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A comparison of generalised urban block 3D model variants considering attributes with an influence on urban analyses

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Abstract. Three-dimensional (3D) city models support geometry-sensitive urban analyses related to energy demand, material stocks, and urban climate. While modelling decisions at the scale of individual buildings have been widely examined—particularly in relation to Levels of Detail (LOD)—the geometric specification of intermediate spatial units such as urban blocks remains weakly defined. In practice, block-level representations are often derived through implicit aggregation of building geometries, without explicitly assessing the generalisation strategies involved or their analytical implications.

This study systematically evaluates alternative 3D urban block modelling variants derived from identical building-based cadastral data. Three 3D generalisation strategies are considered: footprint simplification, height simplification, and semantic grouping of envelope or façade elements. Their combinations generate 19 distinct configurations applied to a morphologically heterogeneous urban block in Zaragoza (Spain).

For each variant, total built volume, exposed envelope area (surface), and geometric complexity (polygon count) are computed and compared. Results show that height simplification primarily affects volumetric estimates, whereas semantic grouping strongly reduces exposed surface area and geometric complexity without affecting volume. Footprint simplification exhibits intermediate effects across indicators.

These findings demonstrate that block-level generalisation strategies significantly influence analytical outcomes and cannot be treated as neutral aggregation steps. The study provides a structured and reproducible framework for evaluating 3D urban block modelling variants in urban-scale analyses.

Submission Type. Analysis. Case Study.

BoK Concepts. [AM13] Representation transformation. [AM14] Generalization and aggregation. [DM5] Modelling 3D, temporal and uncertain phenomena.

Keywords. 3D Model, City, Urban Block, Generalization

1 Introduction and Related Work

Urban areas play a central role in climate mitigation and resource efficiency strategies (IPCC, 2022 – AR6 WGIII, Ch. 8). A large share of greenhouse gas emissions, energy demand, and material consumption is associated with the built environment (IPCC, 2022 – AR6 WGIII, Ch. 9), making cities both major contributors to environmental challenges and key arenas for transformative action. Many contemporary urban strategies—ranging from energy efficiency retrofitting (Malhotra et al., 2022) to solar potential assessment (Rodríguez et al., 2017) and urban climate modelling (García-Sánchez et al., 2021) — rely increasingly on spatial analyses of the built environment (Biljecki et al., 2015). In this context, three-dimensional (3D) city models have become an essential data infrastructure for representing urban form and supporting geometry-sensitive analyses.

Over the past decade, substantial research has focused on the development, standardisation and application of 3D city models. In particular, models encoded in formats such as CityGML enable the representation of buildings at different Levels of Detail (LOD), commonly understood as the degree of geometric resolution in a 3D model. In the CityGML specification, LOD0 typically represents a two-dimensional building footprint or roof edge polygon, LOD1 corresponds to a simple block model obtained by extruding the footprint to a single height with a flat roof, LOD2 includes generalised roof structures reflecting their actual shape and inclination, and LOD3 provides detailed architectural elements such as chimneys, dormers, windows, doors or roof overhangs (Open Geospatial Consortium, 2012). As a result, LOD is often used as a proxy for geometric richness and analytical suitability in urban applications.

However, subsequent research has demonstrated that the concept of LOD does not fully characterise the geometric specification of a building model. Biljecki et al. (2016a) proposed a refined LOD specification for CityGML building models, introducing sub-levels (e.g., LOD x.0, LOD x.1, LOD x.2, LOD x.3) within each nominal LOD to account for additional geometric distinctions. This refinement highlights that geometric variability exists even within formally defined LOD categories.

There are several geometric modelling proposals which go beyond the nominal LOD. Crucially, Biljecki et al. (2016b) showed that within the same nominal LOD, multiple modelling variants may exist depending on how specific geometric references are defined—for example, whether the height of a building is measured at the eaves or at the ridge, or whether the footprint corresponds to the wall position or the projection of roof edges. Their empirical results demonstrate that such modelling choices, often implicit and insufficiently documented, can lead to substantial differences in geometry-sensitive spatial analyses, in some cases exerting an influence that is comparable to or even greater than the nominal LOD classification itself.

