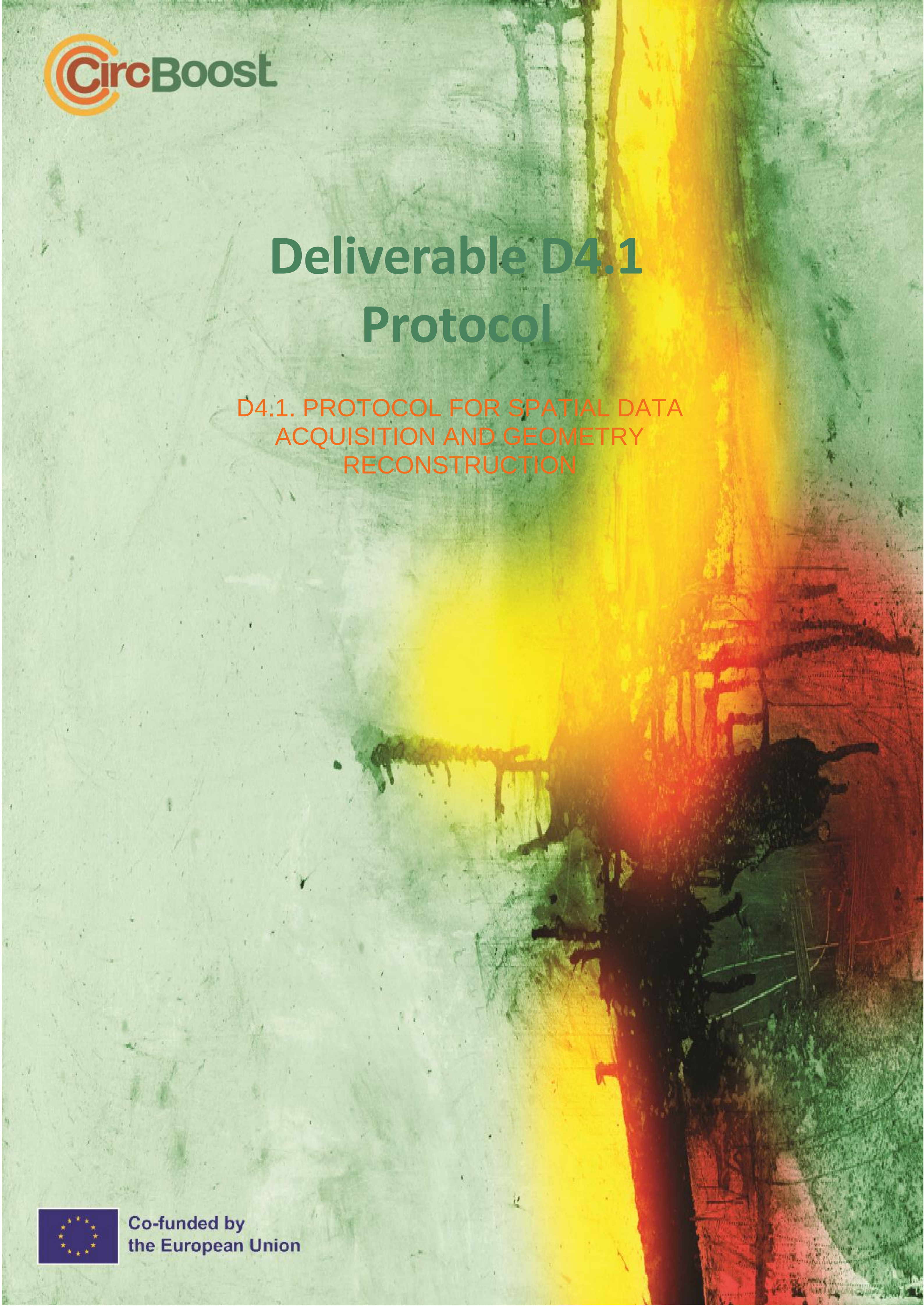

CircBoost

Deliverable D4.1
Protocol

D4.1. PROTOCOL FOR SPATIAL DATA ACQUISITION AND GEOMETRY RECONSTRUCTION

Co-funded by
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Document Information

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List of abbreviations

EC – European Commission

GA – Grant Agreement

WP – working package

1 Executive summary

The *D4.1 Protocol for Spatial Data Acquisition and Geometry Reconstruction* defines a structured, semi-automated approach for upgrading CityGML Level of Detail 2 (LOD2) to Level of Detail 3 (LOD3). By integrating point cloud data, aerial imagery, the protocol facilitates the generation of detailed 3D city models, incorporating building elements such as windows, doors, balconies, and chimneys while maintaining compliance with CityGML standards.

