide an extended LOD specification for tunnels defining five LODs to create consistent multi-scale models and to use them for synchronous engineering collaboration. The LODs are discerned primarily by the list of railway elements that are acquired. Chen (2013) does a similar work for trees defining four LODs i.e. “Level Of Tree-detail”. The feasibility of the acquisition of these representations has been conducted with different airborne laser scanning scenarios.

In the BIM community, Van Berlo and Bomhof (2014) have worked on the refinement of the BIM LODs after analysing industrial practices and conducting a series of geometric tests. This is similar to our approach (Sec. 4 and Sec. 5). Related to the BIM domain, Tolmer et al. (2014) propose additional LODs to allow for a more transversal decomposition of data and objects organisation, and apply them to an urban motorway project.

Wate et al. (2013) emphasise the importance of the relation of the acquisition technique to an LOD, and give acquisition technique guidelines for each CityGML LOD. Vosselman and Dijkman (2001) show how the capabilities (resolution) of acquisition techniques have a direct impact on the LOD of the reconstructed 3D city model. In our work we have analysed acquisition workflows, and we have taken them into account when designing the specification.

Coors (2003) distinguishes the LOD of the acquired geometry from the presented model (view). Related to the visualisation aspect, Çöltekin and Reichenbacher (2011) analyse balancing the cognitive and bandwidth aspects of multi-LOD data, emphasising the economical aspect of each LOD.

Döllner (2005) expresses that in the current LOD approach it is difficult to integrate buildings from different sources and of varying LOD. Furthermore, they discuss the models that can be considered of an LOD between LOD2 and LOD3. Their observations are important for our work because we introduce two LODs that are designed to be acquired with a combination of different sources.

Stadler and Kolbe (2007) propose several levels of spatio-semantic coherence in 3D city models. Their work is one of the foundations in the semantic aspect of 3D city models. Benner et al. (2013) and Löwner et al. (2013) propose the orthogonal decoupling of the exterior and indoor geometry, and a refinement into multiple semantic LODs. The number of permutations, excluded by some prohibited variants, is large enhancing the specification, since they still fit within the present CityGML LODs. For instance, a building with a coarse exterior with no semantic structuring may include a fine interior, and such has a unique designation. The refinement of the indoor LODs is a current research topic, which is also in focus in Hagedorn et al. (2009), Kemec et al. (2012), Billen et al. (2012), Kang and Lee (2014), Kim et al. (2014), and Boeters et al. (2015).

4 Refined levels of detail for buildings

We provide a series that contains 16 LODs (4 refined LODs for each of the LOD0–3), which are shaped after a literature review and inventory of presently available models by finding their main relevant similarities and mutual aspects. A visual example of the refined LODs is shown in Figure 3. We believe that these LODs allow for less ambiguity, and they aid practitioners to standardise their data with an improved definition of the complexity of the models. As mentioned before, this work is not intended to extend CityGML 2.0, it rather provides a supplementary specification that reflects the current practices and that conforms to the current concept, and at the same time solves the ambiguities elaborated in Section 2.

