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# From CityGML to I3S: An Empirical Evaluation of Open-Source Conversion Workflows for Interoperable 3D City Models

Chukwuma Ugwu and Zhihang Yao
Centre for Geodesy and Geoinformatics, Stuttgart Technical University of Applied Sciences (HFT Stuttgart), Stuttgart, Germany
ugwusochukwuma@gmail.com, zhihang.yao@hft-stuttgart.de

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**Abstract**

No documented, reproducible open-source workflow exists for converting CityGML data from a 3D City Database (3DCityDB) instance into functional Indexed 3D Scene Layer (I3S) Scene Layer Packages (SLPK). This study addresses that gap through systematic empirical evaluation of two conversion architectures tested across four datasets spanning single buildings to a district block of 2,571 features, Levels of Detail from LOD2 to LOD4, and multiple schema extensions. The database-driven pathway via 3D Tiles 1.1 fails due to specification incompatibility between toolchain components. The file-based pathway via 3D Tiles 1.0 succeeds reliably, delivering a 565-fold per-unit efficiency gain at district scale, compression ratios up to 11.4:1, and 100% polygon geometry preservation. Semantic retention is schema-selective at building level (0–100%) and reaches complete annihilation at surface and interior levels. Non-polygonal geometry fails silently with 38–62% data loss and no warning. The study contributes the first functional open-source workflow, the Four Thresholds Framework for practitioner decision-making, and the analytical concepts of loss vs. absence and semantic annihilation. The workflow is recommended for individual building visualization targeting I3S Explorer with AAA® or Planning schema at LOD1–2.

## 1. Introduction

Three-dimensional city models have become central to modern urban planning, environmental simulation, and smart city infrastructure (Kutzner et al., 2020). The value of these digital twins depends on data interoperability, which is the ability to move data between systems designed for semantic modelling and those designed for high-performance visualisation (Kim et al., 2024). Two dominant standards define this landscape: CityGML, the OGC standard for semantically rich 3D city models (Gröger and Plümer, 2012), and Esri's Indexed 3D Scene Layer (I3S), a tiled hierarchical format optimised for streaming and web-based visualisation (Esri, 2021).
Despite their complementary roles, no documented open-source workflow exists for converting data from a 3DCityDB instance (Yao et al., 2018) to functional I3S Scene Layer Packages (SLPK). The primary production pathway remains proprietary, with Esri's Feature Manipulation Engine workbench used for creating vendor dependency that limits academic, public-sector, and open-source communities. While prior work has proposed conceptual approaches to I3S encoding for CityGML (Padsala et al., 2023) and examined the new 3DCityDB v5 architecture (Yao et al., 2025), an implemented and validated end-to-end open-source pipeline has not been published. This study fills that gap through a sequential exploratory design executed in four phases: toolchain audit, data curation, workflow implementation, and multi-dimensional evaluation. The central research question is: under what conditions can geometric integrity and semantic fidelity be preserved during open-source CityGML-to-I3S conversion, and what are the precise constraints?

## 2. Related Works

CityGML, standardised by the Open Geospatial Consortium in 2008 and substantially revised in 2021, provides the established semantic backbone for 3D city modelling (Gröger and Plümer, 2012). Its core strength lies in a hierarchical object model encoding geometry, topology, appearance, and thematic attributes across multiple Levels of Detail, alongside an Application Domain Extension (ADE) mechanism for schema extension without breaking core compatibility (Kolbe et al., 2021). CityGML 3.0 introduced a modular core/extension structure, an explicit space concept for indoor modelling, and enhanced versioning support (Kutzner et al., 2020). These capabilities make CityGML indispensable for analytical applications like energy simulation, noise propagation, and 3D cadastre, but its verbose XML encoding presents challenges for web-based delivery and real-time streaming.
For delivery performance, two OGC community standards have emerged. OGC 3D Tiles (OGC, 2022) organises heterogeneous 3D content into a hierarchical spatial tree of binary.b3dm tiles containing batched glTF geometry with per-feature metadata, enabling adaptive streaming. Esri's I3S (Esri, 2021) takes a GIS-native approach, supporting geographic coordinate reference systems, heterogeneous layer types (3D Object, Integrated Mesh, Point Cloud), and rich attribute stores within a Scene Layer Package (SLPK). Both standards employ tiled hierarchical structures and are increasingly used in combination, driven by the need to bridge semantic depth for analysis with efficient delivery for web-based dissemination (Kim et al., 2024).