Developed within the *CIRC-BOOST* project, the protocol extends beyond geometric reconstruction by supporting circular economy principles within the construction sector. By incorporating material-related attributes into LOD3 models, it enables material stock analysis, waste flow assessments, and resource efficiency evaluations, contributing to sustainable urban planning. The methodology accommodates diverse data acquisition approaches, ensuring flexibility in adapting to different urban contexts and varying levels of data availability.

The protocol outlines a workflow that balances automation with manual refinement, addressing challenges related to precision, scalability, and computational efficiency. While point clouds serve as the primary input for LOD3 generation, the framework also integrates raw data formats, allowing for adaptability based on available datasets. The methodology has been tested in the Belgrade use case, demonstrating its applicability in real-world urban environments.

By aligning with *CityGML 3.0* standards and referencing the *CityGML Building Module*, the protocol establishes a standardized approach for detailed city modeling. Developed as part of Task *T4.1.3* at *HafenCity University Hamburg (HCU)* within the *Horizon Europe-funded CIRC-BOOST project (2023–2027)*, this deliverable provides a foundation for further advancements in semantic 3D city modeling, supporting both research and practical applications in digital urban analysis and circular construction practices.

2 Introduction

The *D4.1 Protocol for Spatial Data Acquisition and Geometry Reconstruction*, which describes the methodologies, tools, and workflows required to upgrade CityGML Level of Detail (LOD2) to Level of Detail 3 (LOD3) utilizing the point cloud data, also referencing the essential background processes of CityGML LOD2 generation, including data acquisition. CityGML LOD3, as defined in this protocol, includes the addition of detailed building elements such as windows, doors, balconies, and chimneys. By addressing these enhancements, the protocol provides a comprehensive framework for understanding and implementing the entire pipeline, from raw data acquisition to the final production of semantically rich 3D city models. While point clouds serve as the primary input for LOD3 generation, the protocol also incorporates raw data formats, offering flexibility to accommodate varying levels of detail depending on data acquisition methodologies.

The CIRC-BOOST project, under which this protocol was developed, integrates circular economy principles into the construction sector by providing detailed insights into material use and recovery. The production and use of CityGML LOD3 data aligns with the overall goal of the CIRC-BOOST project, offering higher resolution and more accurate material information for informed decision-making. Upgrading to LOD3 models enables better assessments of material stocks, construction and demolition waste flows, and circularity indices, supporting the project's overarching objective to enhance resource efficiency in the built environment.

The protocol ensures compliance with CityGML standards and refers to the CityGML Building Module for modeling building geometries and semantics, while addressing the unique requirements of the Belgrade use case area. This protocol titled Deliverable D4.1, is developed by HafenCity University Hamburg (HCU) within Task T4.1.3 of the CIRC-BOOST project. CIRC-BOOST is a 4-year project, 2023-2027, funded under the Horizon Europe Programme (*Circ-Boost*, 2024; Kolbe, 2009; Kolbe et al., 2005).

2.1 CityGML Level of Details

CityGML provides different Levels of Detail to represent the geometry of urban spaces and their boundaries with varying degrees of precision and complexity. Such levels allow the representation of the spatial aspects for spaces and space boundaries alike in either volumetric or areal objects, according to the intended application and captured data (Kolbe, 2009; Kolbe et al., 2021).

Figure 1 Level of Detail in CityGML (Biljecki et al., 2016)

CityGML Level of Detail 2 (LOD2) models include simplified building geometries with basic roof shapes and are primarily used for general urban planning and visualization. LOD2 data often lacks detailed facade information, such as windows or small protrusions, and is not sufficient for tasks requiring high spatial accuracy or precise material quantification (Biljecki et al., 2016; Kutzner et al., 2020).