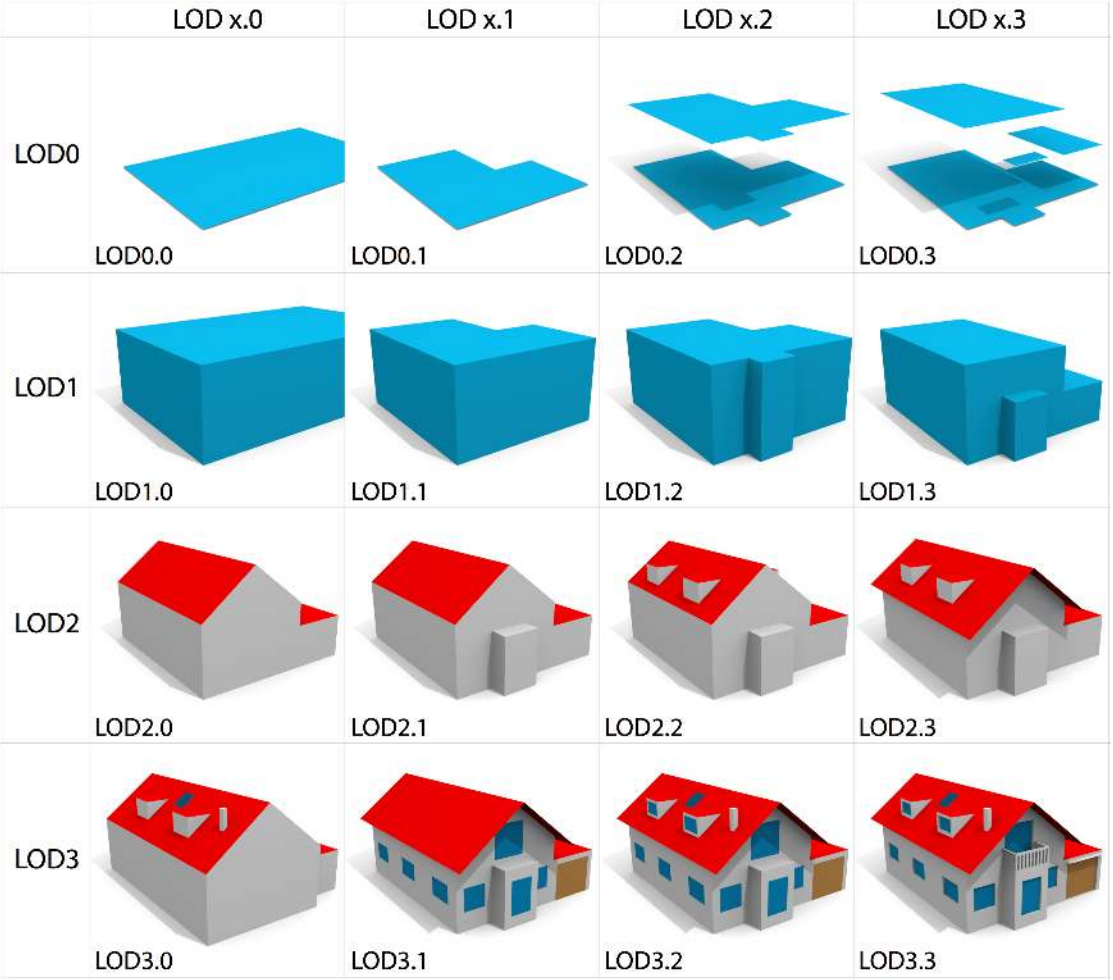

Figure 3: Visual example of the refined LODs for a residential building.

4.1 Methodology

Besides investigating workflows for producing 3D city models (e.g. (Habib et al., 2010; Kedzierski and Fryskowska, 2014; Xiong et al., 2015)), we have examined several categories of sources of data. For instance, national standards and guidelines (AdV, 2011, 2013; Stoter et al., 2014; Blaauboer et al., 2013; Chinese Ministry of Housing and Urban-Rural Development, 2010), examples of series and specifications of 3D city models not related to CityGML (Köninger and Bartel, 1998; Batty et al., 2000; Kemec et al., 2012; Schilcher et al., 1998; Thiemann, 2003; Demir and Baltsavias, 2012), usually in the field of 3D generalisation (Zhao et al., 2012; Li et al., 2013), visualisation

(Andujar et al., 2010; Rau and Cheng, 2013) and 3D reconstruction (Huang et al., 2011; Verma et al., 2006).

Furthermore, we have examined examples of models that refer to the CityGML LODs but do not seem to be stored in CityGML or have any other relation with the standard (Nex and Remondino, 2013; Burochin et al., 2014; Qin, 2014; Becker, 2011; Kaňuk et al., 2015; Zhu and Hu, 2010). Finally, a number of publicly available data sets and specifications from companies, tenders and local governments have been examined as well (Novaković, 2011; Franić et al., 2009; Vande Velde, 2005; Blom ASA, 2011; Glasgow City Council, 2009; Vertex Modelling, 2013; NAVTEQ, 2011; Sanborn, 2014; CyberCity 3D, 2013).

We have analysed the available models from different angles: usability (their intended use cases), acquisition techniques (implying their cost and availability), and specification if available. The dozens of variants of models have been grouped into original CityGML LODs to which they correspond, and which we name *LOD families*. We have found a few general aspects, and various spatio-semantic ambiguities that surface in each LOD family, resulting in four groups of models within each family. The LOD groups are concentrations of models and partially imply their correspondence to the real-world, acquisition technique, accuracy, domain of applications, etc. For each of these LOD groups a common set of requirements has been established, resulting in a specification and refined set of LODs.

Note that in our specification we do not focus on the semantic aspect and the texture. We address the amount of geometric detail that has to be acquired, by focusing on the list of elements of a building, and their granularity. Non-geometric requirements can be supplemented to our specification if required.

A few observations in the survey motivated specific choices. The first matter which we have noticed in our survey is the large number of unique specifications and combinations of various aspects. It is not possible to regard each of the aspects while retaining a reasonable number of LODs. Hence, in this process we have balanced the scope of the specification and the number of the refined LODs, and we have taken care that the models unambiguously correspond to a refined LOD. The goal is to provide a finer specification, but flexible enough to still allow some freedom of modelling and not to result in a too large number of levels. This is beneficial for use cases, since a large number of models have been acquired bearing in mind a specific use case, and a strict specification would not be favourable towards such practices.