The 3D City Database (3DCityDB) is the primary open-source backend for managing CityGML data at scale. Version 4 used a PostgreSQL/PostGIS schema that decomposed geometry into individual polygons (Yao et al., 2018). Version 5 introduced a streamlined schema mapping directly to native PostGIS geometry types, full CityGML 3.0 support, and a command-line citydb-tool replacing the earlier GUI importer/exporter (Yao et al., 2025). These changes align the platform with modern automated pipeline workflows and significantly improve spatial query performance.

Several open-source tools address discrete conversion segments. PG2B3DM generates 3D Tiles 1.1 directly from PostGIS geometries with implicit tiling and structural metadata. The citygml-to-3dtiles library parses CityGML XML files and produces 3D Tiles 1.0 output with building-level attribute preservation in the batch table, though it is no longer actively maintained and supports only a limited set of coordinate reference systems. The loaders.gl tile-converter bridges 3D Tiles and I3S, with version 3.2.6 providing stable support for 3D Tiles 1.0 input. Despite these individual components, no integrated, end-to-end open-source workflow from 3DCityDB to functional I3S SLPK has been documented or validated. Padsala et al. (2023) proposed a conceptual framework for I3S encoding compatible with the OGC CityGML 3.0 building model, demonstrating theoretical viability but stopping short of a fully implemented pipeline. The present study addresses that implementation gap.

## 3. Methodology

### 3.1 Datasets

Four CityGML datasets were selected to represent the operational diversity of real-world city model archives (Table 1). Bau8, sourced from HFT Stuttgart, is an architecturally complex single building at LOD2 and LOD3 carrying the AAA® cadastral extension and EnergyADE attributes, making it the primary test case for semantic richness and texture handling. BW is a district-scale urban block of 2,571 buildings at LOD2 from the Baden-Württemberg Open Geoportal, used to assess processing scalability and performance under realistic load. FZK-1 is a single-building CityGML 3.0 compliance test dataset from TIK Karlsruhe at LOD2, used to probe newer schema compatibility. FZK-2, also from TIK Karlsruhe, covers the same building across LOD2, LOD3, and LOD4 with Planning Extension attributes and interior spaces, enabling multi-LoD and interior semantic evaluation. All datasets underwent coordinate transformation to EPSG:25832, automated validation using citygml4j 2.12.1, and import into a 3DCityDB v5.3.0 instance on PostgreSQL 15/PostGIS 3.4 prior to conversion.

| Dataset | Source | Spatial Extent | Primary LoD |
|---|---|---|---|
| Bau8 | HFT Stuttgart | Single complex building | LOD2, LOD3 |
| BW | BW Open Geoportal | Urban block (2,571 bldgs) | LOD2 |
| FZK-1 | TIK Karlsruhe | Single building | LOD2 |
| FZK-2 | TIK Karlsruhe | Single building | LOD2–LOD4 |

Table 1. Experimental datasets and their key characteristics.

Regarding ADE support in 3DCityDB v5: the Bau8 dataset carries EnergyADE attributes from the CityGML 2.0 era. While 3DCityDB v5 stores ADE-extended data, querying and exporting ADE-specific attributes requires manual schema configuration beyond default installation, an important constraint for practitioners expecting out-of-the-box ADE support.

### 3.2 Conversion Workflows

Two conversion architectures were implemented using publicly available open-source tools with default configurations on a controlled workstation (Intel Core i7-13700K, 64 GB DDR5, NVIDIA RTX 4070 Ti, Windows 11 Pro). **Variant A** (database-driven, 3D Tiles 1.1): 3DCityDB → PG2B3DM → 3D Tiles 1.1 → tile-converter v3.2.6 → I3S SLPK. This pathway queries geometries directly from PostGIS database views. **Variant B** (file-based, 3D Tiles 1.0): 3DCityDB → citydb-tool v1.1.0 → CityGML export → citygml-to-3dtiles v0.6.2 → 3D Tiles 1.0 → tile-converter v3.2.6 → I3S SLPK. Both architectures are illustrated in Figure 1.