CityGML Level of Detail 3 (LOD3) provides a more advanced representation of urban environments, including detailed architectural façade elements such as individual windows, doors, and roof overhangs as well as roof elements such as chimneys. These models are essential for applications requiring greater spatial resolution and semantic richness, such as energy simulations, material stock analysis, and advanced urban planning (Biljecki et al., 2016; Kutzner et al., 2020).

3 Scope and Objectives

3.1 Scope:

The scope of this protocol includes defining workflows for spatial data acquisition(surveying), detailed geometry reconstruction, and semantic enrichment. The protocol incorporates state-of-the-art tools and workflows to achieve precise geometry reconstruction and semantic enrichment. This includes addressing key areas such as standardizing data preparation processes, and geometric modeling of building facades.

Input:

The primary input data for this workflow includes CityGML LOD2 models and point clouds. To increase reproducibility for other cities, the protocol also incorporates the conventional CityGML LOD2 production pipeline, mentioning the foundational steps such as photogrammetry.

Output:

The target output of this work is CityGML LOD3 data, enhanced with additional building elements, including windows, doors, balconies, and chimneys. These detailed models comply with the CityGML Building Module standards.

3.2 Objectives

The primary objective of this protocol is to deliver a step-by-step, structural and practical methodology for upgrading CityGML LOD2 to LOD3, focusing on the incorporation of the 4 architectural building elements: chimney, balcony, window and door following the state of art. Designed to meet the specific requirements of the CIRC-BOOST project, the protocol emphasizes the Belgrade use case while maintaining flexibility for application to other cities and datasets.

In doing so, the protocol also provides a foundation for adapting to various datasets and urban contexts, ensuring the reproducibility of workflows for different use cases within the CIRC-BOOST project. By offering a systematic approach, this protocol supports the efficient and accurate production of high-resolution 3D city models, meeting the growing demand for reliable data in urban management and planning.

3.3 Disclaimer

This workflow represents one of many possible approaches to upgrading LOD2 to LOD3. Developed by the HCU team, the methodology has been validated on 18 buildings in the test area. However, as the project scales up and progresses, the methods may evolve based on new findings and requirements.

4 Development of Methodologies for CityGML LOD3 Creation

This chapter provides detailed background information and overview of the methodologies utilized for developing this protocol. It covers the challenges in aligning the project scope with real-world practices, explores the state of the art in digital city model production, incorporates insights gained through expert consultations, and evaluates available market-ready approaches.

The methodology follows a research-driven, iterative approach, integrating state-of-the-art practices, market-ready tools, and expert insights.

4.1 Identification of the problem

To establish a clear understanding of the challenges at hand, an evaluation of the project's task and deliverable descriptions was undertaken.

Description of the deliverable D4.1:

"Deliverable D4.1 – Protocol for spatial data acquisition and geometry reconstruction: The protocol will specify the digital techniques, determine the methodology for acquiring the necessary data on the geometric building information, and describe the CityGML geometry reconstruction algorithm in detail. (covers T4.1)"

The description of the relevant task:

"(iii) Building stock geometry reconstruction: The CityGML LOD3 geometry will be generated in two steps. In the first step, the areal scanning-based point cloud will be used to generate a rough geometry (i.e., LOD1 or, where possible, LOD2). This will be done by using already established algorithms for the semantic segmentation and geometric reconstruction of roofs. In the second step, the combined point cloud (i.e., merged areal, mobile, and terrestrial scanning-based point clouds) will be used to reconstruct a detailed lateral building geometry. For this step, a custom point cloud semantic segmentation and CityGML geometry reconstruction algorithm will be developed and validated. The final result of this task is a CityGML LOD3 map of the building exteriors"

The task description, which envisioned the development of a new point cloud semantic segmentation and CityGML LOD3 reconstruction algorithm, was ambitious given the resources and timeline. Current research shows that even fully automated LOD2 model creation is still evolving, with challenges in achieving geometric precision. Automated LOD3 creation, especially for intricate façade details, remains in its infancy (Barnefske, 2023; Donkers, 2013; Gruen et al., 2019; Ledoux et al., 2021; Peters et al., 2021).

Therefore, revised research questions were framed to better align with project goals:

- How can CityGML LOD3 models be created using conventional data acquisition techniques, focusing on lateral building geometries such as windows, doors, balconies, and chimneys?
- What is the current state of automation in creating LOD3 models, and how can semi-automated methodologies be optimized for large-scale applications?
- What is the achievable level of automation in producing LOD3 city models with existing tools and resources?

