Height references of CityGML LOD1 buildings and their influence on applications

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Abstract

The geometry of the LOD1 block model of CityGML may be represented in a multitude of valid variants, e.g. it may represent individual buildings or aggregated blocks. The geometric representations within each of these, such as the reference of the footprint of a building, are not standardised in CityGML and are not informed in the metadata. The lack of knowledge of the used representation may possibly cause errors when the models are used for spatial analysis. Further, the effect of using different variants is not investigated. In this paper we (1) discuss this known, but frequently overlooked topic; (2) overview the possible geometric references and show how employing them may cause drastic differences for a GIS operation and/or use-case; (3) focus on the vertical (height) references for the top surface in LOD1, and show how to determine the optimal variant within a use-case with experiments using the Monte Carlo method; and (4) discuss the adoption and extension of metadata in INSPIRE to CityGML to reflect the employed geometric reference.

Keywords: Level of detail, LOD1, Geometric references, INSPIRE, CityGML

1 Introduction

The level of detail (LOD) concept of the Open Geospatial Consortium (OGC) standard CityGML provides guidelines about the acquisition of buildings and other real-world phenomena [34]. The five defined LODs describe a model's complexity and the spatio-semantic coherence that should be achieved in each [27].

The coarsest volumetric representation that the standard contains is the LOD1 model, which is described as "the well-known blocks model comprising prismatic buildings with flat roof structures" [34]. A further clarification is presented by Gröger and Plümer [17]: "In LOD1 volume objects (buildings, vegetation objects, etc.) are modelled in a generalised way as prismatic block models with vertical walls and horizontal 'roofs'".

The block models are usually acquired with extrusion from 2D footprints in combination with points acquired with airborne laser scanning [28], and generalisation from finer LODs [3], for instance, as a bounding box of an LOD2 [11, 12], or of an LOD3 including features such as antennas on roofs [32]. CityGML defines the LOD1 representation for thematic classes such as tunnels and bridges, but in practice it is used only for buildings, hence, this paper is focused on them.

Since LOD1 models are relatively inexpensive to acquire and are not complex, they are ubiquitous, representing a large share of 3D models worldwide [33]. While they are the coarsest volumetric model defined by CityGML, LOD1 models may be very accurate and they find their use in a number of applications [9]. For instance, they have been extensively used in the analysis of the traffic noise for assessing the effect on the quality of life and for the placement of noise barriers [10, 39], in shadow analysis in areas with predominantly flat roofs [41], heat energy demand modelling [2], real estate mass valuation in the urban areas [43], and estimation of the population in a given area [23]. Further, LOD1 models are useful in enhancing the visual representation of other data,

such as in the 3D visualisation of air quality data [40]. For other visualisation applications, such as the visual enhancement of navigation, LOD1 models containing individual buildings are deemed too complex, so they have to be further generalised [16].

The LOD1 model contains no semantics on constituting geometries, and its geometric representation is realised by a `gml:Solid` and/or a `gml:MultiSurface` [30]. This means that LOD1 is the only volumetric model in CityGML where the semantics is out of focus. Taking into account the above, the LOD1 model represents a favourable ratio between the costs and possible uses, being the main factor contributing to their popularity.

However, since the LOD concept of CityGML, besides a narrative description, does not provide specifications and instructions how to geometrically model the features [6], this results in multiple different models being considered legal variants of the same LOD (see [4] for examples).

This also affects the LOD1 model. While being a rough and fairly simple model without semantics, it encompasses a myriad of possibilities how to model its geometry.

The ambiguities caused by the standard may lead to misunderstandings between stakeholders and to the misutilisation of 3D models. Despite being of the same LOD, the geometry of two models acquired with different practices may considerably deviate from each other, potentially leading to errors in the use of the data if such metadata is not known and/or it is not regarded.

