An application-driven LOD modeling paradigm for 3D building models

Lei Tang[a,e], Shen Ying[a,b,e,*], Lin Li[a,c,*], Filip Biljecki[d], Haihong Zhu[a], Yi Zhu[f], Fan Yang[a], Fei Su[a]

[a] *School of Resource and Environmental Sciences (SRES), Wuhan University, 129 Luoyu Rd., Wuhan 430079, China*
[b] *The Key Laboratory for Geographical Information Systems, Ministry of Education, 129 Luoyu Rd., Wuhan 430079, China*
[c] *SRES-Institute of Smart Perception and Intelligent Computing, Wuhan University, 129 Luoyu Rd., Wuhan 430079, China*
[d] *Urban Analytics Lab, National University of Singapore, 4 Architecture Dr., Singapore 117566, Singapore*
[e] *Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Land and Resources,8007 Hongli West Rd., Shenzhen 518034, China*
[f] *Chinese Academy of Surveying & Mapping, 28 Lianhuachi West Rd., Beijing 100830, China*

Abstract

The level of detail (LOD) concept for 3D building models, which indicates the degree of closeness between a model and its real-world counterpart, is deeply rooted among the stakeholders in the field of urban research and 3D geoinformation. However, with the increasing use and demand of a wide range of applications, the LOD definition standardized by the City Geography Markup Language (CityGML) standard appears to be generic, potentially resulting in redundancy and inflexibility. To address this issue, we reconsider the LOD concept from an application point of view and suggest a new context-aware heterogeneous LOD modeling paradigm for 3D building models tailored to specific applications. The new proposal challenges the original homogeneous generic modeling logic and instead adopts a bottom-up approach, putting the focus on the building components rather than on the building itself, resulting in models that may lead to a better fitness for use. In this paper, we first specify a number of discrete LODs for building component models, called CLODs, and then assemble them to derive the LODs of building models suited for particular applications, diminishing redundancy and being tailored for a specific application. To obtain the appropriate LOD specification, we introduce five essential evaluation criteria and a series of semantic and geometrically assembled constraints on the CLODs. We implement two experiments, outdoor component selection and indoor furniture simulation, and conclude that the proposed application-driven LOD definition is more suited in the context of particular applications.

Keywords: Level of detail, 3D building models, Application-driven, Building components, Granularity

1. Introduction

Given a choice of multiple 3D building models with the same spatial extent for carrying out simulations, the most detailed dataset is not necessarily the most optimal dataset. In addition to the degree of detail, factors pertaining to a particular use case context, such as accuracy, lineage, economy, efficiency, and non-redundancy, should also be considered. That is the principal motivation of the proposal [1] for the level of detail (LOD) concept initially developed for computer graphics and the reasons why it is unlikely to fade away in the future.

During the development of LOD theories in computer graphics, four main types of frameworks have emerged: discrete LOD, continuous LOD, view-dependent LOD and hierarchical LOD [2]. The last three frameworks are tailored for run-time rendering, but the discrete LOD framework requires a preprocessing stage to create individual LOD models [3]. Several advantages of discrete LOD were expressed by Heok and Daman [2]; faster rendering

*Corresponding author

Email addresses: leitang@whu.edu.cn (Lei Tang), shy@whu.edu.cn (Shen Ying), lilin@whu.edu.cn (Lin Li), filip@nus.edu.sg (Filip Biljecki), hhzhu@whu.edu.cn (Haihong Zhu), zhuyi@casm.ac.cn (Yi Zhu), yhlx125@163.com (Fan Yang), sftx016@whu.edu.cn (Fei Su)

speed is the most prominent advantage, and it is based on defining some specific selection criteria for picking the most suitable predefined LOD models. However, regarding the definition of discrete LOD, while no official uniform declaration exists to date, there is a widely recognized approach in the GIS research community—that is, a similar concept that uses the well-known term scale. For example, Meng and Forberg [4] mentioned LOD as one of a number of milestones along the scale space when taking the scale space of 3D buildings as a linear continuum. Goetz [5] indicated that LODs are multiscale models that can reflect a variety of perspective, from global and coarse to fine-grained and detailed. According to Biljecki et al. [6] LOD is a concept that conveys both a model's complexity and its degree of abstraction from the real world but is distinct from concepts of accuracy and quality. Even so, it could not be claimed that the two concepts are always equal, since the connotation of LOD for a 3D model is not only confined to differing geometry but also differing in its semantics, appearance and even properties. Thus, it is not easy to specify a universal and persuasive series of LODs such as scale milestones to meet different requirements for urban simulation applications.

Among various proposals, the LOD concept of the OGC standard CityGML 2.0 [7] has been widely applied by stakeholders in both academia and industry. Five well-defined consecutive LODs are described for city objects at different geometric and semantic degrees of complexity [8]. A building model can be represented as a 2.5D polygon of the footprint or roof edge at the coarsest level (LOD0) or as a well-known prismatic block with flat roof structures (LOD1). In LOD2, a building model has thematically differentiated boundary surfaces and generalized roof structures, as well as optionally simplified additional installations (e.g., balcony and dormer) [9]. LOD3 provides a more detailed outer façade, potentially including windows and doors. Until now, the LODs above have denoted four architectural exterior forms that have been applied to various analyses in traditional Macro-GIS fields such as flood inundation and noise pollution. To address indoor scene applications, the last level, LOD4, completes the building model by adding interior structures to LOD3.

Because of the five fixed levels, freedom to configure the models has also been reduced; the standard LOD specification for 3D building models is inflexible to some extent [11–13]. In other words, the specification is designed for general purpose (application-independent without a particular use case in mind). While technically the LODs can be used for most applications,

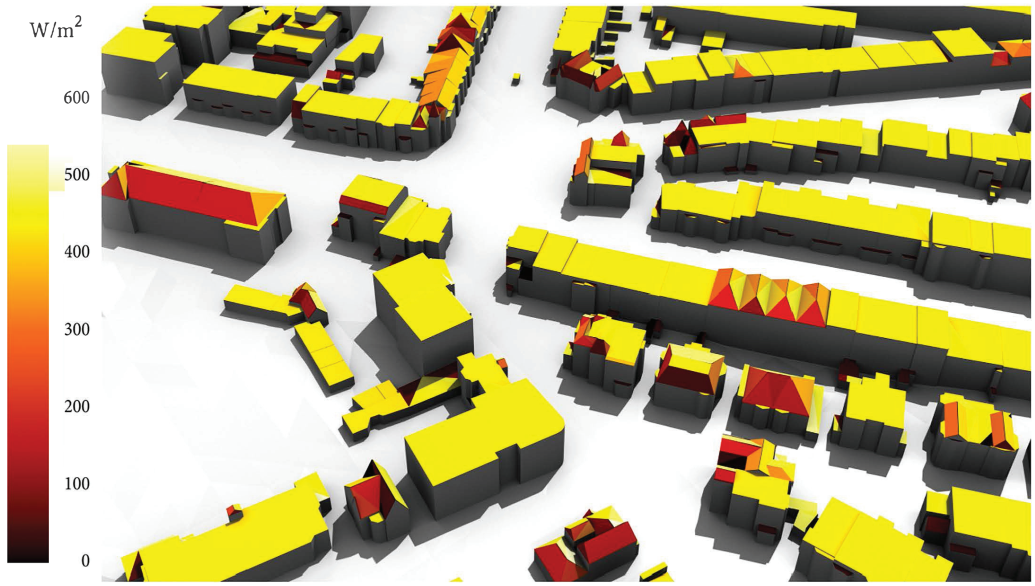


Figure 1: Estimation of rooftop solar exposure, a prominent application of 3D city models used to estimate the feasibility of the installation of solar panels (Source: [10]).

the efficiency of doing so is debatable, due to the homogeneity of the LOD: some portions of the dataset might be unnecessarily inappropriate for some applications (either too detailed increasing costs and hindering the performance of spatial analyses, or insufficiently detailed inhibiting the reliability of use cases). The premise of this paper is that from the perspective of an application, practitioners may prefer to focus on the features they need, so the level of the focus and context [14] do not have to be same or similar throughout the dataset. For example, in the solar potential estimation of rooftops (see Figure 1), the detailed roof structure and its ancillary facilities (e.g. chimney and dormer) are more useful than the rest of the building (e.g. walls and windows). In this analysis the solar exposure is not calculated for walls, and they are only needed to estimate shadow effects on nearby objects, so having them mapped in more detail (such as having façade details and windows) does not bring virtually any benefit [15]. In fact, it may be even detrimental to have, since an excess level of detail may be slowing down the computations for no added benefit in terms of accuracy and reliability of the results, not to mention the increased cost of acquisition. In this particular case and Figure 1, the analysis has been carried out on LOD2 models, where roofs and walls are mapped with a comparable degree of detail. Instead of a homogeneous outlook, we believe that it would be more beneficial to put less focus on mapping walls, in favor of acquiring roofs, i.e. having them in LOD3.