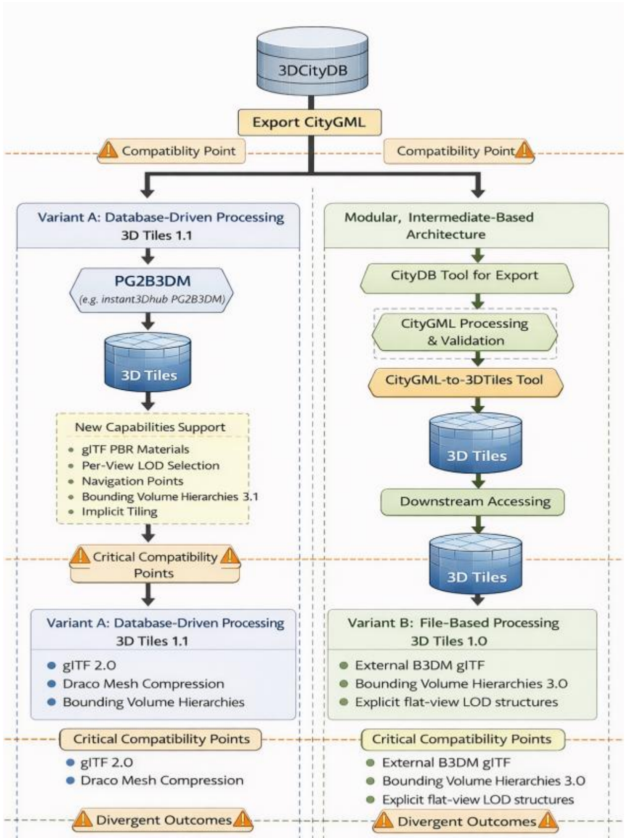


Figure 1. The two implemented conversion architectures. Variant A (left) employs database-driven 3D Tiles 1.1 processing; Variant B (right) uses file-based 3D Tiles 1.0 processing. Critical compatibility points and divergent outcomes are highlighted. (Source:Own creation)

### 3.3 Evaluation Framework

Evaluation applied four criteria across all datasets: (1) functional viability: renderable SLPK generation; (2) geometric integrity: geometry type preservation; (3) semantic fidelity: attribute retention by schema and feature level; and (4) performance: stage-wise processing time and file size reduction. A key methodological contribution is the explicit loss vs. absence distinction, which separates converter failures (attribute present in source, absent in output) from source limitations (attribute never present). The final Variant B workflow was containerised in Docker (sochuma/citygml-to-i3s) for reproducibility.

# 4. Results

## 4.1 Functional Viability

Testing revealed a decisive binary divergence. Variant A produced SLPK files that passed basic validation but failed to render geometry in all tested viewers. Root cause analysis identified a specification incompatibility: tile-converter v3.2.6 is optimised for 3D Tiles 1.0 and cannot process 1.1-specific constructs, specifically implicit tiling and updated metadata schema extensions. Manual removal of 1.1-specific headers proved insufficient, indicating the incompatibility is embedded within binary tile data. Variant B consistently produced functional, interactive I3S outputs across all four datasets and all LODs, with zero failures across 12 execution cycles, as illustrated by the direct visual contrast in Figure 2. This establishes the toolchain ecology principle: interoperability success is determined by the weakest link in the toolchain, not the most advanced specification version.

A notable finding from the FZK-1 dataset concerns CityGML 3.0 compatibility. Variant B processed the FZK-1 CityGML 3.0 input without any special handling, behaving identically to CityGML 2.0 datasets. The schema differences introduced in version 3.0 manifest at the Level of Detail feature configuration level rather than at the conversion pipeline level, meaning Variant B is effectively version-agnostic in practice. Practitioners working with CityGML 3.0 datasets can apply this workflow without modification.


Figure 2. Variant A (left) produced blank geometry; Variant B (right) rendered a complete, semantically attributed I3S scene in I3S Explorer. (Source: Own creation)

## 4.2 Performance and Scalability

Table 2 presents stage-wise processing times. The 3D Tiles conversion stage is the primary bottleneck, consuming 25–97% of total time, driven by topological complexity rather than raw feature count: FZK-2 LOD4 with interior structures required 178 s for tiling while BW with 311,022 vertices but simpler LOD2 geometry completed in 32 s. A critical finding is fixed-cost amortisation at scale: per-unit cost for BW (0.023 s/building, 2,571 buildings) is 565× lower than a single-building conversion, because tool initialisation and cache creation dominate per-job overhead while marginal cost per additional feature approaches zero.

| Dataset | LOD | Export (s) | 3D Tiles conv. (s) | I3S conv. (s) | Total (s) |
|---|---|---|---|---|---|
| FZK-2 | LOD 2 | 3 | 33* | 2 | 38* |
| FZK-2 | LOD 3 | 2 | 2 | 2 | 6 |
| FZK-2 | LOD 4 | 3 | 178 | 3 | 184 |
| Bau8 | LOD 2 | 5 | 4 | 4 | 13 |
| Bau8 | LOD 3 | 2 | 1 | 1 | 4 |
| BW | LOD 2 | 10 | 32 | 16 | 58 |

Table 2. Stage-wise processing times for Variant B across all test datasets (* FZK-2 LOD2 includes first-run caching effects).