It is our experience that most of the ambiguities are caused by the following: (1) the varying reference point for the elevation of the horizontal top surface of the LOD1 block model (see Fig. 1); and (2) are the vertical surfaces (i.e. walls) captured at the footprint of the building or as the projection of the roof edges. The latter is also an ambiguity for LOD2 models.

These different practices, which we name geometric references, have not been much researched. They may also be available under different terms, such as modelling choices [8].

This paper focuses on the geometric reference of representing the height of the block model in LOD1. This topic is important because LOD1 is used widely and it finds its purpose in a number of applications, as shown above. In Sec. 2 we list the frequently used references for the top surface of an LOD1 block model, and relate them to the INSPIRE Data Specification on Buildings [23, 18], which provides a list of references that we further refine to reflect the current practices of the data producers.

We show the importance of this topic by determining the effect of employing different variants to the result of a GIS operation, and how to determine what is the optimal geometric representation with respect a GIS operation and/or use-case. In this process we demonstrate with examples that the differences between the variants may have a drastic influence on the result of an operation (Sec. 3). This is achieved with a Monte Carlo simulation by generating multiple CityGML models of a large number of buildings, and by comparing the results of the computations of volumes of buildings. This is a prominent 3D GIS operation being used in a number of use-cases, such as energy demand estimation [2].

We argue that the LOD concept should continue following the current practices and allow flexibility with the geometric references in each LOD, however, it is something that should be noted in the

Figure 1: A building represented using different geometric representations in LOD1 (orthographic rendering to preserve the dimensions). All of them are valid according to the CityGML standard. The difference between the resulting geometric representations is significant.

metadata, which explicitly explain how the geometries have to be interpreted. Because CityGML does not provide such, we work towards implementing the metadata for the geometric references in it (Sec. 4).

2 Background and context

2.1 Geometric LOD1 variants

Notwithstanding its relative simplicity, an LOD1 model has a multitude of valid geometric representations. For instance, LOD1 may represent individual buildings, but also multiple buildings that are aggregated in blocks [19]. Within each of these, there may be a number of possible variants. On one hand, the bases of the blocks may not necessarily be only rectangular, but they may represent finer footprints. On the other hand, an LOD1 model may contain differentiated flat roof tops, rather than a single top surface [20, 22]. Further, the top surface of the block model may represent a number of different references, depending on the height that was determined as the reference value, e.g. height at the roof edges or height at the half point of the roof. Multiplying the different categories, it is easy to count over a few dozen variants of LOD1, many of them occurring in practice.

The variants can be grouped into two categories: LOD-based, and reference-based. The first group covers the fineness of the representation, i.e. a model of an individual building with differentiated roof tops is finer than a model with a single top surface. Because CityGML is not precise enough with defining the LODs, these variants are considered of the same LOD by the standard, which may be disputed from the computer graphics perspective. The latter group refers to the reference of the features, i.e. what does the position of the top surface represent. This paper focuses on the latter.

Fig. 1 shows seven LOD1 block models of an individual building generated according to different references for the height of the top surface, which we will discuss later in the paper. The centre of the Figure shows the model in higher detail (LOD3) as a reference, with the overlapped top surfaces for comparison. It is obvious that the difference between the geometry of the models may be significant. However, CityGML does not provide metadata for expressing such variants, and in practice for many datasets the used geometric reference is not known.

2.2 INSPIRE Building Model references

The INSPIRE initiative's document Data Specification on Buildings—Technical Guidelines presents spatial data specification for European data related to the theme "Buildings" [23]. The document covers both 2D and 3D representations, and gives a focus on the different concepts of footprint and elevation for buildings, representing a good foundation for this paper. It provides a (code) list and definition of several elevation references of buildings that may serve both as attributes and descriptors of the geometric representation. These references are represented by a value type `ElevationReferenceValue`, i.e. a list of self-explanatory elements considered to capture a vertical geometry. The list contains not only elements that represent higher points of a building, but also lower points such as the elevation at the entrance point to the building, and the bottom of the construction.