Therefore, for a 3D building model, the heterogeneous degrees of component detail (even minor differences may be substantial) regardless of whether exterior or interior, may coexist in a certain LOD. In fact, the CityGML 2.0 documentation briefly mentions that CityGML supports aggregation and decomposition by providing an explicit generalization association between city objects in its general characteristics section [7]; thus, our work is in line with the standard.

In this paper, we provide a new perspective on the LOD concept and propose a less generic and more application-driven specification for 3D building models, taking the aspects of geometry, semantics, appearance, and property into account. Figure 2 illustrates this point of view in a conceptual manner. The original specification (on the left) is generic: increasing detail of a dataset may increase the benefit to a spatial analysis (i.e. accuracy, reliability), but it often also increases the cost of the acquisition and the amount of excess (redundant) detail that the spatial analysis does not benefit from. While with increasing detail there may be a general benefit for a use case, it might not always be consistent and it may be disproportionate to the invested effort in procuring the dataset and the computational complexity. Here we introduce an application-driven approach, which attempts at providing tailored specification that minimize redundancies and keep costs consistent with the attained benefit for a particular application. While this example is general and conceptual, in Section 6 we demonstrate its implementation and results for specific datasets and use cases.

Although some relative standards and studies have attempted to address this issue, as discussed in Section 2, some drawbacks still exist, as analyzed in (Section 3), which deals with the requirements of an optimal LOD specification. In view of these facts, we conduct a more in-depth study of the discrete LOD framework and propose a novel LOD specification for 3D building models in Section 4 and Section 5. Section 6 reports on two experimental cases of outdoor component selection and indoor furniture simulation to demonstrate our proposal. Then, we provide an evaluation of the proposed LOD modeling paradigm and compare it with the original LODs in Section 7. Finally, we also summarize and describe the prospects for future research in the last Section.

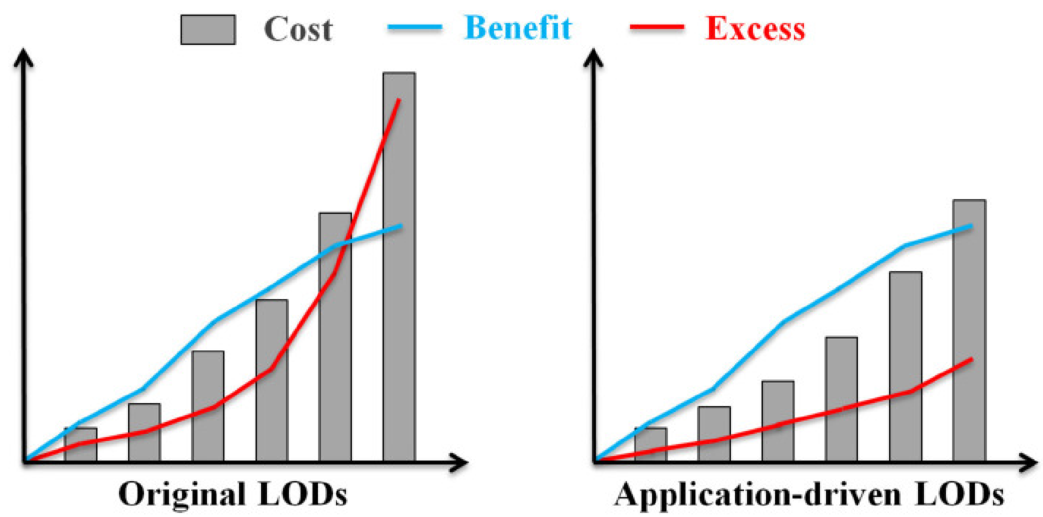


Figure 2: Conceptual relation of cost, benefit and excess for the original and application-driven LODs. Our paper discusses a more consistent relation that is application-specific, minimizing costs and the amount of information that may be irrelevant for the particular use case in question. Our approach may help in maximizing the effort of modelling by directing it into producing pragmatic datasets that have a greater benefit to a spatial analysis.

2. Background and related research

Various discussions for the improvement of the LOD concept have been undergoing by scholars and organizations all over the world.

Biljecki et al. [6] found that the underlying LOD concepts are not entirely clear—neither what LOD comprises nor its motivation; consequently, LODs cannot easily be compared, translated, sorted, or evaluated. They further argued that a LOD cannot simply be defined by the wealth of its geometry: semantics, texture, interior, acquisition techniques, and other factors should also be considered. Therefore, they suggested a formalized LOD framework with six metrics and then derived 10 discrete LODs as an example by combining different metrics. Their proposal achieves a decoupling operation for the standard LODs and allows the creation of a larger number of consistent LODs. However, whether the six metrics should be considered as unrelated factors is worthy of discussion because their mutual constraints are neglected.

In the continuation of the work, Biljecki et al. [16] concluded that an LOD in CityGML might have several variants that would introduce different influences on spatial analyses. They first exposed some shortcomings of the standard CityGML 2.0 LODs and then presented a refined set of 16 LODs focused on the grade of building exterior geometry [8]. Compared to the original definitions, they provided stricter specifications that reduced modeling ambiguity. An advantage of this work is that because different applications have different requirements, the refined specification may be more suitable for specific application contexts (nevertheless, this may also be a disadvantage if a dataset is intended to be used for multiple purposes). Furthermore, indoor structures were not considered.

To introduce indoor scenes into the definition of the LOD concept and decouple building interiors from exteriors, Kim et al. [17, 18] extended the 3D spatial models and services for efficiently managing and representing the facilities of complicated indoor spaces by developing a CityGML Indoor ADE. Löwner et al. [19] proposed differentiating geometrical LOD (GLOD) from semantical LOD (SLOD), as well as their possible combinations. In a related work, Tang et al. [9] advanced a full LOD (FLOD) concept by decomposing and recombining outdoor LODs (OLODs) and indoor LODs (ILODs). To improve the efficiency and communication qualities of 3D urban models in all phases of disaster management, Kemec et al. [20] added three parallel indoor LOD definitions to better reflect building interiors, which constituted a significant improvement that comprehensively relieved the binding relationship between the indoor and outdoor. Based on these foundations, the concepts can be extended; the thought and theory can be applied to address building component constraints.

In fact, some concepts similar to the LOD being discussed here already exist. Foremost among these is the concept of “level of development” in the Building Information Modeling (BIM) field. Although the abbreviation is the same as that in 3D GIS and computer graphics, the connotations of the concepts are different: In BIM, the LOD is a concept developed by the American Institute of Architects (AIA) [21] , where development refers to the level of certainty about an object. Glander and Döllner [22] used the term “level if abstraction” instead of “level of detail”, because the LOD is typically connected to the concept of simplification motivated by computational requirements as opposed to simplification to reduce cognitive effort.

Moreover, development of the next major version of CityGML is ongoing, and from its preliminary publications [23], we know that LOD4 is likely to be removed; instead, object interiors would be expressed through integration with LOD0-–3. This revision will make it possible to model the outside shell of a building in LOD1 while representing the interior structure in LOD2 or 3. Some demonstrations and data for this revision are already available [24]. Note that, as Biljecki et al. [6, 8] has repeatedly emphasized, the research efforts mentioned above and the work we present in this paper are not intended to disrupt the popular LOD categorization in the existing standard, but rather to provide a supplementary or extended specification complementing it for applications.