While these modelling decisions have been extensively investigated at the level of individual buildings—the most common modelling unit in 3D city models—urban analyses are frequently conducted at other levels, and therefore 3D city models based on other modelling units exist. In practice, spatial indicators are often aggregated to intermediate units situated between individual buildings and larger entities such as census tracts, neighbourhoods or districts, particularly in microclimate and environmental modelling studies (Joshi et al., 2022). At such intermediate scales, geometric modelling is no longer limited to the specification of individual objects. Instead, it also involves decisions about how heterogeneous building-level information is aggregated, simplified, or transformed into higher-order spatial entities.

In this context, modelling choices may include processes of abstraction or generalisation, which can be understood as generalisation strategies in the cartographic sense. In cartography, generalisation refers to the systematic simplification, aggregation, selection, and transformation of spatial features to adapt representations to different scales while preserving legibility, structural coherence, and functional relevance (Weibel & Dutton, 1999). Such generalisation controls information density and maintains the interpretability of spatial patterns when moving from fine-grained to more aggregated representations. Similar principles have been discussed in the context of 3D city models, where techniques such as clustering, aggregation, and geometric simplification are applied to manage visual and structural complexity in large-scale urban models (Glander and Döllner, 2008). Related ideas have also been explored in applied building and built-up area generalisation, including the simplification of building footprints (Rainsford and Mackaness, 2002), the derivation of intermediate representations between individual buildings and urban areas (Touya and Dumont, 2017), the continuous aggregation of buildings into built-up areas across scales (Peng and Touya, 2017), as well as recent discussions on pan-scalar urban generalisation in zoomable maps (Gruget et al., 2023) and the composition of generalised built areas for cartographic representation (Kettunen et al., 2023). Accordingly, abstraction at intermediate urban scales can be conceptualised as a form of 3D generalisation, extending cartographic principles from two-dimensional map representations to volumetric urban entities. These strategies may alter properties commonly used in urban environmental analysis. This gap is particularly relevant because modelling intermediate spatial units introduces additional sources of geometric variability beyond those observed at the building scale, yet these have not been systematically specified, documented, or evaluated with respect to their analytical implications.

2 Research Motivation and Objectives

To address the gap discussed in the previous section, this study focuses on the urban block as a representative intermediate modelling unit. An urban block can be defined as a group of adjacent buildings and parcels typically bounded by surrounding streets. Positioned between the individual building and larger administrative or statistical units such as census tracts, neighbourhoods, or districts, it constitutes a recognizable spatial unit. As such, it captures key spatial relationships among neighbouring buildings—including alignment, enclosure, courtyard configurations, and shared boundaries—which are central to urban form analysis. Furthermore, urban blocks are widely used as aggregation units in studies of urban density, energy demand estimation, material flow analysis, and microclimate assessment.

Despite its practical relevance, the geometric representation of urban blocks in 3D city models remains weakly specified. In contrast to building models, where LOD classifications and geometric standards have been systematically defined and analysed, block-level representations are most commonly constructed through the direct grouping of existing building geometries. More explicit geometric transformations are comparatively rare. In either case, aggregation is often treated as a straightforward or neutral operation, without explicitly addressing the geometric assumptions embedded in these procedures. As a result, modelling decisions are rarely documented or evaluated with respect to their potential influence on analytical outcomes.

Consequently, it remains unclear how alternative geometric modelling strategies at block scale—particularly those involving different degrees of aggregation and abstraction of building-level information—affect geometry-sensitive urban analyses. Addressing this gap requires a systematic investigation of block-level modelling variants and an assessment of their analytical implications.

To establish a suitable 3D representation of an urban block, we must consider the geometry of its components, but also some of their semantics. The choices that we take may significantly influence volumetric properties, exposed surface areas, shadow patterns, and other geometry-sensitive indicators.