These values are primarily intended as attributes of objects regardless of their geometry. However, for the 3D representation in LOD1, the standard mandates that the level of a building that was chosen to represent its top has to be documented. This is realised through the attribute `vertical-GeometryReference3DTop`, and preferably using the following values of the subset of all values from the above introduced code list `ElevationReferenceValue`, namely: `generalRoofEdge`, `lowestRoofEdge`, `highestRoofEdge`, `lowestEave`, `generalEave`, `highestEave`, `generalRoof`, and `topOfConstruction`. The list is extensive by also taking into account less common cases, for instance, the case where the height of the eaves is not equal (e.g. the eaves on one side of the building are higher than the eaves on the other side). On the other hand, the value `generalRoof` is somewhat ambiguous because it may refer to any point on the roof surface.

For most of the buildings, many values are equal and may be considered as identical. For instance, in reality `lowestEave` is usually equal to `highestEave`, and all-together they correspond to `generalEave`.

While the standard recommends the above listed values as the references for the top surface in LOD1, we do not believe that this list is complete. For instance, another relevant value may be `highestPoint`, the height level that includes non-roof elements such as chimney and antennas,

and that is frequent in generalisation. This level is a possible value in the code list `ElevationReferenceValue`, but for some reason it is not listed as a recommended value for `verticalGeometryReference3DTop`.

The second relevant concept is the footprint, which is also covered by the INSPIRE Building model. The reference for the geometry of the footprint is expressed through the `HorizontalGeometryReferenceValue`, with possible values such as `footPrint` and `roofEdge`. The reference may be used for both LOD1 and LOD2 models.

2.3 Overview of frequently used references for the top of the block model

In this Section we focus on the reference of the height of the top surface of a building, partly based on the INSPIRE Building model presented in the previous Section. It is our experience that this is the variable that causes most of the ambiguity in CityGML, and may cause significant errors in the utilisation of the models if not regarded.

While INSPIRE provides an extensive list of geometric references for the top surface of the building in an LOD1 block model, we have thoroughly researched are there other values occuring in practice. We did this by examining papers that deal with the production of LOD1 [13, 35, 36, 42], and by contacting a few producers of 3D models. We have found additional values that require extending the references in the INSPIRE Building model, and this research also gave us insights for understanding the source of the different variants.

In airborne laser scanning and photogrammetry, the building's height is usually taken from the median height of the points positioned within the footprint of a building (in most cases it roughly corresponds to the half of the height of the roof), but we have also encountered other values such as one third or two thirds of the height of the roof.

In the extrusion from footprints according to attribute values, some practitioners extrude the footprint to the height in an attribute from OpenStreetMap [15], number of floors [37], or the height available in the cadastral records [21]. For many of these the lineage of the data is not known, propagating to the uncertainty of the height of the generated block model. However, in some cases this height may represent the height at the roof eaves, a value which cannot be acquired from airborne platforms because it is usually obscured.

In the generalisation from finer LODs, the block model is usually derived as a 3D bounding box of the fine LOD [12, 32]. Depending on the starting LOD, this means that in most of the cases the top surface represents either the top of the roof or the highest point of the building, including features such as chimneys, air conditioning units, and antennas. These possibilities are already known from the INSPIRE Building model, however, it shows that even within generalisation, there is no standard variant that is used.

Here we list seven frequent references for the elevation of the top surface of the LOD1 model of individual buildings, obtained from the INSPIRE Building model and our own research. These references are identical to the ones in Fig. 1, observed in the counter-clockwise manner from the

right side of the LOD3 model. For each height reference we assign an internal shorthand for easier referencing in the text.

H0 Height at the roof edges. Because of the roof overhangs, roof edges may have an elevation that is lower than the one of the highest point of the walls, hence this is the lowest possible reference of the top surface.

H1 Height at the roof eaves. This value is typical for terrestrial measurements, as it is usually not visible for airborne acquisition techniques. It may correspond to the reference H0 in the case when there are no roof overhangs.