3. Requirements analysis for an optimal LOD specification

Before the reconsideration of the LOD concept to apply it for specific applications, several key issues about the LOD concept should be made clear: for example, criteria for judging whether an LOD definition is optimal and the conditions those LODs must meet. In general terms, the LODs specified in CityGML 2.0 are ordinal and their spatial-semantic detail progresses homogeneously. However, at the same time, their general classification and encapsulation can be inconvenient during the actual application process. For example, all the interior features are wrapped in LOD4, which is counter to the original intention of categorization; consequently, all indoor applications must be processed only in this LOD: those that require more detailed indoor models but with a coarse exterior or even no exterior are not supported. Therefore, after a literature analysis and summaries, we provide five essential evaluation criteria; then, later in the paper, we build on top of this reasoning. The five essential criteria are as follows:

(1) **Extensive definition.** A model and its related aspects involved in the definition should be extensive or even nearly complete. This criterion allows maximizing the number of stakeholders and then subsequently promoting further model completeness. According to the viewpoints in [6, 7, 12, 25], four model aspects (geometry, semantics, appearance, and property) play the major roles in influencing the level of model detail, which may be directly reflected by the presence of the city objects and elements themselves or embodied by visual changes or expressed via some rendered processing. Actually, to evaluate LOD concepts, Löwner and Gröger [11] introduced six considerable criteria, among which the first three (richness of aspect, completeness of the LOD concept, and completeness of models in a particular LOD) all emphasize the concept of completeness of definition.

(2) **Wide sharing.** In recent years, an increasing number of organizations and companies have built virtual three-dimensional city models for different applications, including urban planning [26], path navigation [27, 28], solar simulation [29, 30], and heritage preservation [31]. However, because the intended usages are different, model reusability is seriously inhibited. Thus, a more general modeling approach is needed, which is precisely the motivation behind our proposal of the LOD concept. Therefore, an excellent LOD definition should be widely shared by stakeholders in related application fields insofar as is possible.

(3) **Low redundancy.** Low redundancy is equally important in the LOD definition, although it would seem to be at odds with the aforementioned wide sharing. The "implicitGeometry" defined in CityGML is a workable method because it means that the geometry of a prototype object is stored only once in a local coordinate system and then referenced by other objects. Similarly important, a good definition of topological relation can also contribute to avoiding redundancy because geometric objects can then be referenced by other features or other geometries (for more details, please refer to our previous research [32]). Additionally, free collocations of city objects by practitioners themselves may be another and even better solution.

(4) **Increased freedom.** From a consumer perspective, people may be re-

luctant to pay the bill for the redundant model components (excess detail), which in turn limit reusability (revisiting the rooftop solar potential estimation example in Figure 1, it is unrealistic to expect a user to pay extra to have wall windows modelled if the dataset will be used only for the aforementioned purpose).

(5) **Easy acquisition.** All of the above criteria would be purely academic if the model dataset is difficult to obtain. The current major data acquisition techniques include aerial surveys, terrestrial measurements, image analyses and cadastral management [33–37]. In mapping fields, an easier data acquisition method exists, for example, OpenStreetMap (OSM) [38], which is a free, open-source and editable map service created for the public Internet. This idea could be extended to the acquisition of LOD models. Nevertheless, publicly uploaded data should undergo a review process to ensure its security and integrity before its final release.

4. Application-driven specifications for 3D building model

In this section, tackling the deficiencies of the generic LOD approach, we propose a novel application-driven LOD modeling paradigm. While we focus on 3D building models, the approach is applicable to other types of city objects as well. In contrast to existing works, we adopt a "context-aware" approach to reach a specification that puts the intended use upfront, defining the LODs for building component models first and then assemble them to derive the LODs for the building models based on the importance of the components (context or focus) to specific applications. With this approach we achieve 3D city models that are tailored for a particular application, in contrast to the traditionally available general purpose datasets, which may be used for many applications, but at the same time are not optimized for any of those, potentially resulting in redundancies and unnecessary cost (in terms of acquisition, performance, processing, and so on).

4.1. Methodology

4.1.1. Reverse outlook on the LOD of 3D building models

Traditionally, LOD specifications have been top-down process, that is, the detail levels of the building model is stipulated first, which regulates the eligible components at the corresponding level. For example, in LOD2 of the five LODs of CityGML, the position and height accuracy is proposed to be 2 m or better (below 0.5 m), and it is suggested that all objects with a footprint of at least 4 m $\times$ 4 m (less than 2 m $\times$ 2 m) be considered. This is actually a holistic and homogeneous idea because it means that the detail level is finite; each component in a particular LOD should have the same or similar complexity (at least the minimum acquisition criteria should be satisfied). This approach contrasts with the heterogeneous approach that we propose in this paper. While not discounting the benefits of a generic approach, the problem of trying to satisfy many applications simultaneously while not being specifically suited for any particular application may be obvious. We deem that for a certain application, we need only the degree of detail of the targeted partial components.

Consequently, we reverse the original mode of thought and adopt a bottom-up method to complete the definition of the LOD concept. Using this approach, the granularity is constrained to the building components rather than to the building model; the detail level of the component models is specified first; then, the LODs of the building model are deduced by assembling the different components.

4.1.2. Assembly concepts in 3D modeling

In fact, the application of this assembly technique in 3D modeling is not novel; the most widely known application is constructive solid geometry (CSG) [39], a powerful way of describing solid objects for computer graphics and modeling. In CSG, primitives are assembled into a larger objects and space can be carved out of a primitive. Going back even further, the recognition-by-components (RBC) theory [40], is a bottom-up process proposed by Irving Biederman in 1987. According to RBC theory, we achieve objects by first separating them into their main component parts and then assembling them in various arrangements, allowing the formation of a virtually unlimited number of objects. Another embodiment is the family concept in BIM, which employs a parametric idea to control sets of components of the same type but that may have different structures, sizes, appearances, and properties [41]. Under the concept of component families, allowing users to assemble and customize functionality becomes achievable.

As a result, in this paper, we consider it would be better to obtain the LODs of building models by assembling different components with diverse LODs than by specifying the building LODs directly. Figure 3 shows the decomposition of two distinct detail levels of the same building model; then, the components can be selected and assembled into many more building model combinations. In the figure, A and B denote different levels of component detail.

4.2. LODs of buildings and their component models

4.2.1. The LOD definition of building component models

In this subsection, we focus on the LODs of components, which we call CLODs to distinguish them from existing LODs. It is important to note that "component" here is a collective term that includes structures, installations, furniture, and similar features. To foster adoption, we use a grading principle similar to the LOD concept in CityGML to address component classification; the five major aspects mentioned in Section 3 act as the general guiding ideologies. The highest level of our new CLOD concept is 3, but the total number of CLODs is six because we add two supplements: one before CLOD0 and one after CLOD3.

(1) **CLODn:** Different from other schemes, the starting level here is not "0" but "n", which means "none", "nothing" or "nil". The "n" provides an explicit way to express the non-presence of city objects (or those obscured by others). This concept is represented visually by using dashed lines. This is similar to the ClosureSurface concept in CityGML, but the term "placeholder" may be more accurate. Using this level, the semantics of a component can be preserved even with no geometric expression.

(2) **CLOD0:** Drawing a lesson from the LOD0 definition for building models in CityGML, a component at this level is also represented as the vertical projection surface of its upper or lower façade. In some special scenarios, such as decoration design, superposition of multiple projection surfaces is also allowable, as illustrated in the last image in Figure 5(b). However, the datum plane is not limited to the ground, but could be attached to the floor, wall, ceiling or any other surface.

(3) **CLOD1:** Similarly, the model in CLOD1 consists of a generalized geometric representation of the exterior shell, namely, it is a classical block volume extruded by a projection of a CLOD0 surface to its vertical height. In practice, the aligned axis bounding box (AABB) algorithm is adopted as the simplified representation for components.

(4) **CLOD2:** Unlike the building model, the shape of a component—furniture, especially—is usually irregular or oddly shaped. The simplified algorithm used for CLOD1 is too general to reflect the details of components; consequently, it loses most of the semantic information; however local detail