2.1 Research questions

This study addresses the following primary research question: How do alternative generalisation strategies in 3D urban block models influence the results of geometry-sensitive urban analyses?

In particular, the study investigates whether simplified block representations can yield results comparable to more detailed configurations, and whether specific generalization strategies can reduce geometric complexity while preserving analytical robustness.

By systematically defining and evaluating a set of alternative block-level modelling variants, this work represents a first step towards a structured assessment of abstraction strategies at intermediate urban scales.

3 Urban Block Modelling Variants and Experimental Design

This study investigates how alternative 3D urban block representations, derived from identical building-based input data, influence geometry-sensitive urban analyses. The modelling variants are developed through three transformation steps: footprint simplification, height simplification, and semantic grouping of envelope elements. Each step addresses a distinct dimension of geometric abstraction and can be combined systematically to generate multiple block-level configurations.

3.1 Step 1: Footprint simplification (horizontal aggregation)

The first step addresses horizontal fragmentation within the block footprint. Building-based datasets often represent blocks as collections of numerous small polygons, which may be geometrically valid but unnecessarily complex for block-level analyses. For instance, some polygons may correspond to very small inner courtyards, rooftop service rooms, elevator overruns, or other minor architectural elements that introduce geometric detail without significantly affecting overall block-scale metrics.

Alternative 1.1 – As-is footprint:

All original building-part polygons are retained, preserving maximum horizontal fidelity. This variant serves as the baseline configuration.

Alternative 1.2 – Area-threshold aggregation:

Polygons smaller than a predefined threshold (35 m² in this study) are merged with the adjacent polygon sharing the longest common boundary. The height assigned to the resulting polygon is computed as a volume-weighted average of the original polygons in order to preserve total built volume.

Alternative 1.3 – Fully aggregated footprint:

All building-part polygons are dissolved into a single block-level footprint. A single representative height is assigned to the polygon using the volume-weighted average of the original building-part geometries, representing the highest degree of horizontal abstraction.

3.2 Step 2: Height simplification (vertical aggregation)

The second step focuses on reducing vertical heterogeneity across the block. In the input dataset, each building-part polygon is associated with its own height value, resulting in a highly detailed — and often highly variable — vertical profile. However, block-level analyses do not necessarily require preserving the full range of height variability.

In addition, vertical simplification also serves an analytical purpose. By discretising height values into a limited number of representative levels, it becomes possible to visually distinguish and compare urban volumetry more clearly. Such abstraction can enhance the visual discrimination of built mass, facilitate the identification of differences in occupation patterns and density, and improve the legibility of 3D representations.

Rather than modifying the horizontal subdivision of building parts, this step simplifies the vertical dimension by discretizing the continuous distribution of heights into a limited number of representative height levels.

Alternative 2.1 – Real height:

Original height values are preserved for all building parts, maintaining full vertical variability.

Alternative 2.2 – Three-level discretisation:

Heights are simplified into three classes: non-built (height = 0), low-rise, and high-rise. Non-built polygons are assigned directly to the zero class. The remaining polygons are separated using one-dimensional k-means clustering (k=2), and the representative height of each class is defined as the median of its members.

Alternative 2.3 – Binary discretisation:

All non-zero heights are aggregated into a single built class represented by the median height of built polygons, while non-built areas retain zero height. This configuration represents the strongest vertical abstraction.

3.3 Step 3: Envelope extraction through semantic filtering

The third step addresses the semantic structure of the vertically extruded geometry. When each footprint polygon is extruded independently, the resulting model contains vertical faces not only along the outer boundary of the block, but also along shared boundaries between adjacent polygons. In this study, these shared-boundary faces are considered internal vertical surfaces. Depending on whether adjacent polygons belong to the same building or to different buildings, they are retained or removed in different ways in each alternative.