H2 Height at one third of the height of the roof. The height of the roof may be somewhat ambiguous, depending on the lowest reference of the roof. For instance, if the roof is considered to start at H0 or H1. In this case we consider the total height (from the point H0).

H3 Height at half of the height of the roof. This reference is related to the extrusion coupled with LiDAR point clouds, where it is typical to use the median value of the height of the points within a footprint [28].

H4 Height at two thirds of the height of the roof. This is a case that we have encountered with a 3D GIS company, and it can also be related to the extrusion where superstructures such as dormers and chimneys are present because they elevate the median of the height of the roof points.

H5 Height at the top of the roof. This is a value typical for generalisation from LOD2. It can also be derived from point clouds if necessary.

H6 Height at the top of the construction of the building. This height encompasses the whole construction, and it is usually used with generalisation from LOD3. In case there are no superstructures that extend beyond the top of the roof, the value corresponds to H5.

Each of these find use in specific applications. For instance, in the case H1 the model retains the walls and the building body, but it may completely disregard the roof structure. This may be useful in applications where the roof is not important. Models constructed by abiding by references H5 and H6 may be good in analyses such as visibility [43, 44], but having little value in other applications such as calculating the surface area of walls for marketing purposes [1].

The seven reference heights have been related to the INSPIRE's in Tab. 1. The Table also includes our additions that are not present in INSPIRE, hence, we extend the INSPIRE's references reflecting the additional possibilities, and introduce provisional notations for the new references.

3 Experiments with volumes of LOD1 buildings

In the previous sections we have argued that the selection and employment of different modelling variants has a direct effect on the results of a (3D) GIS operation, and that generally there is no good

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Table 1: List of representations for the height of the top surface of the LOD1 block model. The equal sign means that the reference is re-used from INSPIRE.

Code (§2.3)	Height at	INSPIRE reference	Our reference
H0	Roof edges	`generalRoofEdge`	=
H1	Roof eaves	`generalEave`	=
H2	One third of the roof height	`generalRoof`	`oneThirdRoof`
H3	Half of the roof height	`generalRoof`	`halfRoof`
H4	Two thirds of the roof height	`generalRoof`	`twoThirdRoof`
H5	Top of the roof	`topOfConstruction`	=
H6	Highest point of the building	`highestPoint`	=

or bad modelling variant because they are all valid within the present CityGML LOD concept and the INSPIRE Building model.

The goal of this section is twofold. First, we introduce a method that determines which is the most suitable geometric representation with respect to a GIS operation, or a set of operations (i.e. use-case). Second, by realising the method with a GIS operation we prove the claim that different geometric variants within LOD1 may have a drastic impact on the result of a GIS operation.

We discuss the operation of the computation of volumes of buildings, which is essential in use-cases such as energy demand estimation [25, 38], determination of property taxes [7], estimation of the population in a given area [23], and in the volumetric visibility analysis of urban environments [14]. We compute the results on the seven variants of LOD1 listed in Tab. 1, and compare the results to the computations on LOD3 models, which for this purpose we consider as ground truth.

3.1 Methodology

The method that we introduce consists of four steps, which are explained below in more detail.

1. *Defining the geometric references.*
   First the method requires to list and define possible geometric variants within an LOD. This is explained in the previous Section. However, the selection of the references to be considered is related to the producers and users, because in some occasions not all representations are available. For instance, in the case where only airborne measurements are possible, the reference H1 (`generalEave`) is not obtainable and it should not be taken into consideration for the analysis and experiments.