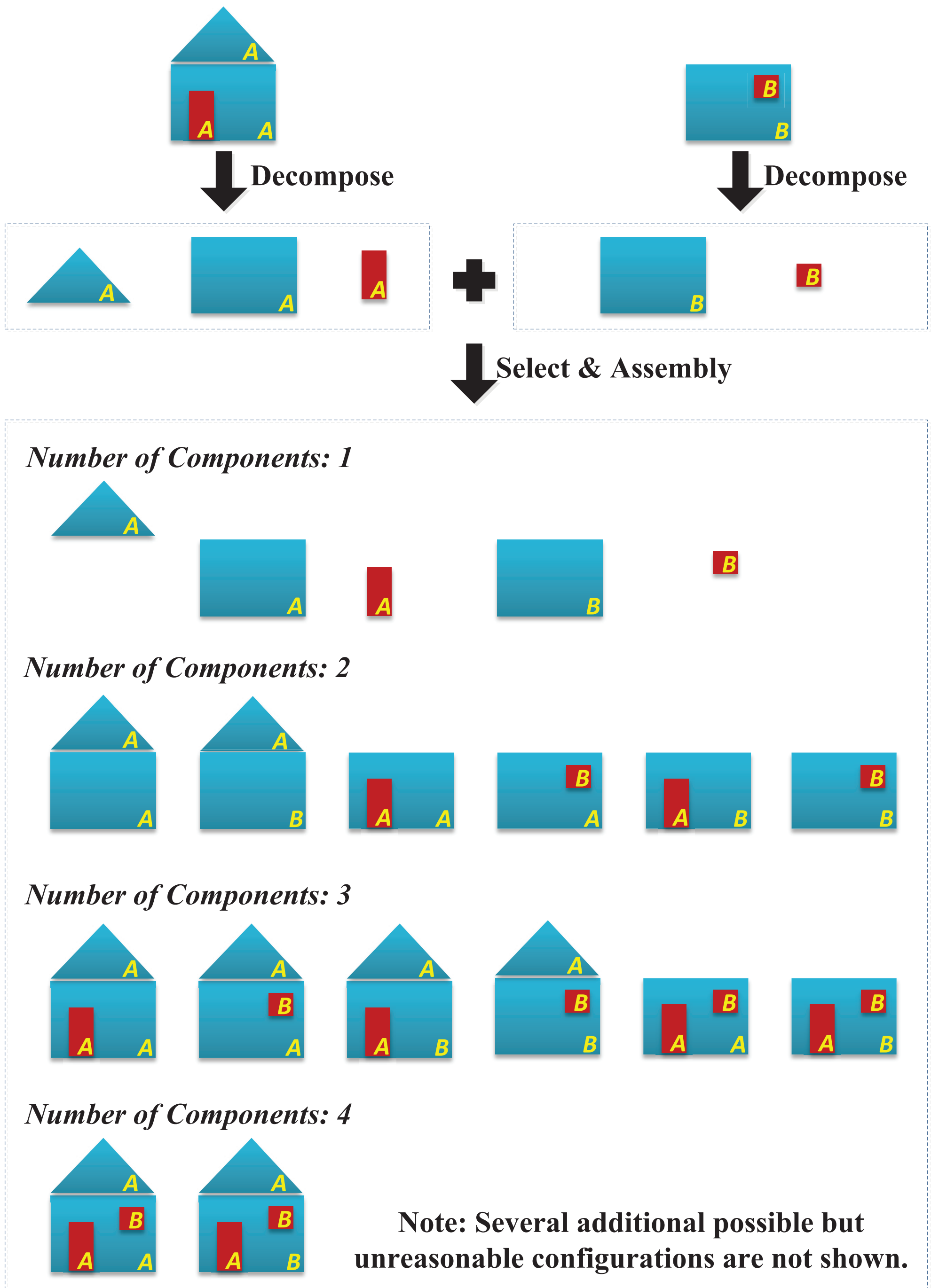


Figure 3: The reverse process of 3D building modeling: decompose and assemble.

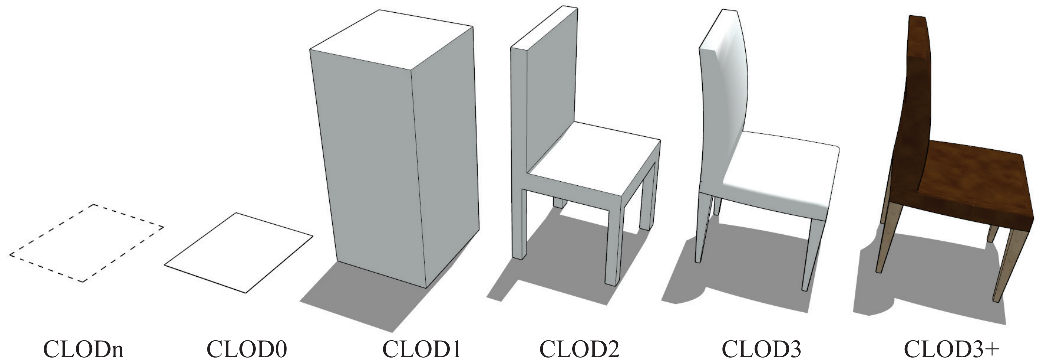


Figure 4: Six levels of component representation detail.

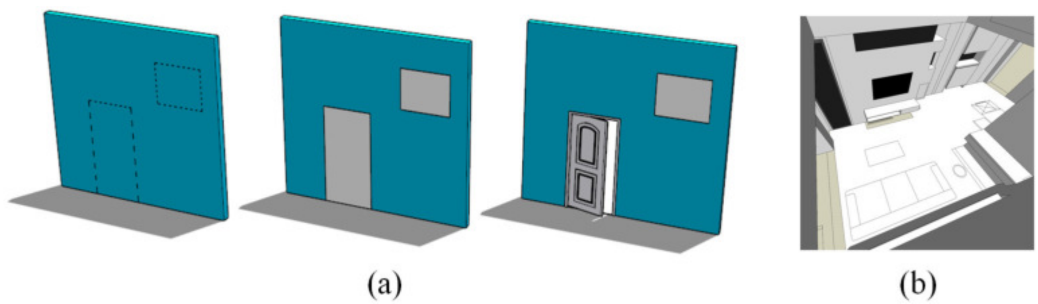


Figure 5: Different CLODs of components and their combinations. This approach allows a specification to be tailored to suit the needs of a particular model.

is highly important for some applications. Therefore, a more appropriate simplified algorithm for components is required that preserves the corresponding component detail level.

(5) **CLOD3(+):** CLOD3 is the most detailed level in both its geometrical and semantic aspects. These component models have the highest level of resolution: even their interiors (if pertinent, i.e., drawers and interlayers) are available for special applications. CLOD3+ is a supplement to CLOD3 that allows appearance and other properties to be appended to the CLOD3 model to achieve a maximum reduction.

Figure 5 shows several building components with different CLODs and their combinations. Figure 5(a) demonstrates the feasibility of combining different levels of component detail: such as a wall in one CLOD but its embedded door and window in different CLODs, as shown in the third picture, where the detail level of the wall is CLOD1, while that of the window

Table 1: Different representations of the aspects of geometry, semantics, appearance and properties of the component models from CLODn to CLOD3 (+).

	Geometry	**Semantics**	**Appearance**	**Property**
CLODn	no	optional	no	no
CLOD0	plane (2D)	homogeneous	homogeneous	separated
CLOD1	block (3D)	homogeneous	homogeneous	separated
CLOD2	generalized	generalized	generalized	separated
CLOD3(+)	real	real	real	real

is CLOD0 and that of the door is CLOD3. Furthermore, the last image demonstrates many more aggregations of components with different CLODs; the detail level is completely dependent on the requirements of the targeted application.

While defining this CLOD series, we considered the following points: (1) CLODn is an optional level (not displayed by default) whose intention is to provide a way to reserve only the semantics to let others know that something exists in that position; (2) CLOD0 and CLOD1 are the two- and three-dimensional geometrical abstractions of components, respectively. Owing to their simple geometrical expression, they can be regarded as homogeneous substances; in other words, they represent only one type of semantic and appearance; (3) In CLOD2, component models retain their main parts, implying that their less important parts are generalized and, accordingly, that their corresponding semantics and appearance are also generalized; (4) The aspect of properties from CLOD0 to CLOD2 should be treated separately for geometrical and non-geometrical aspects. Undoubtedly, the geometric property should be closely related to the modeled geometry (e.g., length, area or volume) and its derivations (e.g., heat dissipation or shadow occlusion), while non-geometrical properties tend to be the inherent or social characteristics and are similar to properties such as location, construction year, property owner and so on; (5) in CLOD3 and CLOD3+, not only the geometry and semantics but also the appearance and properties are complete restorations of real scenes; and (6) rather than predefining the confirmed LODs for components, we would tend to suggest a graduated approach, thus CLOD1 and CLOD2 may look almost identical for regular-shaped objects (e.g., columns or beams) and the total number of levels does not have to be constant.

Moreover, two key issues concerning the CLOD definitions require further explanation. First, why do we deliberately define a supplemental level for CLOD3 but not for other levels? The contradiction between geometry and property is the crux of the matter. As mentioned earlier, in a component model, the partial properties (e.g., geometrical properties and derivations) are determined by the geometry, such as the volume of the block model in CLOD1, which plays an important role in estimating building heat consumption. However, geometry prior to CLOD3 is actually a simulation of the real component; consequently, there must be some structural differences between them. Moreover, their geometrical properties are not completely accurate; thus, a geometric analysis result based on these levels would be meaningless in a sense.