While geometrically valid, many of these internal vertical elements are not relevant for block-scale environmental analyses and unnecessarily increase model complexity. In particular, building and urban energy simulations primarily depend on envelope surfaces, as these define thermal exchange, solar exposure, and boundary conditions. Similarly, envelope elements are central to life cycle assessment (LCA), material flow analysis (MFA), embodied carbon estimation, and solar potential studies, where façade and roof surfaces determine material quantities, environmental loads, and exposure conditions. Internal vertical surfaces, by contrast, generally do not contribute to these analyses at block scale.

This step therefore applies semantic filtering to vertical surfaces in order to extract envelope representations at different spatial scales.

Alternative 3.1 – As-is extrusion:

All vertical surfaces generated by individual polygon extrusions are retained. This configuration preserves maximum geometric detail and serves as the baseline reference.

Alternative 3.2 – Building-level envelope extraction:

Internal vertical surfaces within each individual building are removed, while the outer boundary of each individual building is preserved. Each building is thus represented by a coherent external envelope, so the block still contains separations between buildings.

Alternative 3.3 – Block-level envelope extraction:

Only the outermost vertical envelope of the entire urban block is retained. All the internal vertical surfaces are removed, including shared walls between adjacent buildings, and the block is represented as a single volumetric entity. Although total built volume remains unchanged, this configuration substantially reduces polygon count and significantly alters the amount and distribution of exposed surface area.

3.4 Indicators and experimental setup

To assess the analytical implications of the modelling variants, three geometry-sensitive indicators are evaluated:

- Total built volume, relevant for material stock estimation and energy-related analyses.
- Total surface area, relevant for exposed envelope area, influencing heat exchange, energy demand, and life cycle assessments.
- Number of polygons in the resulting 3D model, used as a proxy for computational complexity and processing cost.

All variants are derived from the same input dataset and processed through identical computational procedures. This ensures that observed differences in analytical outcomes can be attributed exclusively to modelling choices rather than data inconsistencies.