2. *Randomisation of buildings.*
   In this step we generate a large number of different models in the selected geometric variants in a Monte Carlo simulation. Because every building is different, experiments that consider

a large number of buildings are required. For instance, an LOD1-H6 representation is different in the case of a building with a chimney, and another building of same dimensions without a chimney. We have developed a method and implemented it in a software prototype that generates random buildings, and their creation in CityGML in multiple LODs and geometric representations. The method, which we have recently introduced in [5], is based on the Monte Carlo method [26] and serves for generating a large number of dissimilar scenarios. The buildings are generated in an automatic and random process where a large number of building parameters, such as building height, size of chimneys, length of roof overhangs, are randomly sampled from a uniform probability distribution function. We support four most common roof types: gabled, flat, shed, and hipped [24]. Each of these has different reference points when it comes to the top of LOD1, so it is important to include more than one roof type. The datasets that were generated for this purpose are described in Sec. 3.2 in more details.

3. *Perform the GIS operation on all instances and on the ground truth.*
First, for each representation r, the volume of a building b is calculated: V_r^b. Second, for each building, its ground truth V_{gt}^b is computed. We have implemented this in the Feature Manipulation Engine (FME) by Safe Software Inc.

4. *Evaluation of the differences.*
In this step we compare the results and compute the errors. This part is more related to the used GIS operation, and the used values may depend on it. For each building b, and for each of the used representations, the error in the volume is calculated, along with the relative error:

$$\epsilon_r^b = V_r^b - V_{gt}^b, \qquad \mu_r^b = \frac{V_r^b - V_{gt}^b}{V_{gt}^b} = \frac{\epsilon_r^b}{V_{gt}^b}$$

The relative error may be a useful indicator to assess the discrepancies because it gives the relative difference between the results, which may be more relevant in the context of a certain use-case since it does not depend on the size of a building. Afterwards, for each of the geometric references two root mean square error (RMSE) values are computed:

$$\text{RMSE}_{\epsilon_r} = \sqrt{\frac{\sum_{b=1}^n \left(\epsilon_r^b\right)^2}{n}}, \qquad \text{RMSE}_{\mu_r} = \sqrt{\frac{\sum_{b=1}^n \left(\mu_r^b\right)^2}{n}}$$

where n is the number of buildings. As another error metric, we sum the volumes of all buildings for each representation ($\sum_b^n V_r^b$), and compare them to the ground truth ($\sum_b^n V_{gt}^b$) by computing their ratio.

The presented methodology is focused towards the computation of volumes for buildings, but it can be applied to virtually any other (3D) GIS operation.
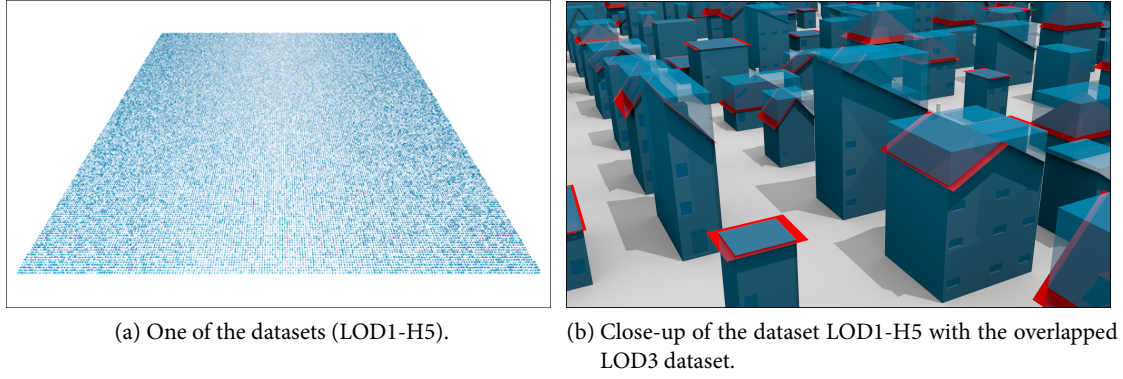
(a) One of the datasets (LOD1-H5).

(b) Close-up of the dataset LOD1-H5 with the overlapped LOD3 dataset.

Figure 2: Visualisation of the datasets generated with our engine "Random3Dcity".