4.2.2. Derived LOD definition for 3D building models

In a three-dimensional city scene, different objects may have different levels of detail according to their importance or distance. The same is true with building levels; it is both reasonable and feasible for different components with varying LODs to coexist in one building scenario due to their contributions to certain applications. For example, in building ventilation analysis (which will be subject of Section 6), a higher window LOD is an important factor for calculating the results, while wall or others LODs are less important. Therefore, the former LOD requirement that all the components in a building model must be represented at a unified level is both unnecessarily restrictive and inappropriate. In this paper, we argue that the LOD specification of a building model cannot be generalized by several (or a series of) fixed levels but rather should be construction with a flexible collocation set oriented to specific applications.

Another improvement introduced here is the view that a building model is an organic whole. This perspective breaks with the traditional boundary between indoor and outdoor modeling. In recent years, an increasing number of scholars and companies have focused their research perspectives on indoor scenes or on indoor-outdoor combinations, especially since the rise of BIM theory and technology [42–45]. Therefore, gradually, it appears to be increasingly unnecessary to artificially separate indoor from outdoor areas.

For a better explanation, Figure 6 depicts a revised UML diagram on which the building model in CityGML 2.0 is based. Because of the specific definition of LOD4 for indoor scenes, the features were accordingly distinguished by the prefixes “Interior” or “Outer”, for example, “InteriorWallSurface”, “OuterCeilingSurface”, “OuterFloorSurface” and “IntBuildingInstallation". In contrast, in this revision, we reconsolidate them and simplify their correlations: the boundary between interior and exterior is blurred because the internal and external component concept becomes irrelevant. Here, the same as the building model in CityGML 2.0; a building is still the pivotal class and consists of different structures, furniture, and installations. In addition, several representative inherited installations (e.g., stairs, elevators, beams, columns, dormers, and chimneys) are instantiated along with their dependency relationships. Furthermore, to express the level of these components, the postfix "_LODs" are appended after each class. Note that the features demonstrated in Figure 6 are given only as an example; in practice, a real model would include more complete components and more complex relationships.

In accordance with the above diagram, the practitioner could then create a compact application-driven building model by selecting the necessary components at the appropriate levels. In this sense, the conclusion can be summarized as follows: application should determine the LODs of component models, which subsequently determine the LOD of the building model.

However, following this notion, the sharing of building models becomes another major problem due to application specificity. To solve this problem, we similarly suggest changing the approach of the model sharing from one of sharing buildings to one of sharing components. On one hand, this approach solves the aforementioned problem; practitioners can retrieve a building model by assembling the shared component models. On the other hand, it broadens the opportunities for data providers, who could provide partial (even one) models, rather than a strictly completed building model. For instance, aerial photographers could create various LODs of roof models, and window manufacturers would need to address only the LODs for their products. Therefore, the application scenario is also becomes redefined—from one-to-many (one publisher with many subscribers) to many-to-many (many publishers and many subscribers), as shown in Figure 7.

5. Constraints between the various LODs of different components

Theoretically, a plethora of building models could be created by combination of the components at different levels, especially in the wake of the increasing number of furnishings and installations. However, that is bound to lead to inconsistencies due to unconstrained free combinations. For example, having a suspended chimney without its standing roof or a dangling

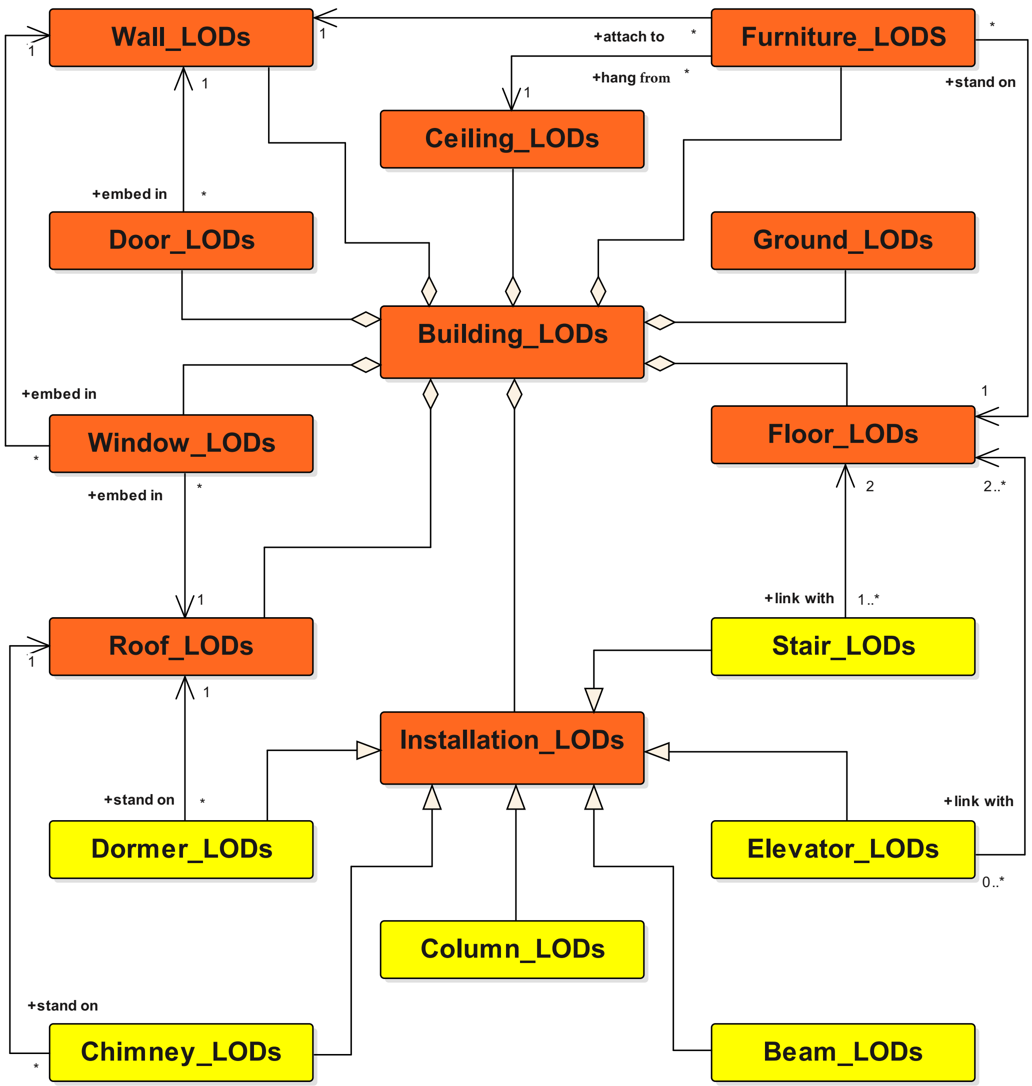


Figure 6: Revised UML diagram for building a model based on CityGML 2.0.

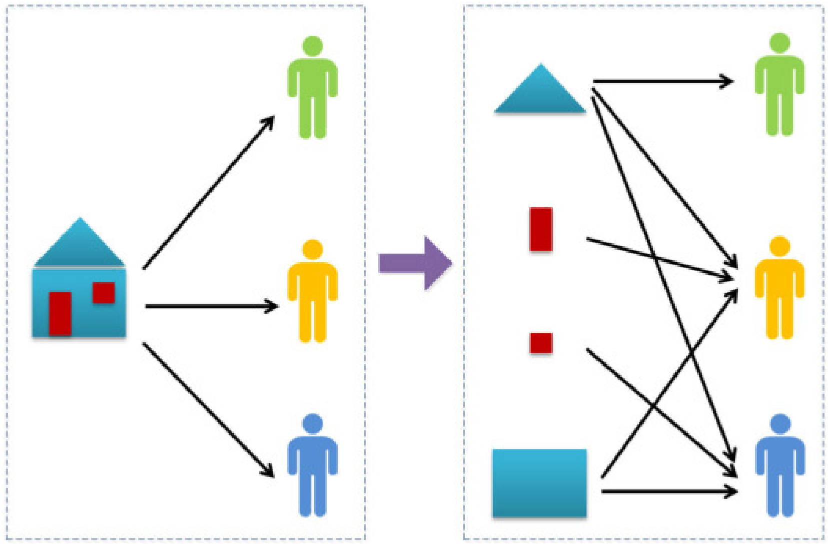


Figure 7: Redefined application scenario from one-to-many (general purpose models) to many-to-many, more suited for applications.

beam without its supporting structures would make little sense in any application. Thus, the above definition of the LODs only completes the first step for 3D building modeling; the relative constraints between components must be explored next.