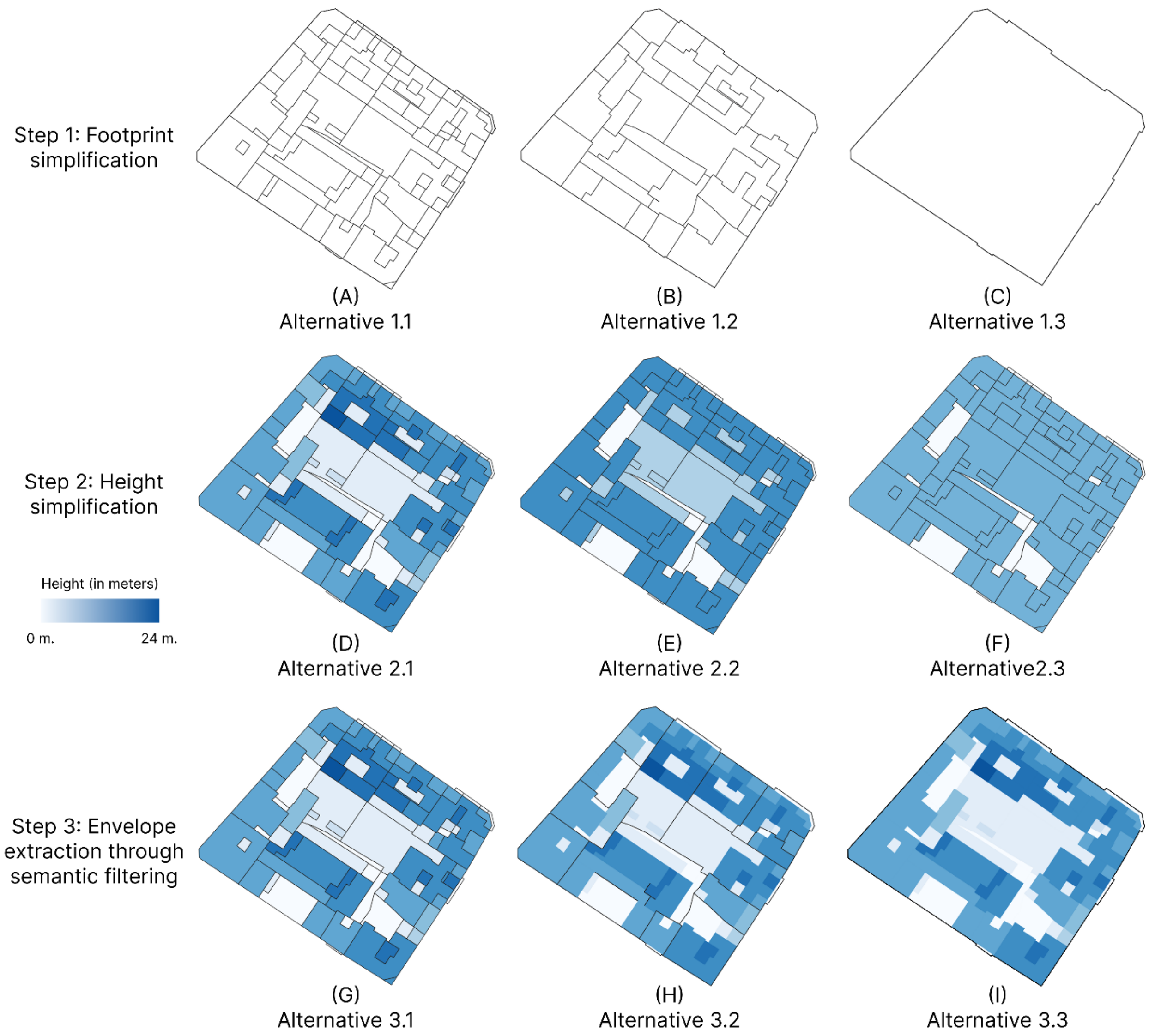

Figure 1. Illustration of the three abstraction steps applied independently to the baseline building-part representation. The input data consist of cadastral polygons representing building parts, including both built elements and internal courtyards. In Step 1 (top row), black outlines indicate building-part boundaries. In Step 2 (middle row), colours represent building-part height values. In Step 3 (bottom row), black lines represent vertical surfaces; their absence between adjacent polygons indicates that shared coplanar walls have been removed. Each row shows the progressive effect of footprint simplification (top), height simplification (middle), and envelope extraction (bottom), without combining transformations across steps.

4 Experimental Results

4.1 Study area and input data

The empirical evaluation is conducted on a single urban block located in the historic centre of Zaragoza, Spain, selected due to its geometric heterogeneity and morphological complexity. The block comprises 14 buildings represented by 90 building-part polygons. Building-part heights range from 0 m to 24 m, with a mean value of 10.13 m.

The input data are derived from the Spanish Cadastral vector cartography, obtained through the official electronic portal in shapefile format. Specifically, the CONSTRU layer—representing urban sub-parcels corresponding to built volumes—was used. Each polygon corresponds to a building part and includes attributes for building identifier and number of floors (encoded as alphanumeric values).

Cadastral floor codes were converted into integer storey counts using the equivalence table proposed by García Martín (2017). Building-part heights were estimated assuming an average inter-storey height of 3.0 m per floor. The original building-part dataset is treated as the reference configuration and serves as the baseline against which all abstraction variants are compared, without implying absolute physical accuracy.

4.2 Modelling workflow and variant generation

Alternative block-level representations were generated through a structured workflow. In QGIS, the selected block was extracted and geometry was validated according to topological rules. Footprint and height simplification were implemented via custom Python scripts. Horizontal aggregation (Step 1) involved retaining the original building-part polygons, merging polygons below 35 m², or dissolving all polygons into a single block-level footprint. Vertical aggregation (Step 2) consisted of preserving original height values, discretising heights into three classes using one-dimensional k-means clustering (k = 2 for built elements), or collapsing all built heights into a single representative value while preserving non-built areas. Three-dimensional geometries were generated in Blender using its integrated Python environment, where routines extruded footprints and removed internal vertical surfaces according to the semantic grouping rules (Step 3), producing either building-level or block-level envelope representations.