Another observation that led to a specific choice was a small number of *outliers*—specifications that are not in line with the common practices in 3D city modelling. They are rather designed for a specific application and as such cannot be accommodated in a uniform specification. For instance, Kemec et al. (2012), Ioannidis et al. (2015), and Frommholz et al. (2015) define an LOD2 model with generalised footprint and fenestration; and the specification in Kartverket (2014) which defines LOD1 models with non-flat top surfaces. Such models are not considered, since their inclusion would compromise the simplicity of our concept, but it would also not be in line with the standard CityGML LODs. However, the rationale of our specification can still be used to define such *customised* LODs in addition to our series.

4.2 Selection criteria for objects to be acquired

The selection of objects (e.g. building elements such as dormers) to be mapped is an important part of the LOD specification. This is also analogous to 2D maps (Touya and Brando-Escobar, 2013), where the selection criteria is mostly based on their significance and minimum size, and it depends on the object's class (Biljecki, 2007). This reasoning can be followed in 3D as well. However, it should be stated that the significance and size are both fuzzy terms that also depend on the use case, and cannot be strictly defined, as other concepts related to scale and LOD.

The minimum size can be expressed as the minimum length and/or width of an object, and/or the minimum footprint area. For instance, a requirement may state that dormers that are wider than 1 m, and/or their footprint projected onto the roof is larger than 1 m^2 should be acquired. This can be applicable to both the size of a feature and its granularity, e.g. minimum size of a land cover area or its *spikes*.

In expressing the thresholds, it is important to define both the 1D and 2D requirements. For instance, a chimney may be longer than a dormer (1.5 m > 1.0 m), but much smaller when considering its footprint on the roof (0.15 m × 0.15 m ≈ 0.02 m^2). A 3D requirement (volume) will not be used because it is not applicable to all types of features (e.g. windows).

4.3 General rules and principles of the specification

The main principles of our specification are:

1. A model must adhere to all of the requirements to be considered of a specific LOD.
2. With a few exceptions, the specification is designed in such a way that each LOD$x.i$ contains more detail over LOD$x.(i-1)$, i.e. all requirements of an LOD$x.i$ should also satisfy the requirements of an LOD$x.(i-1)$. However, observe that an LOD$x.i$ is not necessarily more *detailed* than an LOD$(x-1).(i+1)$. This is comparable to the discussion related to Figure 2.
3. The list of building elements to be acquired is composed from the most common occurrences of such features, for instance, windows and dormers. This list applies also to other elements of comparable function and size.
4. The selection criteria to model an object or not have been determined based on the minimum size of the building's element to be acquired. The minimum size is expressed as a distance, which can be applied to the length, width, or height of a feature, and as a projected footprint area. The footprint projection is not necessarily on the ground. For instance, for windows the projection onto the walls is considered, and roof superstructures on the (inclined) roof. These requirements are specified separately for each feature's type (e.g. chimney). If no footprint selection criteria is stated, only the length criteria applies. Such minimum size selection criteria may cause disregarding some features that in certain settings could be important for a particular application. If that is the case, users may still opt for modelling smaller features beyond the threshold.

5. The specification provides general requirements that leave space for an extra number of variants. An LODx model that is modelled finer than it is required in LOD$x.i$, but below the specification of LOD$x.(i+1)$, is considered as LOD$x.i$. For instance, if an LOD$x.i$ and LOD$x.(i+1)$ require all buildings parts larger than 4 m and 2 m to be acquired, respectively, and a model contains a part 3 m long, it may be considered as LOD$x.i$.
6. The specification defines that sizeable building parts, extensions and annexes such as garages and alcoves, may be acquired and treated distinctly. This should be distinguished from the cadastral point of view. Such objects are still part of the building, but their geometry is acquired in a way that these features are perceptually distinguishable.

4.4 Refined LOD specification for the geometry

The specification is given in Table 1, and a visual representation of the models is provided in Figure 3. In this section each LOD family is refined with four LODs that are described.

Because LOD1 is in essence an extrusion of the LOD0 model (or its generalised product), both are examined and redefined in conjunction.

4.4.1 LOD0 and LOD1 families

The coarsest volumetric representation that the standard contains is the LOD1 model, a generalised model which is only described as “the well-known blocks model comprising prismatic buildings with flat roof structures” (Open Geospatial Consortium, 2012). Block models have also been described in “patent language” in the US Patent Application by Guskov and Brewington (2015), as a set of extruded polygons (right prisms) that comprise a volume which is defined by a base height from which extrusion begins, and an extrusion distance.

LOD0 is briefly described as a representation by 2.5D horizontal polygons with footprint level height and optionally roof level height (Gröger and Plümer, 2012).