5.1. Semantic constraints on components without considering LOD

Some research works have already focused on semantic topological constraints. For example, after analyzing numerous CityGML datasets from different sources, Biljecki et al. [46] derived a list of prevalent topological errors in the geometrical or semantic aspects of building models using the open-source software val3dity, described in [47] for validation. Liu et al. [48] adopted an XML-based description and a DTD-based verification technique to exert semantic control over the topology and combination of different building components used to represent house styles correctly. Li et al. [49] presented six recapitulative rules (on, cover, exist, join, extend, and exclude) to restrain combinations of predefined structural and decorative semantic components. Higashi et al. [50] proposed a parametric design method that achieved a product model in the computer according to topological and geometrical constraints. In this paper, capitalizing on the advantages of former research, we propose a Subject-Verb-Object (SVO) method, one that is

Table 2: A Subject-Verb-Object Classification for the components listed in Figure 6.

Classification	**Components**
Subject	Furniture; Stair; Elevator; Beam; Door; Window; Dormer; Chimney; Floor; Ceiling; Column; Wall; Roof
Verb	stand upon; hang from; attach to; link with; embed in
Object	Ground; Floor; Ceiling; Beam; Column; Wall; Roof; Dormer

similar to grammatical rules to ensure semantic topological correctness.

According to the force role, we classify the components listed in Figure 6, referring to Table 2. First, components that cannot exist independently constitute force makers (Subject), such as a chair and that in reality, these components cannot stand without support due to their own gravity. Correspondingly, the supporting components are regarded as force receivers (Object), such as floors, which play the supporting role for the chair. Due to the complexity of architectural structures, some structural components can be both a subject and an object, for example, a wall stands on the floor, but supports the ceiling at the same time. Finally, the relations between subjects and objects must be explored. In light of their positional relationships and mutual states, we generally summarize five behaviors (Verbs): stand upon, hang from, attach to, link with, and embed in. Certainly, are additional verbs exist (e.g., cover, hook, clamp, lean and strut) that are not considered here; the five enumerations here simply act as a reference.

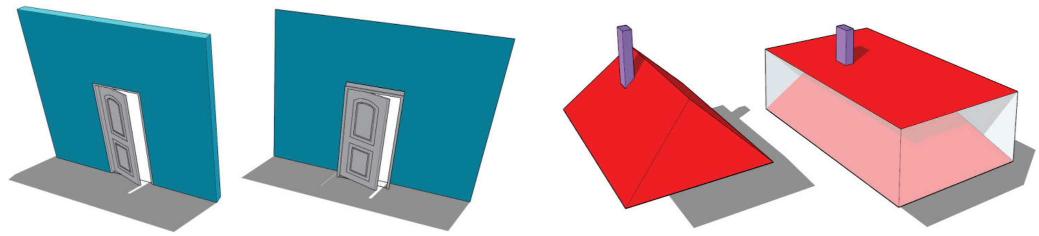
By the same token, collocations of the SVO relations cannot be unrestricted because some are unreasonable or extremely unusual in reality. For instance, one cannot put a bed on the ceiling. For this reason, we propose the following semantic formula:

$$f(Subject) = Subject.\,[Verbs]\,.\,[Objects]$$

Taking the component "Window" as an example:

$$f(Window) = Window.\,[embed\ in]\,.\,[Wall\ ||\ Roof\ ||\ Dormer]$$

A more detailed collocation of SVO relations is listed in Table 3. It is worth reemphasizing that the subjects, verbs and objects included here are



(a) (b)

Figure 8: Two model groups by the same components but in different CLODs.

for demonstration purposes only, and the verbs are all abstracted from a visualization perspective. The real situations and actual structures may be considerably more complex and manifold, but the principle is the same.

5.2. Geometric constraints on components at different detail levels

Note that the component constraints in different LODs may have certain differences due to their matching degree in geometry. Figure 8 shows two assembled model groups that use the same components but consist of different CLODs, which is used as an example for further explanation below.

In Figure 8, the first group describes a wall with an embedded door. The wall is represented differently as a 2D surface (CLOD0) and a 3D volume (CLOD1), while the door is a detailed 3D model (CLOD3). It is easy to determine that there an explicit contradiction of geometric dimension exists. The door is exposed when embedded in a 2D wall surface, which is disturbing or even inaccurate from any visual or analytical point of view. Consequently, we compare the dimensions of subject and object when applying different verbs (see Table 4). Under normal circumstances, there are no restrictions on the subject and object dimensions, namely, free combinations of two- and three-dimensions are supported; therefore, the comparison results could be ">", "=" and "<". However, this approach cannot be applied to the last two verbs. In this paper, we take "link with" as a verb example of a subject component (e.g., stair or elevator) that connects two other object components in the vertical direction. This presupposes that the dimension of the subject component should be 3 (or at least 2.5), and it could not be less than the object components (represented by "×"). By contrast, as Figure 8(a) shows, ">" seems to be impossible when using the verb "embed in" when the requirement calls for the same or a higher dimensional component.

Table 3: A more detail collocations of the subjects, verbs and objects listed in Table 2.

Subject	**Verb**	**Object**
	stand upon	Ground
		Floor
Furniture	hang from	Ceiling
		Roof
	attach to	Wall
		Roof
Stair	link with	Floor
Elevator	link with	Floor
Beam	stand upon	Column
	link with	Column
Door	embed in	Wall
		Wall
Window	embed in	Roof
		Dormer
Dormer	stand upon	Roof
Chimney	stand upon	Roof
Floor	stand upon	Ground
		Beam
Ceiling	stand upon	Column
		Wall
Column	stand upon	Ground
		Floor
Wall	stand upon	Ground
		Floor
		Beam
Roof	stand upon	Column
		Wall

Table 4: Dimension comparison between subjects and objects for different verbs.

Verb	**Dim (Subject) vs. Dim (Object)**		
stand upon	$>$	$=$	$<$
hang from	$>$	$=$	$<$
attach to	$>$	$=$	$<$
link with	$>$	$=$	$\times$
embed in	$\times$	$=$	$<$

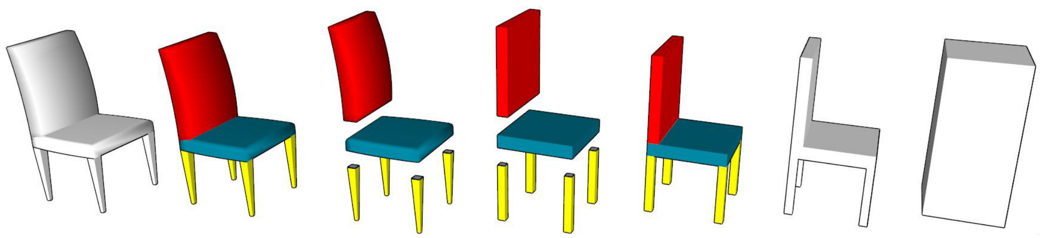


Figure 9: Geographic simplification algorithm involving the structural details.

Geometric topological relations are another important factor that should be considered. Figure 8(b) shows a representation of a chimney standing on the roof of two different detail levels: sloping in CLOD1 and flat in CLOD2. Due to the differences in the supporting roof shape, the chimney height should be adjusted accordingly, as well as the junction polygon formed by these two components. That is, the topological relations should be reasonably maintained when performing the assembly, although the structures of the components may be changed. Even if the supporting component is filtered out, the dependent components should be addressed correspondingly, especially when the dependency relationship is unique.

In addition, as defined in Section 4.2.1, a geographic simplification algorithm involving the structural details is another novel introduction in the LOD specification. It benefits applications that require additional component details relative to the traditional whole block model. Therefore, a prior semantic segmentation is needed at this level, but the remaining procedure is the same as in CLOD1, creating an enveloping operation for segmented objects (see Figure 9). Similar processing idea can refer to the literature [51]. Generally, only the significant details need to be preserved when taking the workload and performance into account.