4.2.1 Data and Software Availability

The input data are derived from the Spanish Cadastral vector cartography, which is publicly available through the official electronic portal. The analysed urban block can be reproduced by extracting the corresponding cadastral polygons for Zaragoza.

All scripts used for data processing and 3D model generation (QGIS and Blender Python scripts) are publicly available at:

https://doi.org/10.5281/zenodo.19495301

To facilitate reproducibility, a sample dataset corresponding to the study area, along with instructions for data preparation and processing, is also provided in the repository.

The workflow was implemented using QGIS 3.40.7 and Blender 4.3.4.3 Results

The "as-is" configuration (Variant 1–1–1) is used as the high-detail reference representation. All other variants are evaluated in terms of deviation from this reference. A total of 27 theoretical combinations arise from the three abstraction steps (3 × 3 × 3); 8 configurations produced geometrically equivalent outputs and were excluded, resulting in 19 distinct variants.

Table 1. Configuration matrix of the analysed variants.

Variant	Step 1 Alt.	Step 2 Alt.	Step 3 Alt.
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1

4.3.1 Built volume

Relative deviations in total built volume show that height simplification is the dominant factor. With original heights preserved (Step 2 Alternative 1), deviations depend on footprint configuration: from the baseline (Variant 1–1–1, 49,713 m³) to footprint simplification Alternative 2 the volume decreases by approximately −5.5% (Variant 10: 46,994.5 m³), while full horizontal aggregation increases volume by approximately +35% (Variant 19: 67,245.66 m³). Three-level discretisation (cfr. Step 2 Alternative 2) increases volume by approximately +6% in the baseline footprint (Variant 4: 52,698.7 m³), while binary aggregation (cfr. Step 2 Alternative 3) increases it by approximately +11% (Variant 7: 55,290.7 m³). Semantic grouping (cfr. Step 3) does not affect volume.

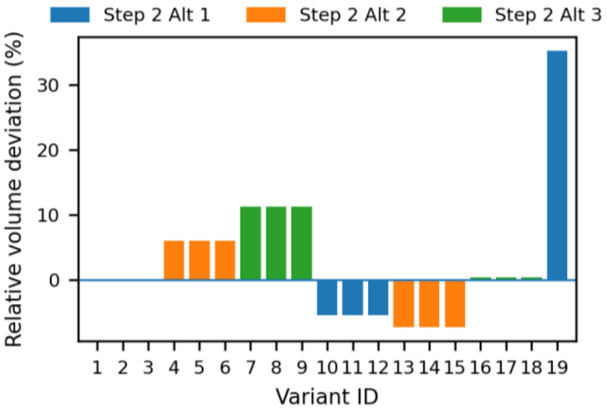

Figure 2. Relative volume deviation (%) of the analysed variants grouped by Step 2 alternative.

Table 2. Absolute volume values (m³) for all analysed variants.

Variant	Step 2 Alt.	Volume (m³)
1	1	49713
2	1	49713
3	1	49713
4, 5, 6	2	52698,7
7, 8, 9	3	55290,7
10, 11, 12	1	46994,5
13, 14, 15	2	46079,2
16, 17, 18	3	49921,61
19	1	67245,66

4.3.2 Surface area

Surface is strongly influenced by semantic grouping and, to a lesser extent, footprint simplification. The baseline yields 33,986.25 m². Building-level envelope extraction (Step 3 Alternative 2) reduces this to 21,177.65 m² (Variant 2; −38%), while block-level extraction (Alternative 3) reduces it to 16,359.89 m² (Variant 3; −52%). When combined with height discretisation, reductions increase: Variant 9 (1–3–3) yields 11,849.12 m² (approximately −65%) and Variant 15 (2–2–3) yields 12,667.07 m² (−63%). Height simplification alone has limited influence when semantic grouping remains unchanged.