LOD1 models are usually derived with extrusion to a uniform height (Buyuksalih et al., 2013; Ledoux and Meijers, 2011; Over et al., 2010; Ordnance Survey, 2014; SwissTopo, 2010; Arroyo Ohori et al., 2015b; Sargent et al., 2015), and generalisation from finer LODs (Baig and Abdul-Rahman, 2013; Meng and Forberg, 2007), for instance, as a bounding box of an LOD2 (Diakité et al., 2014; El-Mekawy et al., 2011). As a consequence, there are only horizontal and vertical surfaces, and no projection to the xy plane of two horizontal surfaces can overlap (not counting the *ground surface*).

Although LOD1 models are the coarsest volumetric representation, they can be derived from very accurate and detailed footprints (Van den Brink et al., 2013a; Kolbe et al., 2015) (see also Figure 2).

LOD1 models provide a relatively high information content and usability comparing to their geometric detail (Henn et al., 2012; Hofierka and Zlocha, 2012). For instance, they may be used for shadowing simulations (Strzalka et al., 2012; Alam et al., 2013; Li et al., 2015), estimation of noise pollution (Stoter et al., 2008), energy demand estimation (Strzalka et al., 2011; Bahu et al., 2013), simulating floods (Varduhn et al., 2015), analysing wind comfort (Amorim et al., 2012), and visualisation (Gesquière and Manin, 2012).

While the LOD1 model is the simplest volumetric 3D city model, it may be modelled in multiple ways. Götzelmann et al. (2009), Glander and Döllner (2009), Meng and Forberg (2007) and Mayer (2005) all generalise LOD1 models creating a coarser LOD1 model. Agugiaro (2014) generates two variants of block models from footprints: one from a cadastral source, and one from a topographic map. Therefore, we have identified the following relevant aspects in the LOD0 and LOD1 families:

- The models may represent individual or aggregated buildings (buildings that in reality are not adjacent and between which there is a gap, but are close enough to be modelled as one entity, at a smaller scale). Some specifications enforce this, for instance, the 3D standard of the Netherlands requires individual buildings prohibiting their aggregation (Stoter et al., 2014; Blaauboer et al., 2013).
- Since 2D footprints are extruded to a uniform height, and the resolution of the footprint directly implies the LOD of the 3D model, they are the focus of LOD0 and LOD1. However, their complexity may considerably deviate (Yang et al., 2011), from coarse to fine footprints as seen in Prandi et al. (2013) and Ellul and Altenbuchner (2013). This is especially the case in generalisation from finer LODs (Forberg, 2007; Anders, 2005).
- Besides the footprint, LOD0 models may contain a roof-edge surface.
- Multiplicity of top surfaces: LOD1 models are not necessarily extruded to a uniform height, which is a common misconception about the production of the LOD1 model, since the number of top surfaces are not restricted by the standard. We have encountered several instances of enhanced LOD1 block models with *differentiated* roof tops (Emem and Batuk, 2004; Commandeur, 2012; Oude Elberink et al., 2013; Döllner et al., 2006; Ellul and Altenbuchner, 2013; He et al., 2013; Häfele, 2011; Sanborn, 2014) that include multiple flat surfaces instead of a single surface for the top, to differentiate terraced houses, large roof constructions, etc. Related to extrusion, sizeable parts of buildings (e.g. veranda, carport, garage, and alcove) may be modelled separately with a different value of the height, resulting in multiple top surfaces, even if they *belong* to the same footprint. This may be to a degree incompatible with the traditional LOD1 notion, however, their occurrences warrant a separate LOD, and not all LOD1 models are derived with extrusion.

We define four LODs in each LOD family with the minimum requirements: LOD0.0 and LOD1.0 are the coarsest models: they require all buildings larger than 6 m to be acquired, and buildings may be aggregated. These are the only two instances in our specification in which neighbouring buildings may be aggregated in a single geometric entity. In LOD0.1 and LOD1.1 buildings must be individually modelled and all large building parts shall be acquired. LOD0.2 and LOD 1.2 have the requirement that smaller building parts and extensions should be acquired (e.g. alcoves), and are extruded to a single height. This addition may result in more accurate spatial analyses, such as line of sight (Yaagoubi et al., 2015). In addition, LOD0.2 requires the roof-edge polygon to be acquired as well. We have found that the LOD1.2 is the most common LOD1 model in practice. LOD0.3 and LOD1.3 also require the same features to be acquired, but it allows multiple top surfaces if their differences are higher than a threshold (e.g. 2 m). For instance, a large recess in a wall might have its height separately modelled and may be individually extruded. This approach can benefit use cases such as estimating the internal area. Such modelling practice may be considered counter-intuitive from the extrusion point of view, where a footprint polygon is extruded to a single height. However—due to a substantial number of such models, the increased accuracy they may bring to spatial analyses, and the fact that not all LOD1 models are derived by extrusion—introducing such LOD is necessary. Finally, LOD1.3 cannot contain multiple horizontal surfaces at the same planar coordinate.