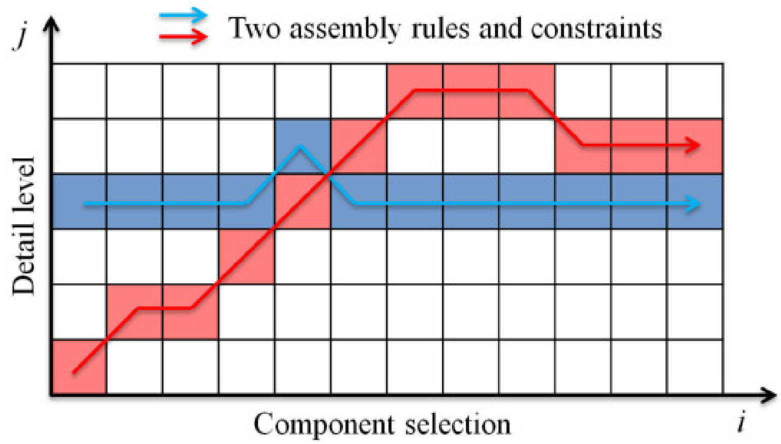


Figure 10: An example diagram showing the hybrid LOD specification for 3D building models.

5.3. Hybrid LOD specification for 3D building models

To summarize, we can obtain a hybrid LOD specification for 3D building models. The definition is expressed by the following formula, where f denotes the assembly rules and constraints on the components, i and j are the indices of the component and its detail level, respectively, while N and L denote the range of values.

$$LOD(building) = f(CLOD_1(j), CLOD_2(j), \cdots, CLOD_i(j)),\ i \in N, j \in L$$

As the formula shows, the LOD of a building model is now determined jointly by the component selections and their detail levels, as clarified by Figure 10. The light blue or red cells in the grid denote the selected component (transverse axis) and its LOD (longitudinal axis), and the corresponding radial line represents the interactive relationship between the components. It also signifies that the LOD specification in this paper adopts a new "context-aware" modeling paradigm of tailoring data based on application, which contrasts with the typical design of general purpose (application-independent) LOD specifications. In terms of applications, such an approach results in a more consistent progression of LODs, especially when it comes to the benefit of a particular application (also see Figure 3).

6. Implementation and demonstration

In this section, we implement the theory presented so far by focusing on two applications: an outdoor component selection(for shadow analysis) and an indoor furniture simulation.

It is obvious a priori that a model built using our method will be the most lightweight for its application-driven essence because it will retain the parts that are useful for the application analysis results while omitting others. We conduct experiments by procedurally generating building models group based on the open-source procedural modeling engine Random3Dcity [52] and then deriving compact models that can be applied to sunlight analysis. The goal of this application is to predict the direct solar exposure of the ground, an instance where 3D city models come in handy [53, 54].

For this application, architectural contour information plays a significant role in the calculated results; consequently, determining the components that influence the outline is a relatively more important task. Thus, in this experiment, the complete roof structures and wall should be retained while less essential aspects such as windows, for example, a window embedded in a dormer, can be ignored. Figure 11 shows a shadow calculation of five sample building models and their deriving compact counterparts. It can be found that using much simpler datasets (around a tenth of the polygon count) we obtain the same results, i.e. the areas of the building shadow are nearly the same while the number of triangles has been greatly reduced, which actually proves that the reduction of the non-essential components would not make any influence (or a tiny difference) to the final analysis results (even if there is a minuscule difference in the results, it certainly does not justify the substantially increased cost of acquisition and processing). Based on this conclusion we continue a further work respectively on the two model datasets to analyze the sunshine intensity by using a SketchUp plugin Sunshine 2019. A similar conclusion can be drawn from the comparison diagram in Figure 12—that we can use lightweight application-adapted 3D models yet still retain the same quality of the analysis results at less cost (in triangles, memory, computational complexities and runtimes). This savings trend becomes more pronounced as scenes become more complex.

Our second demonstration is a theoretical indoor use case of an office building model (see Figure 13). To reduce the data volume, some simplification procedures can be applied to the components while attempting not to affect the application analysis results. In this example, the level of the furni-

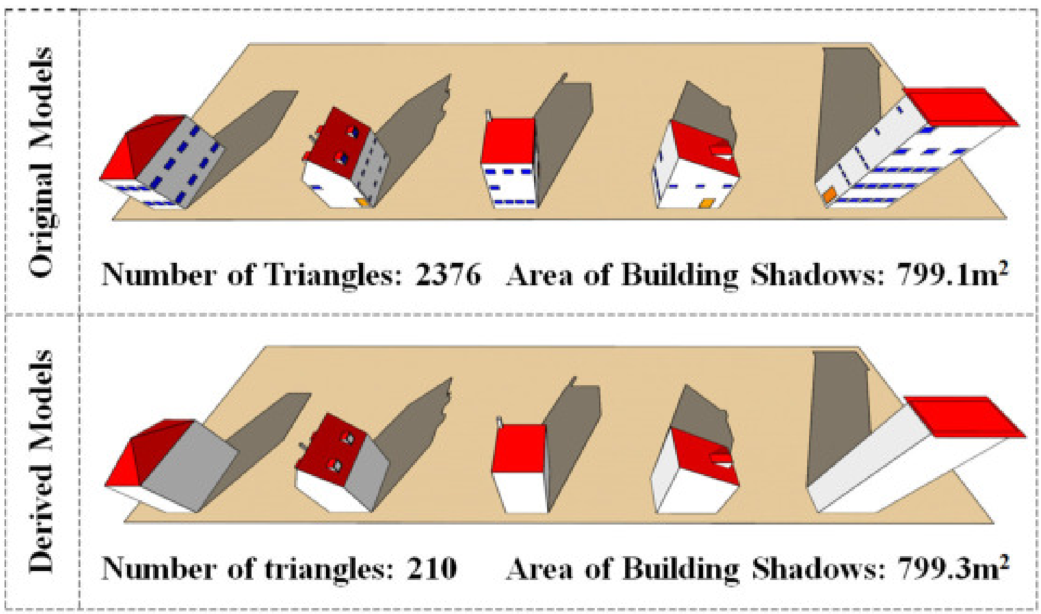


Figure 11: Shadow calculation for five building models (top) and their derived compact counterparts (bottom), where it can be found that the areas of the building shadows are nearly the same while the number of triangles has been greatly reduced.