Table 3 presents file size reduction. Compression correlates positively with source complexity, ranging from 1.25:1 for a simple 8-feature LOD2 model to 11.4:1 for the district-scale BW dataset. The compression budget is attributed to binary glTF encoding with gzip (40–50%), semantic attribute stripping (30–40%), and geometric simplification (10–20%).

| Dataset | LOD | CityGML (MB) | SLPK (MB) | Ratio | Reduction |
|---|---|---|---|---|---|
| FZK-2 | LOD 2 | 0.01 | 0.008 | 1.25:1 | 20% |
| FZK-2 | LOD 3 | 0.16 | 0.04 | 4.0:1 | 75% |
| FZK-2 | LOD 4 | 9.04 | 1.10 | 8.2:1 | 88% |
| Bau8 | LOD 2 | 0.03 | 0.01 | 3.0:1 | 67% |
| Bau8 | LOD 3 | 0.08 | 0.02 | 4.0:1 | 75% |
| BW | LOD 2 | 51.99 | 4.57 | 11.4:1 | 91% |

Table 3. File size evolution and compression efficiency for Variant B across all test datasets.

## 4.3 Geometric Integrity

Polygonal geometry was preserved at 100% across all datasets and LODs. Window and door geometries are visible at LOD3; interior spaces are present at LOD4. The FZK-2 dataset exposed a critical limitation: LineString features representing architectural outlines and ridges were silently dropped, causing 50% component loss at LOD2, 38% at LOD3, and 58% at LOD4. No warning is propagated to the SLPK output. Visual fidelity assessment, shown in Figure 3, exposed a viewer-dependent issue: all datasets render correctly in I3S Explorer, but the BW district dataset exhibits severe geometric distortion in ArcGIS Pro 3.2 (there are meshy artefacts affecting wall and roof surfaces). This distortion is unique to BW and does not occur for single-building datasets. Hypothesised causes include

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vertex count thresholds (311,022 for BW) or Building-part hierarchy complexity (1,043 Building-part features). ArcGIS Online rendered none of the SLPK outputs.

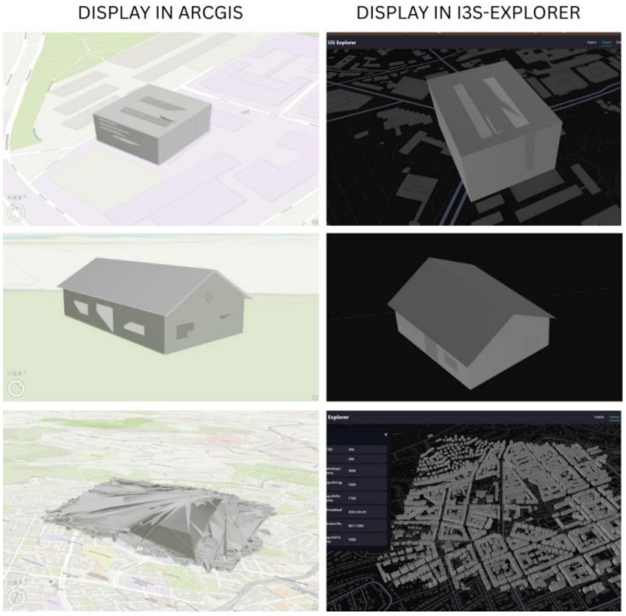


Figure 3. Visualisation of final I3S output in ArcGISPro (left) and in I3S-Explorer (right). (Source: Own creation)

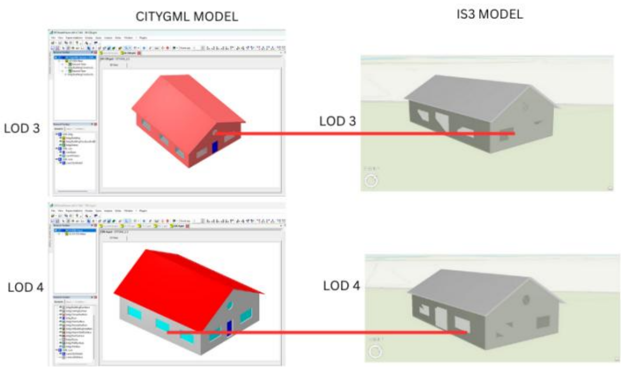


Figure 4. Visualisation of final I3S output in ArcGISPro (left) and in I3S-Explorer (right). (Source: Own creation)