The reframing of these questions guided the transition from a theoretical to a practical methodology, balancing innovation with feasibility, following points are remarked.

Lack of Standardized Workflows: Existing methods for producing LOD3 data vary widely, with limited agreement on best practices for integrating diverse data sources such as photogrammetry, LiDAR scans,

Automation Challenges: Semi and fully automated approaches for producing LOD3 models remain underdeveloped, especially in handling complex facade geometries and maintaining semantic accuracy. Even LOD2 models produced with fully automated approaches lacks the geometric accuracy. In the market, LOD2 model generation is conducted using many manual tasks.

Resource Constraints: Developing novel methods for LOD3 production requires significant time, expertise, and computational resources, making it impractical within the scope of the CIRC-BOOST project timeline.

To address these challenges, this protocol adopts a semi-automated methodology that balances efficiency with accuracy, leveraging market-ready tools validated through research and expert consultations.

4.2 State of the Art in Digital City Model Production

CityGML LOD2 models are widely used in Europe for urban visualization and planning. Approximately 14 cities provide open-source LOD2 datasets for 56.7 million buildings. Examples include Vienna, Prague, Helsinki, Lyon, Berlin, and Zurich. However, LOD3 models, which include detailed façade elements, remain rare, with only three cities—Ingolstadt with 56 buildings, Munich with 28 buildings, and Poznan with 14 buildings— publishing public LOD3 datasets, covering a total of 169 buildings (Wysocki et al., 2024).

Country	Total	Level of Detail (LOD)	Source
Czech Republic	0.1 M	2	Housing statistics
Estonia	0.8 M	1,2	Dataset
Germany			
12 States	45.8 M	2	Federal agency report
Ingolstadt	56	3	Dataset
Munich: tum2win*	28	3	Dataset
Japan: PLATEAU Project			(Seto et al., 2023)
>150 cities	18.3 M	1,2	(Seto et al., 2023)
12 cities	816	3	Dataset
Netherlands	10.0 M	2	(Peters et al., 2021)
Poland	15.5 M	1,2	Federal agency report
Poznań	14	3	Dataset
Switzerland	57.1 K	1,2	Dataset
Zurich	57.1 K	1,2	Dataset
United States of America			
Open City Model*	125.0 M	1	Dataset
New York City	1.1 M	1,2	Dataset
Subtotal LOD1+2	**216.5 M**		
Subtotal LOD3	**913**		
Total	**216.5 M**		

Table 1: Total number estimates of semantic 3D building models for selected countries from public authorities and third parties. CityGML LOD3 Datasets are highlighted. Updated by the authors upon the work of (Wysocki et al., 2024).

The city of Hamburg claims to have upgraded approximately 350,000 buildings to LOD3, but these datasets only include roof details without façade-level information, reflecting the limitations of current methodologies.

The automated generation of LOD2 models is achievable using certain software tools; however, these models typically exhibit lower geometric accuracy due to their methodological limitations. In most cases, facades are created by extruding the building footprints from the roof geometry, resulting in a lack of critical details such as roof overhangs.

Emerging methods that utilize deep learning to enhance automated LOD2 creation by incorporating roof overhang data are still in the early stages of development. Given the current state of the art, proposing the development of a new semi-automated LOD3 creation algorithm using the resources and timeline available in the CIRC-BOOST project does not align with the practical capabilities of the field. Instead, adapting proven methodologies and tools is more reflective of real-world progress and technological maturity.

Given that, many cities currently follow these fundamental steps for producing LOD2 city models:

- Aerial imagery or surveying to capture raw data.
- Geometric corrections and point cloud generation from the imagery.
- Photogrammetric restitution to semi-automatically delineate building roof and facade details for LOD2 datasets.
- Construction and validation of LOD2 geometries.
- Export of CityGML LOD2 datasets for further use.