3.2 Datasets

We have generated 40 000 buildings with our software prototype "Random3Dcity", and represented them in seven LOD1 CityGML datasets, one for each of the geometric variants described in Sec. 2 and Tab. 1. Further, a detailed LOD3 model has been generated as the *ground truth* model for which the reference volume can be calculated. Because this dataset is synthetic and it is generated from a set of known building parameters, we may consider the LOD3 model as the exact representation and therefore use it as a reference value. The buildings being randomly generated, means that there are no two buildings that are the same, and it makes our method statistically unbiased.

Figure 2 shows the visualisation of the randomly generated datasets. In Fig. 2a the whole extent of the dataset LOD1-H5 is shown (in a grid of 200×200 buildings), while the Fig. 2b shows a close-up with two datasets: the LOD3 and the LOD1-H5. In the latter figure, since the top surface of LOD1 represents the top of the roof, notice that some of the chimneys of the LOD3 model protrude the block model.

The magnitude of $n = 40\,000$ was determined by running the algorithms multiple times. With this value, the discrepancies between instances were negligible.

3.3 Results and their interpretation

We present the results of the computation of volumes in Tab. 2 and in Fig. 3. It can be seen that the LOD1 generated when taking the reference H3 for the height of the top surface, causes the smallest errors in the computation of volumes, therefore we can conclude that is the most suitable for this operation. The errors caused by other references may be too significant for a number of use-cases, raising the importance of the awareness of the used reference.

The small difference in error between the references H5 and H6 may be attributed to the fact that not all buildings have chimneys and other superstructures that are higher than the top of the roof, and

Table 2: Results of the simulation for the volume computation (n = 40 000). The footprint represents the actual position of walls (comparable to the footprint obtained from cadastral sources). We have also computed the data for the ground truth for self-validation purposes.

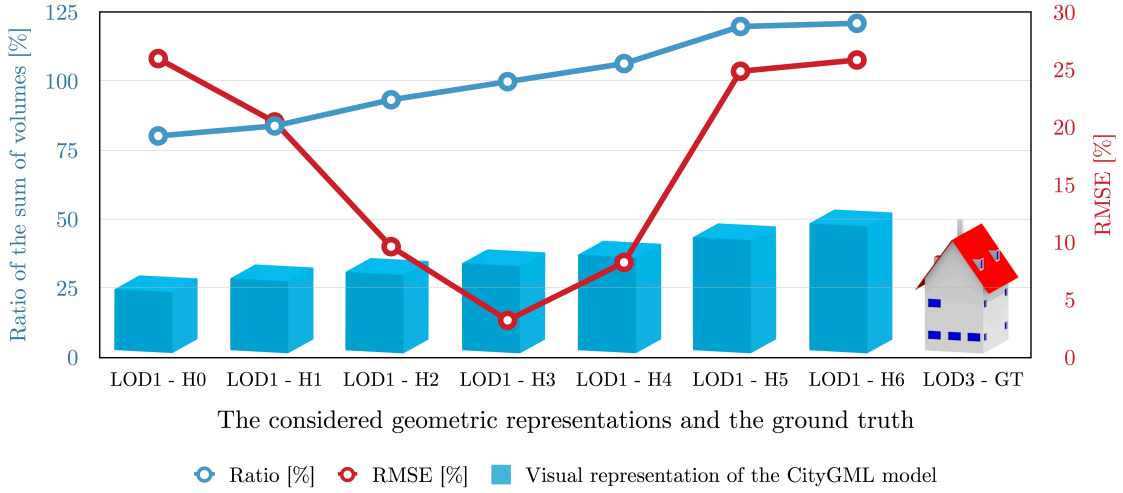| Model (LOD and top reference)	RMSE [m^3]	RMSE [%]	$\sum V_r$ [m^3]	$\sum V_r / \sum V_{gt}$ [%]
LOD1 - H0	82.56	25.95	10 109 678.38	80.11
LOD1 - H1	67.95	20.44	10 568 599.85	83.74
LOD1 - H2	29.70	9.60	11 764 718.94	93.22
LOD1 - H3	8.89	3.20	12 592 239.21	99.78
LOD1 - H4	26.80	8.23	13 419 759.49	106.33
LOD1 - H5	81.35	24.85	15 115 676.86	119.77
LOD1 - H6	85.87	25.83	15 261 200.42	120.92
LOD3 (ground truth)	0.00	0.00	12 620 500.20	100.00