### 4.4 Semantic Fidelity

Building-level retention is strongly schema-dependent (Table 4). The AAA® cadastral extension achieves 100% preservation. The Planning Extension achieves 75%. Core CityGML metadata is systematically filtered to 6–9%: only gml:id survives. EnergyADE attributes are completely lost (0%).

| Dataset / Schema | Source | SLPK | Verdict |
|---|---|---|---|
| Bau8 - Core CityGML | 13 | 1 | Severe loss |
| Bau8 - AAA® Extension | 21 | 21 | Perfect |
| Bau8 - EnergyADE | 2 | 0 | Failure |
| BW - Core CityGML | 11 | 1 | Severe loss |
| BW - AAA® Extension | 6 | 6 | Perfect |
| FZK-2 - Core CityGML | 17 | 1 | Severe loss |
| FZK-2 - Planning Ext. | 4 | 3 | Good |

Table 4. Building-level semantic attribute retention by dataset and schema category.

Surface-level and interior semantics underwent semantic annihilation: a 0% retention across all datasets, all surface types, and more than twenty individual attributes, as visualised for the LOD3/LOD4 case in Figure 4. Definitive evidence of intentional filtering is provided by the Bau8 anomaly: the @cityeditor:layer attribute is preserved at building level but eliminated at window-surface level for the same feature in the same dataset, demonstrating a deliberate architectural choice in the converter, not incidental loss.

## 5. Discussion

### 5.1 Four Thresholds Framework

Synthesising the empirical evidence, we propose a practitioner decision framework around four operational thresholds (Table 5). The framework explicitly captures not only what is suitable but what is not, enabling calibrated expectations before conversion is attempted. The workflow's operational sweet spot is individual building visualisation at LOD1–2 with polygonal geometry and AAA® or Planning schema, targeting I3S Explorer or CesiumJS. For district-scale ArcGIS Pro deployment, non-polygonal data, EnergyADE semantics, or applications requiring sub-building semantic fidelity, alternative approaches must be sought.

For LOD complexity, practitioners working with LOD3 models should accept that window and door geometries will be geometrically present but semantically unlabelled. LOD4 interior models are geometrically converted but rooms become anonymous volumes, making this workflow unsuitable for indoor navigation or facility management. For schema compatibility, the divergence between AAA® (100%) and EnergyADE (0%) reflects the converter's design target. Practitioners with EnergyADE data should retain the original 3DCityDB instance for energy analysis and use the I3S output for spatial visualisation only. A practical workaround is to pre-populate building-level attributes using AAA® or Planning Extension schema patterns before export, ensuring critical identifiers survive conversion.

| Threshold | Recommended | Caution | Not suitable |
|---|---|---|---|
| 1. LOD complexity | LOD1–2 | LOD3 (windows visible, unlabelled) | LOD4 (anonymous interiors) |
| 2. Schema compatibility | AAA® (100%)Planning Ext. (75%) | Core CityGML (6–9%) | EnergyADE (0%), surface/interior schemas (0% — semantic annihilation) |
| 3. Geometry type | Polygon / MultiSurface | Solid (LOD2 only) | LineString, Curve, Point (silent failure, 38–62% loss) |

| Threshold | Recommended | Caution | Not suitable |
|---|---|---|---|
| 4. Viewer platform | I3S Explorer / CesiumJS | ArcGIS Pro (partial; district distortion) | ArcGIS Online (no display) |

Table 5. The Four Thresholds Framework for CityGML-to-I3S conversion suitability.

For non-polygonal geometry, the most effective mitigation is pre-conversion validation: the citygml4j library can inventory geometry types before conversion, allowing practitioners to remove or polygonalise LineString features ahead of time. Without this step, 38–62% component loss occurs silently with no output warning. For viewer platform, the ArcGIS Pro district-scale distortion observed for the BW dataset remains under investigation, but a practical workaround is to split large districts into sub-tiles and load them as separate scene layers. For district-scale deployment I3S Explorer or CesiumJS currently provide more reliable rendering.

### 5.2 Toolchain Ecology and Specification Maturity

The failure of Variant A illustrates a recurring pattern in applied interoperability research where specification advancement outpaces toolchain implementation. The OGC 3D Tiles 1.1 standard offers theoretical advantages like implicit tiling, enhanced metadata, but the absence of support in tile-converter v3.2.6 renders these irrelevant in practice. The empirical evidence is unambiguous because 3D Tiles 1.0 enables functional conversion while 3D Tiles 1.1 does not. Therefore toolchain compatibility audits are essential before workflow design, not an afterthought.