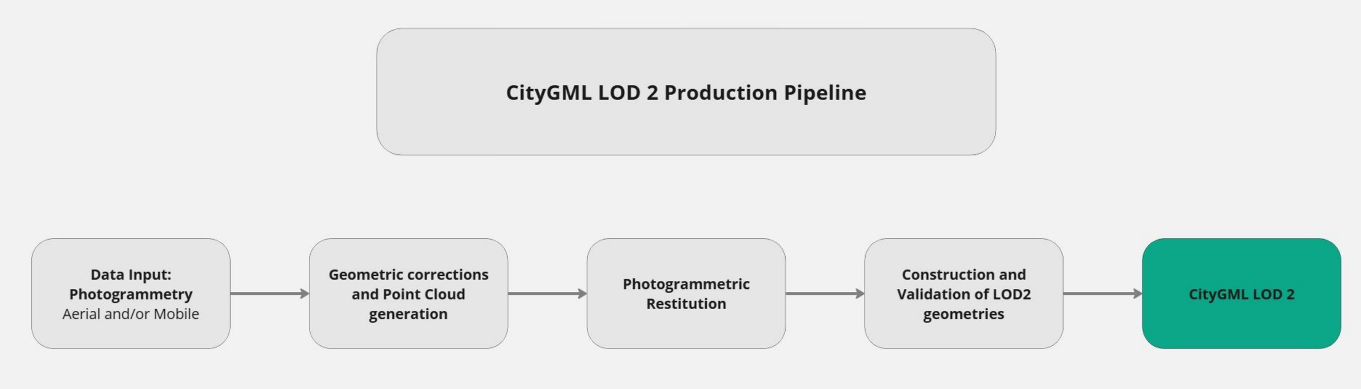


Figure 2 CityGML LOD2 Production Pipeline

4.3 Expert Consultations

To validate the methodology and adopt proven practices, consultations with leading institutions and experts are conducted.

Hamburg’s State Office for Geoinformation and Surveying (LGV)

LGV’s experience with upgrading Hamburg’s 350,000-building database to LOD3 offered valuable insights. Their approach, which combined photogrammetric data with cadastral floor plans, successfully incorporated roof details, demonstrating the utility of integrating different data sources.

LGV's emphasis on open-source solutions and its collaboration with HCU, particularly on the Hamburg Geoportal, provided a strong foundation for adapting their methods to the Belgrade dataset.

Industry Experts and Market Solutions

Consultations with experts and software providers revealed the capabilities and limitations of existing tools for LOD3 production. Solutions that directly support CityGML schema manipulation and advanced modeling functionalities were prioritized, ensuring semantic and geometric consistency.

4.4 State of art in Market Ready Solutions

The research concluded that leveraging market-ready tools is more feasible than developing a novel algorithm. Delivery within the timeline is possible with utilization of a market-ready tools rather than developing a novel algorithm. Therefore, a research on the market-ready solutions have been conducted.

Free Software Options

Free software options exist but offer very limited functionality, primarily for viewing CityGML data. They are incapable of editing or manipulating CityGML files beyond basic operations.

Examples include:

- tridicon® CityDiscoverer light
- eveBIM
- GEORES for Sketchup
- KITModelViewer (FZKViewer)
- Liquid XML Editor
- GML Viewer
- TerrainView
- Aristoteles

Commercial Software Solutions

Several commercial tools were evaluated for their ability to handle LOD3 creation:

FME Software: Capable of reading CityGML files and performing basic tasks such as texture assignments. However, it does not offer robust tools for deep editing or restructuring of CityGML data, which is critical for our project scope.

Terrasolid: Primarily used for processing point cloud data, Terrasolid can create CityGML LOD2 data from point clouds but lacks the tools necessary for generating and modifying LOD3 elements.

CityGRID: Direct modeling within the CityGML schema, integration of point clouds and aerial imagery, and support for semantic and geometric consistency.

Comprehensive CityGML Manipulation

CityGRID directly operates on the CityGML data format and provides the comprehensive set of tools necessary for our project goals. Its modular approach (including Manager, Administrator, Texturizer, FME Interface, Modeler, Shaper, and Solid) allows for deep and precise manipulation of CityGML data. This capability is essential for upgrading from LOD 2.0 to LOD 3.0 and ensures that all semantic and geometric aspects are maintained and accurately represented.

Advanced Features and Functionalities

Integration of Point Cloud and Aerial Data: CityGRID integrates point cloud data and aerial images to produce highly accurate building models, enhancing the detail and precision of our LOD3 models.