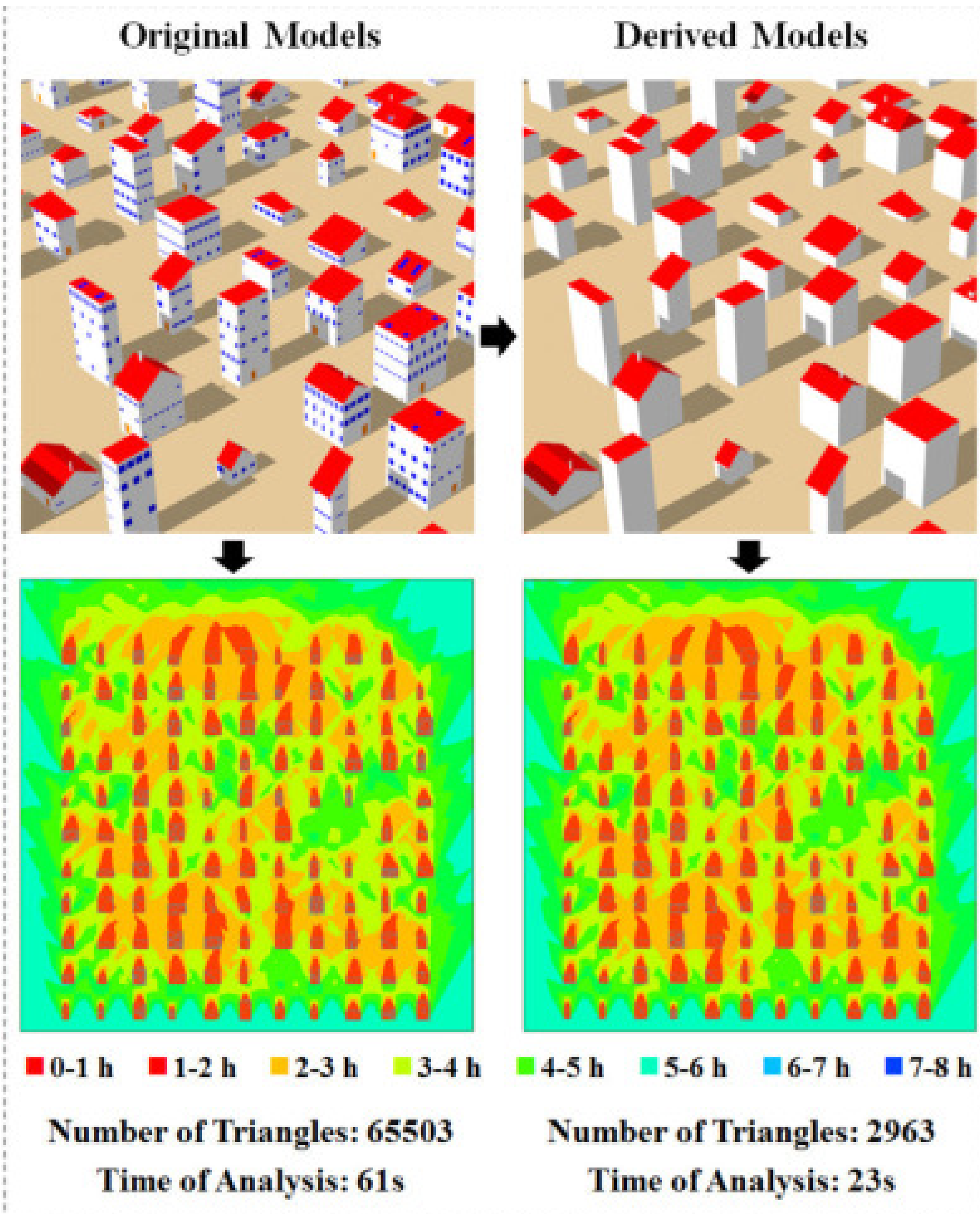


Figure 12: Sunlight analysis for the building model group (left) and its derived compact counterpart (right). It is the result of simulation experiment in Amsterdam area, where the computational daily duration of exposure is 8 hours from 8:00 a.m. to 16:00 p.m. An application-driven dataset, being significantly simpler, yields equally good results.

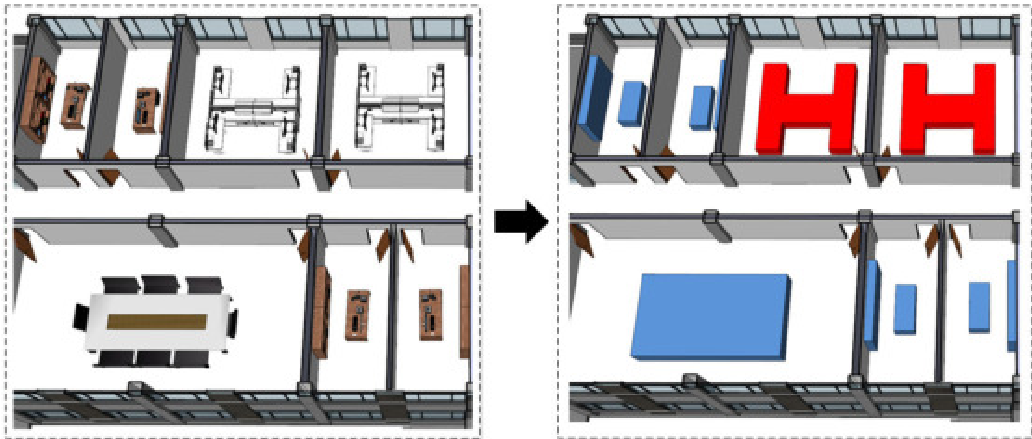


Figure 13: Two CLODs of furniture for different indoor application scenarios.

ture is CLOD3+, which includes considerable local detail and occupies most of the required storage space. Because the local details and appearances of furniture have less impact on applications such as indoor navigation, it is useful to downgrade them in such cases. As the bottom part of Figure 12 shows, there are two simulation methods for furniture, distinguished by the blue and red colors that exactly correspond to the two levels introduced in Section 4.2.1: CLOD1 and CLOD2. The reason why we place the furniture shown in red into CLOD2 rather than directly into CLOD1 is that the intervening furniture spaces are sufficiently large to accommodate a person standing or moving around; in some emergency situations (e.g., terrorist attack), these may form a suitable hiding place. Additionally, in this experiment, we assume that the furniture in the building is all stationary; consequently, we can regard the close conference table and chairs (in the lower left corner) as a whole and model them together as a block box. Obviously, modeling a dynamic scene would be trickier and more difficult, which is another topic worth further studying in future research.

7. Evaluations for the new proposal

Thus far, we have introduced the proposed application-driven LOD concept for 3D building models. Combined with the five requirements of the optimal LOD specification given in Section 3, we perform a targeted evaluation item by item:

(1) **Regarding extensive definition,** we start the specification from the LOD definition for component models and then derive various LODs for building models. Due to the huge number of components, their possible aggregations, and their application orientation, completeness must be guaranteed to satisfy various types of application requirements.
(2) **Regarding wide sharing,** we change the subject of sharing from macroscopic building models to microscopic component models. This approach expands the channels for providing data, thereby allowing more practitioners to be involved in the sharing process (see Figure 7). Therefore, not only the degree of utilization but also the degree of model sharing increases under our method.
(3) **Regarding low redundancy,** we switch model granularity to the component level. Then a building model is generated by assembling the necessary components based on the requirements of a certain application (see Figure 3). The result is that the obtained model is the most compact; in other words, the building model redundancy is the lowest under our approach.
(4) **Regarding increased freedom,** due to the maximization of model-providing channels, practitioners could freely select the most suitable component models to synthesize the desired building model from anyone or from anywhere (if possible). However, we note that the assembly process is not completely rule-free; it is limited by structural constraint conditions to avoid building unrealistic models (see Section 5).
(5) **Regarding easy acquisition,** benefiting from the aforementioned wide sharing, practitioners will be able to acquire models more easily. In contrast to earlier specialized model providers, "amateur" personnel could also be relevant as providers, similar to furniture manufacturers mentioned in Section 4.2.2. As a result, model acquisition would become increasingly easy as the number of participants increased.

8. Conclusions and future works

The generic LOD definition for 3D building models in CityGML 2.0 is popular for a reason, but it tries to please too many applications at the same time, resulting in datasets that nominally can be used for a multitude of applications, but eventually are optimal for none. With the increasing number of applications it might appears to be insufficient or inflexible for building relatively stereotyped specifications under the increasing demands of various applications. To address this issue, in this paper, we introduce a new LOD modeling paradigm that allows building context-aware 3D city models tailored to specific applications. This outcome was achieved primarily through a change to the assembly technique. The presently available LOD specifications are generic (application-independent), which—while popular and certainly beneficial (e.g., the ability to produce one dataset for multiple applications)—nevertheless has some shortcomings as exposed in this paper. This situation means that the building model LODs are indirectly derived rather than reflecting a direct definition based on the required detail levels of the assembled component models.

In contrast, the LOD specification in this paper pays closer attention to the aspects of geometry, semantics, appearance, and properties and also considers their internal relations. Note that the specific accuracy requirements are debatable and should be considered discussion proposals whose final form will be determined by standard setters or defined by users themselves based on their application requirements. In addition, the five stated requirements for optimal LOD specification are intended to be a reference based on the authors' experiences; consequently, there are likely to be more items to evaluate that we have not considered due to our limited knowledge. Similarly, the specifications for the LODs of building components and the constraint on their relative assembly also require further investigation. The contribution of this paper lies in providing a new way of thinking about the LOD definition for 3D building models that provides an application-driven specification. Our hope is that these ideas will inspire standards-setters and other scholars.

There are many opportunities for future work. Above all, CityGML 2.0 has specified the LODs for more than 10 thematic models, but most of the current studies emphasize buildings; studies at the large-scale city level that include multiple city objects are still rare. Therefore, for future research we plan to work into three directions:

(1) In this paper we have presented a specification that is heterogeneous on the building level (the LOD of some parts of a building are different from another). A continuation of the work would be to explore this concept on an urban scale, resulting in variable LOD across multiple city objects depending on the application, e.g. for noise pollution studies having more detailed models closer to the noise source, potentially reducing costs and increasing performance. This is akin to computer graphics, where datasets are rendered in variable detail depending on the point of

view.

(2) Conversion of general purpose models into application-tailored LODs for a particular use case would also be an important topic to explore. Perhaps we can build generalization methods that are application-driven, removing details that are not necessary for a particular application.

(3) We plan to explore more applications, resulting in a series of LODs for each.

Acknowledgments

We would like to gratefully acknowledge the anonymous reviewers for their constructive comments and suggestions concerning this paper and express our most sincere appreciation to the cited experts and scholars for providing valuable inspirations. Furthermore, we thank the software obtained from institutions and companies about their modeling practices which have served as guidance for this work. This research is funded by the National Natural Science Foundation of China (41671381,41871298), Hubei Provincial Natural Science Foundation for Distinguished Young Scholars (2017CFA050), and Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Land and Resources (KF-2019-04-019).

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