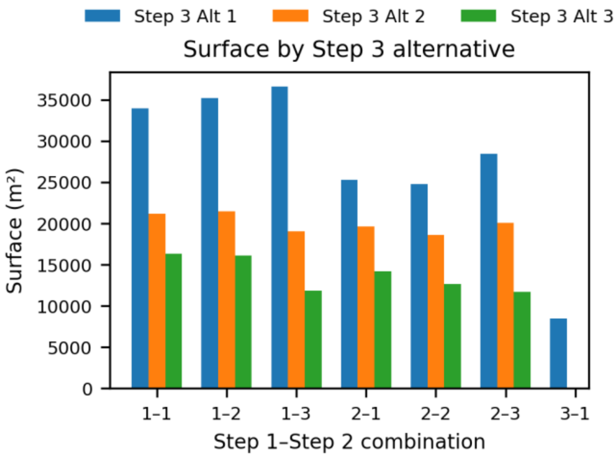

Figure 3. Surface (m²) across Step 1–Step 2 combinations grouped by Step 3 alternative.

Table 3. Absolute surface area (m²) for all analysed variants.

Variant	Step 3 Alt.	Surface (m²)
1	1	33986,25
2	2	21177,65
3	3	16359,89
4	1	35196,09
5	2	21501,99
6	3	16086,69
7	1	36574,72
8	2	19029,66
9	3	11849,12
10	1	25290,14
11	2	19606,26
12	3	14226,01
13	1	24758,58
14	2	18615,69
15	3	12667,07
16	1	28437,58
17	2	20067,43
18	3	11722,3
19	1	8460,63

4.3.3 Number of polygons

Geometric complexity (polygon count) shows the strongest variation. The baseline contains 699 polygons. Footprint simplification alone reduces this to 491 (−30%), while height discretisation does not affect polygon count. Semantic grouping substantially reduces complexity:

building-level envelope extraction yields 584 polygons (Variant 2) and block-level extraction 495 (Variant 3). Combined with footprint simplification, Variant 18 (2–3–3) yields 240 polygons (−66%), and the most extreme abstraction (Variant 19) yields 62 (−91%).

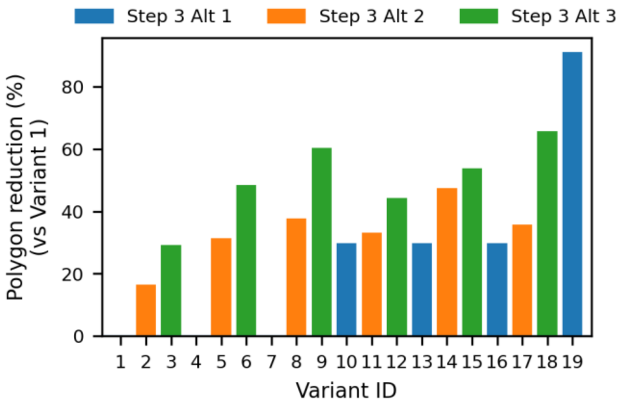

Figure 4. Relative reduction in polygon count (%) across variants grouped by Step 3 alternative.

Table 4. Absolute number of polygons for all analysed variants.