4.4.2 LOD2 family

LOD2 is a more detailed model than LOD1, in which individual buildings are mandated, and are modelled as simple structures containing standard and simplified roof structures. They are usually derived from point clouds or photogrammetry, and their combination with building footprints (Alexander et al., 2009; Haala and Brenner, 1999; Haala and Kada, 2010). They can also be derived with generalisation from an LOD3 (Mao et al., 2012).

The models provide a relatively favourable relation between the costs of acquisition and usability. Acquisition-wise, they can be automatically derived from point clouds (Suveg and Vosselman, 2004; Brenner, 2005; Kada and McKinley, 2009). Usability-wise, they can be used in a wider range of applications than LOD1, such as the estimation of the solar potential of rooftops (Fath et al., 2015; Biljecki et al., 2015a)), or as an improvement in accuracy over LOD1 (e.g. in energy demand estimation (Kaden and Kolbe, 2014)).

Stoter et al. (2014) recognise the ambiguity of roof overhangs in LOD2, i.e. whether they should be explicitly modelled or not, as overhangs may add value to certain use cases. The CityGML standard allows overhangs in LOD2 if known, but it does not require them (see again Fig. 2). This results in various LOD2 models with and without overhangs (for examples see Benner et al. (2010); SwissTopo (2014); Steinhage et al. (2010); Oude Elberink (2010); Leszek (2015); and Fan and Meng (2012); Van den Brink et al. (2013b); Kada and McKinley (2009); Schilling et al. (2012); Prechtel (2014); Schwalbe et al. (2005); Förstner (1999); Henn et al. (2013), respectively). Most of the models from national mapping agencies do not have explicitly modelled roof overhangs (Aringer and Roschlaub, 2014; Brasebin et al., 2012). LOD2 models with differentiated roof overhangs cost more to acquire since they generally require a combination of two acquisition techniques (airborne and terrestrial). When roof overhangs are not available, the walls are usually obtained as projections from the roof edges to the ground, inherently increasing the volume of the building (Biljecki et al., 2016).

A second ambiguity of LOD2 buildings are building installations such as dormers, and chimneys, which are allowed in LOD2, but they are rarely found in LOD2 models in practice. LOD2 models that contain building installations only include large features which considerably protrude the wall or roof structure (Gröger and Coors, 2011; Ben Fekih Fradj and Löwner, 2012; Vosselman and Dijkman, 2001). The German Federal 3D building modelling guideline (AdV, 2013) explicitly states that dormers and other objects of similar size should not be acquired. On the other hand, we have encountered LOD2 models which have dormers and other roof superstructures modelled, in academia (Buyuksalih et al., 2013), national mapping agencies (Kartverket, 2014; Stoter et al., 2015), and in municipal data sets (Döllner et al., 2006).

We have grouped the occurrences of LOD2 models into four LOD2 variants based on the aforementioned aspects:

- LOD2.0 is a coarse model with standard roof structures, and potentially including large building parts such as garages (larger than 4 m and 10 m^2).
- LOD2.1 is similar to LOD2.0 with the difference that it requires smaller building parts and extensions such as alcoves, large wall indentations, and external flues (larger than 2 m and 2 m^2) to be acquired as well. In comparison to the coarser counterpart, modelling such features in this LOD could benefit use cases such as estimation of the energy demand because the wall area is mapped more accurately.
- LOD2.2 follows the requirements of LOD2.0 and LOD2.1, with the addition of roof superstructures (larger than 2 m and 2 m^2) to be acquired. This applies mostly to dormers, but also to other significantly sized roof structures such as very large chimney constructions. Because the roof is mapped in more detail, this LOD can be advantageous for the estimation of the insolation of roofs (Biljecki et al., 2015a).
- LOD2.3 requires explicitly modelled roof overhangs if they are longer than 0.2 m, therefore the roof edge and the footprints are always at their actual location, which has advantages for use cases that require the volume of the building.

4.4.3 LOD3 family

LOD3 adds openings (i.e. windows, doors), balconies, more detailed roof structures (e.g. chimneys and antennas), and mandatory roof overhangs. This enhancement benefits some applications, for instance, openings are important for estimating heat losses (Lee et al., 2013), luminance mapping and glare analysis (Saran et al., 2015), planning energy-efficient retrofits (Previtali et al., 2014), and for accounting the area available on vertical walls for solar panel installation (Catita et al., 2014). LOD3 models are also appreciated in visualisation (Garnett and Freeburn, 2014).

The acquisition of LOD3 models is a laborious process (Buhur et al., 2009), hence they are in practice of limited availability, and are usually restricted to smaller areas. They are normally derived from terrestrial laser scanning (El Meouche et al., 2013; Akmalia et al., 2014), very dense airborne laser scanning (Truong-Hong and Laefer, 2015), their combination (Kedzierski and Fryskowska, 2014), from the conversion and generalisation from architecturally detailed models such as BIM (Donkers et al., 2015; Geiger et al., 2015; Isikdag and Zlatanova, 2009; de Laat and van Berlo, 2011) and CAD (Lewis and Séquin, 1998; Huang et al., 2008), from architectural plans (Yin et al., 2009), ground imagery (Xiao et al., 2009), and with procedural modelling (Goetz, 2013; Smelik et al., 2014; Martinović et al., 2015). Recent research in the acquisition of LOD3 models is focused to automatisation, especially automatic detection of windows and other façade details (Becker, 2009, 2011; Van Gool and Martinović, 2013).