### 5.3 Semantic Trade-offs and Implications

The semantic results reveal a fundamental trade-off inherent in converting from an information modelling standard (CityGML) to a visualisation streaming format (I3S). I3S's indexed mesh buffers are optimised for rendering performance, not semantic richness; the 30–40% of compression attributable to semantic stripping quantifies this trade-off directly. Practitioners must maintain original CityGML datasets for analysis. The I3S output is appropriate for dissemination and visual exploration, not analytical workflows dependent on semantic completeness. The silent dropping of non-polygonal geometry is a separate usability failure: tool developers should implement explicit warnings for unsupported geometry types as a high-impact, low-complexity improvement.

## 6. Conclusion

This study delivers the first documented, empirically validated, and reproducible open-source workflow from 3DCityDB to functional I3S SLPK, containerised as a Docker image (sochuma/citygml-to-i3s). The indirect route via 3D Tiles 1.0 and tile-converter v3.2.6 is the only viable pathway in the current toolchain. It is recommended for LOD1–2, polygonal geometry, and AAA® or Planning schemas targeting I3S Explorer and CesiumJS. It is not suitable for EnergyADE semantics, non-polygonal geometry, sub-building semantic requirements, or large-scale ArcGIS Pro deployment.

The study's scientific contributions extend beyond the workflow: the toolchain ecology principle, that interoperability is constrained by the weakest link, as demonstrated by the 3D Tiles 1.0/1.1 divergence; the loss vs. absence distinction for precise attribution of converter limitations; the concept of semantic annihilation for the systematic elimination of sub-building semantics; the Four Thresholds Framework as an evidence-based decision too.

Subsequent to this study, the Variant B workflow has been applied at significantly larger scale (9.7 million LOD2 buildings from the Open Bayern dataset rendered on CesiumJS via 3DCityDB v5) confirming the computational scalability findings reported here. More recent developments have also addressed the texture limitation identified in this study, direct 3DCityDB-to-I3S conversion with real appearance support is now achievable, with outputs rendering correctly in both ArcGIS Pro and CesiumJS, as shown in Figure 5. These developments motivate integration of an I3S export module into a future 3DCityDB release. The Docker image (sochuma/citygml-to-i3s) has recorded over 300 pulls since publication, providing early evidence of community adoption.
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Future work should investigate the ArcGIS Pro district-scale rendering distortion, implement non-polygonal geometry warnings, develop configurable semantic mapping profiles, and re-evaluate the 3D Tiles 1.1 pathway as tooling matures.

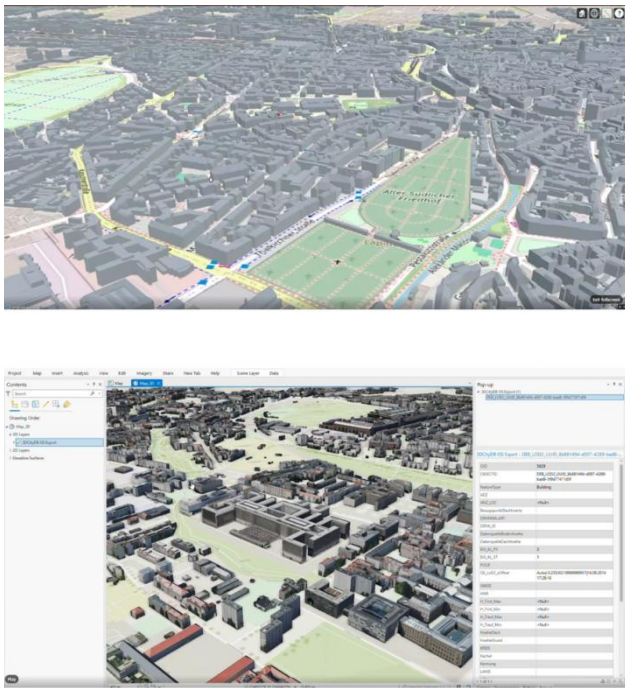

Figure 5. Improved workflow output demonstrating direct 3DCityDB-to-I3S conversion with real appearance support, rendered in ArcGIS Pro (below) and CesiumJS (above), applied to 9.7 million LOD2 buildings from the Open Bayern dataset. This development addresses the texture limitation identified in the original workflow. (Source: Yao, 2025)

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