Variant	Step 3 Alt.	No. polygons
1	1	699
2	2	584
3	3	495
4	1	699
5	2	480
6	3	361
7	1	699
8	2	436
9	3	277
10	1	491
11	2	467
12	3	390
13	1	491
14	2	367
15	3	323
16	1	491
17	2	449
18	3	240
19	1	62

4.3.4 Comparative sensitivity across abstraction dimensions

Across indicators, each abstraction dimension affects outcomes differently, which suggests different implications for geometry-sensitive analyses. Height simplification primarily influences built volume, and is therefore likely to be most critical for applications relying on volumetric estimates, such as material stock estimation, aggregate energy demand modelling, or analyses where built mass is used as an explanatory variable. By contrast, semantic grouping has no effect on total built volume but strongly modifies exposed surface area and polygon count; it is therefore particularly relevant for applications that depend on envelope geometry, such as thermal exchange assessment, solar exposure studies, life cycle assessment, or façade- and roof-based material estimations. Footprint simplification shows a more intermediate behaviour, moderately affecting both volume and surface while consistently reducing geometric complexity.

These results indicate that different generalisation strategies should not be understood as neutral preprocessing steps, since they selectively privilege some analytical dimensions over others. In this sense, no single block representation can be considered universally optimal. Rather, the appropriate level and type of abstraction depends on the intended analytical use. Variants such as 2–2–2 and 2–3–2 appear to offer a useful compromise, achieving substantial reductions in geometric complexity while maintaining comparatively moderate deviations in volume and surface. This suggests that partially simplified block models may support efficient urban-scale analysis when computational manageability is needed.

5 Conclusion

This study has presented an exploratory investigation of alternative generalisation strategies for 3D urban block models and their effects on attributes relevant to geometry-sensitive urban analyses, such as solar/shadow analysis, urban energy modelling, and material flow analysis. Starting from a detailed building-part representation derived from cadastral data, block-level variants were generated by systematically modifying footprint structure, height information, and semantic envelope definition. The results demonstrate that modelling decisions at block scale can substantially influence derived geometric attributes, such as height and volume, even when based on identical input data. As these attributes underpin geometry-sensitive urban analyses—such as solar and shadow analysis or material flow analysis—these modelling choices can ultimately affect analytical results.

Each abstraction dimension affects analytical indicators differently. Height simplification primarily influences volumetric estimates, producing deviations of up to approximately +35% / −5.5% depending on footprint configuration. Semantic grouping has no impact on total built volume but strongly reduces exposed envelope area and geometric complexity; block-level envelope extraction reduced surface estimates by up to ~65% relative to the high-detail reference configuration. Footprint simplification shows an intermediate behaviour, influencing both volume and surface area, particularly when combined with vertical abstraction. Several intermediate variants achieved polygon-count reductions exceeding 30% while maintaining moderate deviations in volume and surface area. Overall, different generalisation strategies selectively affect different geometric indicators—namely volume, surface area, and number of polygons—, and no single modelling variant is universally optimal.

The results underline the need to explicitly document block-level modelling decisions, as higher geometric detail does not necessarily guarantee more robust outcomes at aggregated scales. Partially simplified models can yield comparable results to the reference configuration while substantially reducing geometric complexity, suggesting potential gains in computational efficiency without compromising analytical validity. The methodology further shows that block-level models can be systematically derived from widely available cadastral datasets, supporting reproducible generation of simplified representations.

While the exact numerical deviations reported here are specific to the analysed block, the main contribution is transferable to other use cases at the methodological level. The results suggest that footprint simplification, height simplification, and semantic grouping affect different geometry-sensitive properties in different ways, and therefore should be explicitly defined according to the intended analytical application. In this sense, the study provides not a universally optimal block representation, but a structured framework for documenting, comparing, and selecting block-level modelling variants in urban analysis.

This study is limited to a single urban block in Zaragoza and to three indicators. Future work will extend the analysis to more diverse blocks within Zaragoza and to other European cities to assess robustness across morphologies and cadastral data structures. Additional geometry-sensitive analyses (e.g., shadow casting, MFA, LCA) and further abstraction strategies, including automated parameter selection and the integration of complementary data sources such as airborne LiDAR, will also be considered.

Declaration of Generative AI in writing

The authors declare that they have used Generative AI tools in the preparation of this manuscript. Specifically, the AI tools were utilized for language editing, improving grammar, and sentence structure, but not for generating scientific content, research data, or substantive conclusions. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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