LOD3 models are significantly more detailed than LOD2 models, and less ambiguity is present from the 3D GIS point of view (while it would be possible to nitpick among different variants of LOD3, they will hardly make any difference to spatial analyses). The only differentiation between LOD3 models we have detected is the minimum size of features that are acquired, especially whether the embrasures of openings are modelled or not. For instance, Besuievsky et al. (2014) create multiple variants of LOD3 models, one with flat windows, one with the embrasures, and a third with minor façade details. The finer two have the roughly the same size of linear features rendering their difference negligible from the GIS standpoint, hence, we merge them.

We define: LOD3.2, an architecturally detailed model that contains features of size larger than 1.0 m, and LOD3.3—one that contains features of size larger than 0.2 m, including embrasures of windows (i.e. making windows 3D), awnings and similar features of comparable size. The latter is beneficial over the former for high-quality visualisation and virtual reality applications (e.g. Portalés et al. (2010)), and it is usually a product of the conversion from BIM and architectural models.

However, we have encountered a number of models that cannot be fully accommodated in the traditional LODs, but are common in the acquisition workflows and which technically belong to LOD3. For instance, Franić et al. (2009) and Novaković (2011) create a model from an aerial survey with roof details finer than in LOD2.3, but with other features of lesser detail comparable to LOD2. We denote such models of mixed LODs (e.g. different LOD for *aerial* and *terrestrial* features) as *hybrid* LODs. Two such LODs that reflect the acquisition workflows have been defined, and to attempt to accommodate models of specific configurations. Because they both contain openings, we add them to the LOD3 group.

LOD3.0 is a model where roof structures are mapped in finer detail than LOD2.2, but other features such as walls are acquired as LOD2.2. Roofs may include roof windows. Windows of dormers do not have to be acquired.

LOD3.1 is its terrestrial counterpart, defined for terrestrial acquisition techniques, such as mobile mapping systems (Kaartinen et al., 2012). Since these techniques operate from the ground, roof features may be out of reach. Therefore this instance requires all features below roof to be acquired with the LOD3.2 grade, and the roof as LOD2.3, since overhangs may be explicitly modelled. This LOD is advantageous for use cases that require only the wall surface to be modelled in finer detail, such as estimating the solar potential of façades or for pedestrian navigation.

5 Proving the specification with geometric experiments

For the experiments, we have generated a CityGML data set of 100 buildings in the 16 LODs we propose. The data has been generated procedurally with a CityGML engine developed by Biljecki et al. (2014a), and it has been converted to the OBJ file format to broaden their usability. The

Table 1: Specification of the refined levels of detail fitting the current CityGML 2.0 LODs.

Requirements	Refined levels of detail															
	0.0	0.1	0.2	0.3	1.0	1.1	1.2	1.3	2.0	2.1	2.2	2.3	3.0	3.1	3.2	3.3
Individual buildings		●	●	●		●	●	●	●	●	●	●	●	●	●	●
Large building parts (>4 m, 10 m^2)		●	●	●		●	●	●	●	●	●	●	●	●	●	●
Small building parts, recesses and extensions (>2 m, 2 m^2)			●	●			●	●		●	●	●	●	●	●	●
Top surface(0)			S	M	S	S	S	M								
Explicit roof overhangs (if >0.2 m)												●		●	●	●
Roof superstructures(1) (larger than 2 m, 2 m^2)											●	●	●		●	●
Other roof details (e.g. chimneys >1 m)													●		●	●
Openings(2) (>1 m, 1 m^2)													R	W	●	●
Balconies (>1 m)														●	●	●
Embrasures, other façade and roof details, and smaller windows (>0.2 m)																●

(0) Applicable only to LOD0.y and LOD1.y: S—Single top surface; M—Multiple top surfaces if the difference in height of the extruded building elements is significant (larger than 2 m).

(1) It includes dormers and features of comparable size and importance (e.g. very large chimneys).

(2) R—only openings on roofs; W—only openings on walls. In R, openings on dormers are not required.

conversion was done with the tool CityGML2OBJs (Biljecki and Arroyo Ohori, 2015), and in the process the models were triangulated with Triangle (Shewchuk, 1996).

We have computed the following quantitative properties of the models: (1) average triangle count per building, akin to the computer graphics complexity metric; (2) total surface area; (3) area of the `WallSurface`; (4) volume of the corresponding solids; and (5) size in memory for each of the representations.