Figure 3: Results of the computation of volumes with the errors depending on the used geometric representation.

when they have, in many cases they rather insignificantly increase the height of the block model, leading to a relatively small increase in the volume.

In Fig. 4 we focus on the distribution of individual errors of the volumes within a reference for the better understanding of the deviations. This is conveyed with the histograms of relative errors and it is expressed in percentages. Fig. 4a shows the distribution for H3. The peak at 0 can be explained by the presence of flat roofs, which is the optimal case for this reference. In Fig. 4b the distribution for H5 is shown, and again a favourable peak at 0 caused by flat roofs is present, but on the right side it also shows the distribution of deviations of non-flat roofs. This difference is particularly manifested in shed roofs because of the higher overhangs.
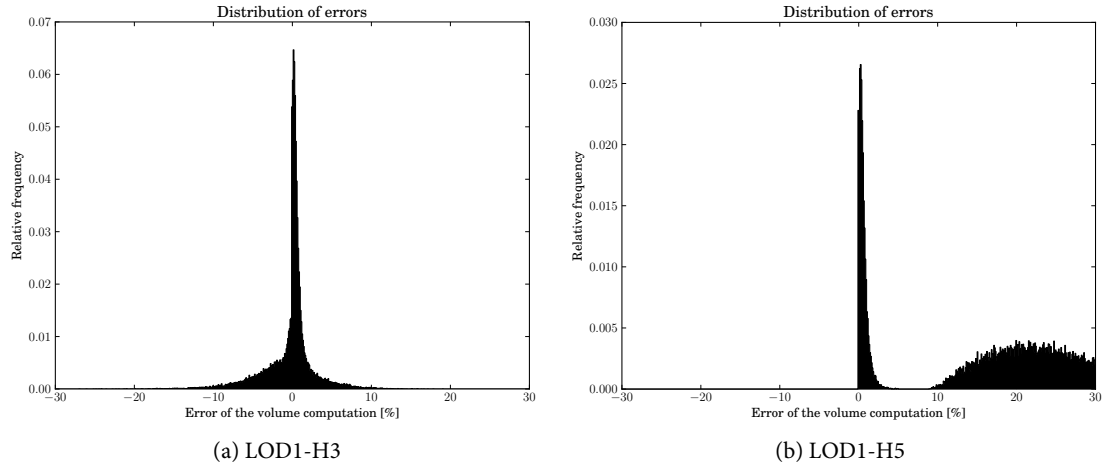
(a) LOD1-H3   (b) LOD1-H5

Figure 4: Histogram of the relative errors (μ_r) in the computation of volumes comparing to the ground truth for two references.

4 CityGML implementation

In a recent paper describing the aforementioned interoperable building model of the European Union, Gröger and Plümer [18] state the possibility of introducing the metadata of the geometric representations to CityGML. In this Section we follow their conclusion, and we investigate a possible way to implement the metadata which denote the reference for the elevation of the top surface in LOD1, and also the reference for the horizontal footprint.

The INSPIRE building data specification provides a CityGML Application Domain Extension (ADE) for the Core 3D profile of the INSPIRE building model, but it might be desirable to encode this information in the core of CityGML.

Fig. 5a shows a possible solution through a UML extension of the CityGML data type by adding the attributes describing the references. This solution is strongly influenced by the INSPIRE Data Specification on Buildings, potentially resulting in interoperability. In Fig. 5b we show the implementation by hard-coding the extension as attributes of the tag of the LOD1 geometric representation.