Advanced Modeling and Editing Tools: The software offers robust editing capabilities, including a CityGRID Modeler plugin for 3DS Max, providing high-level modeling features unavailable in other tools.

Direct Modeling in CityGML Schema: CityGRID models buildings and details directly within the CityGML schema, ensuring that our data structure aligns perfectly with LOD 3 standards.

Automatic and Manual Texturing: CityGRID supports both automatic and manual use of aerial, mobile, and manually-captured facade images for creating realistic textures.

Support for CityGML 3.0: Unlike most alternatives, CityGRID supports the emerging CityGML 3.0 schema, aligning with future-proof data practices.

Database Compatibility: With built-in support for Oracle, SQL, and PostgreSQL databases, CityGRID offers integrated solutions for managing complex 3D city models effectively.

Proven Reliability

Case Study – Hamburg: CityGRID's reliability is evidenced by its use in the LOD3 upgrade of 350,000 buildings by the Hamburg state agency (LGV). This large-scale implementation demonstrates the software's capability, robustness, and effectiveness in achieving complex data upgrades. Moreover, many other European cities, including Cologne, Linz, Zurich, Prague, Cassel's state units currently work collaboratively with the UVM systems for the creation and upgrade of their city models (*3D Citymodel*, n.d.; *UVM Systems*, n.d.).

One of the significant challenges in system selection was the editing of CityGML files directly and the addition of LOD3 details to existing CityGML models. Following expert consultations and thorough market research, the HCU team has decided to adopt the UVM System CityGrid software suite as the preferred solution.

4.5 Guide to the CityGML LOD3 Workflow

This section serves as a guide for navigating Chapter 5 LOD3 Workflow based on the dataset available. Two primary data input types are outlined in this protocol:

1. **Aerial Imagery**: This is the conventional method for creating city models and has been widely utilized for years.
2. **Point Cloud Data from LiDAR Scans**: This is a more recent and relatively expensive technology, supported by aerial imagery.

This protocol aims to address workflows for both data types to ensure flexibility and applicability to diverse projects. **Chapter 5, CityGML LOD3 Workflow**, begins with the steps of the conventional method, starting from aerial imagery to city models. If aerial imagery is the primary input, it is recommended to review the entirety of Chapter 5 before proceeding to **Chapter 6.**

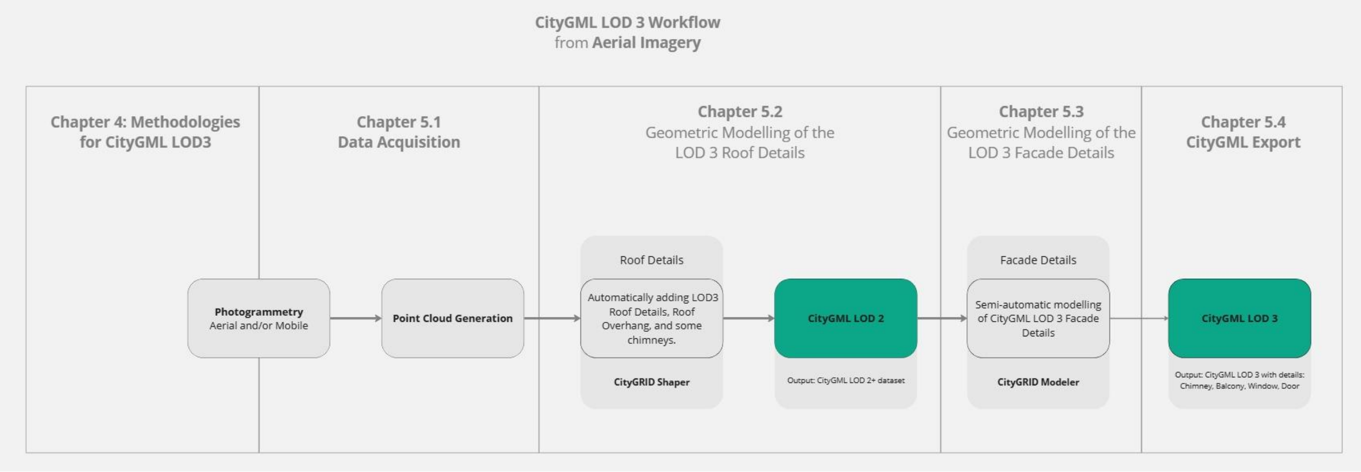


Figure 3 CityGML LOD 3 Workflow from Aerial Imagery

For those employing LiDAR Scans as the primary surveying technique, the relevant section begins with **Chapter 5.1.4, Point Cloud Generation**, which outlines the process for generating point clouds from LiDAR data. From this point onward, **Chapter 6** should be followed to complete the workflow.