The results (2), (3), and (4) have been calculated as a sum for all buildings in the data set. Notice that these values are commonly used as a base in several spatial analyses. For instance, they are used in urban planning (Ahmed and Sekar, 2015), in the volumetric visibility analysis of urban environments (Fisher-Gewirtzman et al., 2013), energy estimations (Nouvel et al., 2013; Eicker et al., 2014), predicting thermal comfort (Chwieduk, 2009), predicting cooling requirements of buildings (Perez et al., 2013), in thermal simulations involving computational fluid dynamics (Hsieh et al., 2011; Maragkogiannis et al., 2014), in urban design evaluation (Yang et al., 2007), for calculating development densities (Meinel et al., 2009), and in investigating the urban heat island effect (van der Hoeven and Wandl, 2015).

The values are given in percentages of the absolute deviation from the results of the computations on LOD3.3, as the finest LOD in this series. The geometric computations were conducted with MeshLab* (Cignoni et al., 2008).

The used semantic levels in these representations are the standard ones in CityGML (e.g. see thematically differentiated surfaces for each LOD in the Figure 1).

The results are given in Table 2 and in Figure 4. They prove numerically that each of the representations is different from the others, and that it can be considered as a unique and standalone LOD, not only from the geometric aspect, but also from the pointview of a spatial analysis. From these results also the magnitude of the deviations within the same LOD family are evident (e.g. the volume the difference between two models within LOD2 may be 24%). The refined specification presented in this paper decreases such differences.

These experiments show the grouped results for all buildings in the data set, and are sufficient for the aim of this section. In future work on this matter we plan to conduct a detailed error propagation analysis for each of the representations (e.g. root mean square error and distributions of the deviations), and to relate it to particular use cases, such as energy demand estimation.

6 Conclusions and future work

The current LOD categorisation of CityGML has two shortcomings:

1. lack of a precise specification of each LOD; and that
2. the current five LODs are too generic and therefore they are not always capable to separate one LOD from the other (i.e. two significantly different levels of abstraction may still be considered as the same LOD as per the current specification).

The refined LODs that we have introduced are a result of a literature review, analysing acquisition workflows, and examining publicly available specifications. The specification is compliant with the existing LOD concept in the well established standard CityGML, hence, while improving the shortcomings of the current concept, the refined specification does not damage the commonly used five standard LODs—it is completely compatible with it. It is possible to determine the LOD of an existing data set, and to store in the documentation or metadata of the model (since

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*A tool developed with the support of the 3D-CoForm project.

Table 2: Results of the experiments with the models acquired in the refined levels of detail. The size of the test data set is 100 buildings. The geometric results of the area and volume computations are expressed as absolute deviations in percentages from the results of the computations on the LOD3.3 model.

Family	Characteristic	Refined level of detail			
LOD0		LOD0.0	LOD0.1(5)	LOD0.2(4,5)	LOD0.3(4,5)
	Triangles(1)	0.32	2.16	4.72	4.54
	Total surface area dev.	17.94	85.82	71.62	71.62
	`WallSurface` area dev.	(0)	(0)	(0)	(0)
	Volume dev.(2)	(0)	(0)	(0)	(0)
	Memory(3) [kB]	16	98	152	156
LOD1		LOD1.0	LOD1.1(4,5)	LOD1.2(4,5)	LOD1.3(4,5)
	Triangles(1)	1.92	12.64	13.44	13.44
	Total surface area dev.	214.49	7.45	7.59	7.29
	`WallSurface` area dev.	(0)	(0)	(0)	(0)
	Volume dev.(2)	784.40	23.36	23.43	22.94
	Memory(3) [kB]	45	283	291	291
LOD2		LOD2.0(5)	LOD2.1(5)	LOD2.2(5)	LOD2.3
	Triangles(1)	13.70	14.50	19.30	26.18
	Total surface area dev.	5.74	5.80	6.04	3.72
	`WallSurface` area dev.	17.41	17.47	17.90	7.51
	Volume dev.(2)	21.45	21.48	24.02	1.77
	Memory(3) [kB]	528	545	686	661
LOD3		LOD3.0(5)	LOD3.1	LOD3.2	LOD3.3
	Triangles(1)	26.22	302.58	317.50	596.30
	Total surface area dev.	6.07	3.72	3.45	0.00
	`WallSurface` area dev.	17.95	5.77	5.41	0.00
	Volume dev.(2)	21.55	1.84	0.70	0.00
	Memory(3) [kB]	808	4 242	4 554	11 775

(0) Computation not possible due to dimensionality and/or insufficient semantic level.

(1) Average number of triangles per building. The values of the aggregated LOD0.0 and LOD1.0 are low due to one block model covering multiple buildings.

(2) Volume of the solid representation. The deviation of LOD1.0 is high due to aggregation.