In this way, the reference applies to all features within a representation. An alternative would be to attach the metadata to each feature separately, however, we do not expect cases of mixing different variants between features within the same dataset to be occurring in practice.

This introductory work is a first step towards the implementation, and therefore it leaves open questions for discussion and future work. For instance, a matter not regarded by INSPIRE is the cardinality between LODs and their geometric references, i.e. should CityGML enable the representation of two equal LODs with different variants. This is currently not possible because of the

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+ lod1geometry: BuildingGeometryLOD1

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+ verticalGeometryReference3DTop

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(a) UML diagram.

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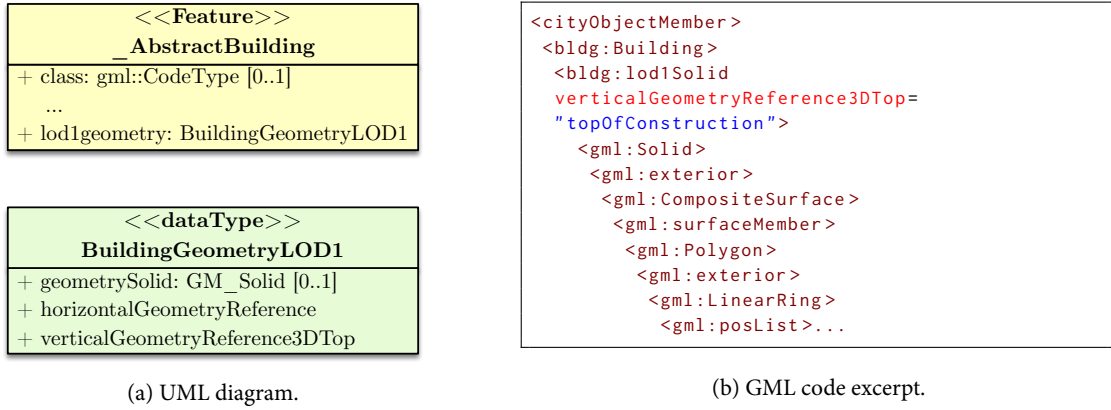
(b) GML code excerpt.

Figure 5: Implementation of the horizontal and vertical geometric references for the LOD1 model in CityGML.

1:1 relation between the building feature and its LOD*x* geometry. While this may not be frequent and not feasible, it might be an interesting point of discussion.

5 Conclusions

In this paper we have thoroughly examined the ubiquitous LOD1 block model, and we have focused on the geometric reference for the height of the top surface, as its most prominent ambiguity. We have shown that, while LOD1 is the simplest volumetric form in CityGML, it is surrounded by potential ambiguities because its geometry may be modelled in many variants. This is caused by the shortcoming of the standard when it comes to describing the multiple geometric representations, and because it is not possible to store such information in the metadata. Since the LOD concept of CityGML is intended to reflect the spatio-semantic complexity of a model, the geometric references are not related to the level of detail, and they are rather a closely related category of metadata, that it is important to note because it may influence all downstream applications.

Our contribution is that we have stressed this topic, we have shown with experiments the potentially drastic difference between the variants with respect to a GIS operation (volume computation), and we have explained how to determine the optimal reference with respect an operation. We have discovered in a simulation that, when using block models in the computation of volumes, the variant where the top represents the half of the roof height is the most suitable variant. The framework that we present can be used for determining the best variant in other GIS operations.

We propose adding metadata to CityGML, and we have shown a provisional solution, which may be relevant for the developers of the next version of the standard (v. 3.0 due in 2016; see [29, 31]). Further, we have refined the INSPIRE building model's reference `generalRoof` with three new references, that are especially relevant for extrusion to point clouds, the frequent method for generating LOD1 models.

For future work we plan to simulate a point cloud from a LiDAR survey to find the exact roof median as an alternative to the half of the roof (point H3), to extend this work to LOD2 and the varying representations of the footprints, and to involve more GIS operations and use-cases.

Acknowledgements

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