(3) For all buildings in the data set, without compression.

(4) The geometric reference of half of the roof was selected to represent the top of the LOD0 and LOD1 models, which is common in the reconstruction of buildings from point clouds.

(5) For these representations the geometric reference for the walls are projections from roof edges, as it is common in airborne acquisition techniques.

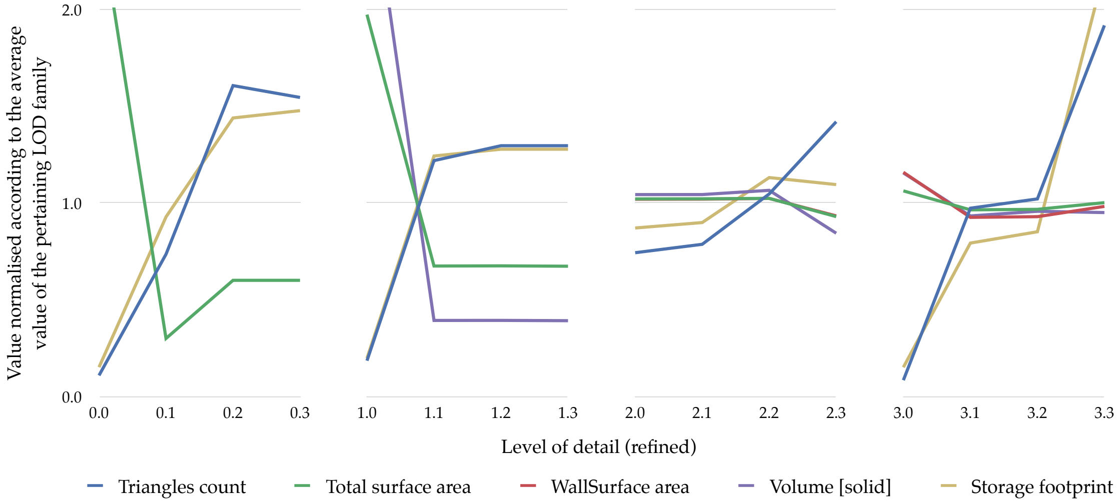

Figure 4: Graphical depiction of the results of the experiments. The newly defined 16 levels of detail are examined from five numerical aspects. The values are normalised according to the average value in the corresponding LOD family, and it proves that each LOD is unique. Furthermore, these values expose the fundamental problem with the CityGML LODs: due to their insufficient number, the relative differences of the models within each family may be significant, e.g. for the total surface area the difference between two models within LOD3 may be 6%, which may cause discrepancies in spatial analyses. Our paper refines the LODs to diminish the ambiguity and alleviate potential misunderstandings between stakeholders.

CityGML 2.0 does not support storing such information). However, we foresee that our specification may be integrated as a user defined profile in the upcoming CityGML 3.0, where a generic LOD framework is planned (Löwner and Gröger, 2016).

We have covered the vast majority of cases we have found in practice, and while further differentiations are possible, we believe that it is not beneficial to define more than 16 LODs. The extended specification is simple and it is intended to be of special interest to the data producers, addressing their critic of ambiguity that the current LODs present. Most importantly, not much modelling freedom is allowed anymore, diminishing potential misunderstandings between 3D stakeholders and potential errors in the usability of the models.

As much as the current LODs of CityGML 2.0 are used outside the CityGML format, these improved LODs may also be considered as independent of CityGML, and applicable to any other 3D format or context. For instance, they may become an important factor in contracting the data acquisition, and as a more precise paradigm to express and benchmark the capabilities of a 3D city model reconstruction technique. Furthermore, practitioners can find them useful to better define their product portfolios, and national mapping agencies to implement them in their specifications. The classification has already been adopted by the EuroSDR 3D Special Interest Group (SIG) as a base for a forthcoming European standard for national mapping in 3D. Finally, researchers can find them useful to unambiguously express the level of detail of models they are analysing, primarily in work on generalisation and 3D use cases.

We have reinforced our solution by running the data sets through a few 3D GIS operations, which yield different results for each, showing that the variants may be considered as standalone LODs. In addition, the significant difference between different LODs of the same LOD family shows how important it is to further differentiate LODs and to specify these differentiations. While the new LODs are defined in a more precise way, allowing significantly less ambiguity, they still permit a degree of flexibility allowing additional requirements driven by use cases, following the reasoning of Stoter et al. (2014).

We have covered buildings as the most important and most modelled features of the urban environment. For future work, we plan to work on the other thematic modules. Furthermore, we plan to investigate how to automatically validate whether a data set is modelled according to a certain LOD, and we intend to conduct detailed experiments of the performance of each LOD in a particular use case, aiding the practitioners to choose the optimal LOD for a use case when also considering the costs of the acquisition. Experiments carried out in Section 5 are the first step towards such research.

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