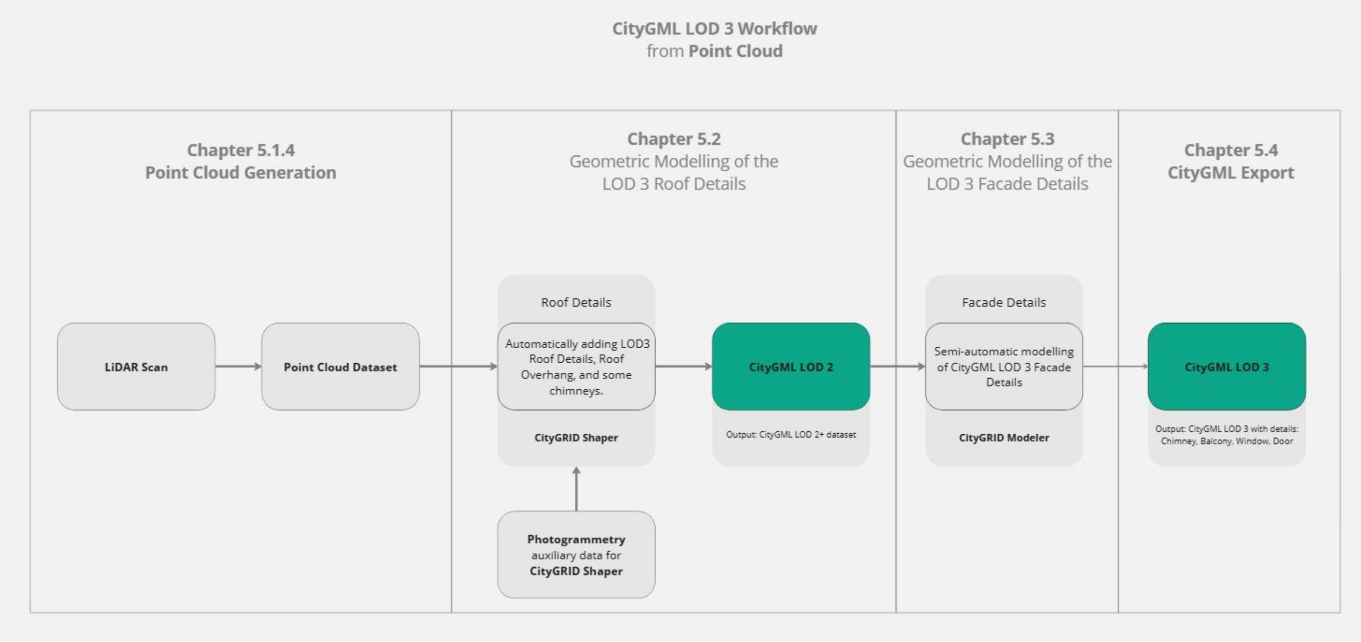


Figure 4 CityGML LOD 3 Workflow from Point Cloud

5 CityGML LOD3 Workflow

5.1 Data Acquisition

The production of raw data and preparation for LOD3 modeling within the CircBoost framework is the foundation. As similar data pipelines will be used to produce LOD3 models for other partner cities in the later stages of the project, this part summarizes key aspects to consider during the raw data acquisition, surveying phase. The goal is to highlight critical areas where partners should pay closer attention when providing surveying services, ensuring a more accurate and efficient workflow.

1. **Objective:** To acquire, preprocess, and prepare raw spatial data for accurate and detailed 3D reconstruction of building geometries.
2. **Input:**
   - Aerial imagery (from UAVs or planes)
   - LiDAR point clouds
   - Surveyed GCPs
3. **Output:** Processed point clouds classified for building extraction and a digital terrain model (DTM) to support the modeling workflow.

5.1.1 Flight Planning for LOD3 Production

Flight planning is the foundation of the entire workflow, as errors or inconsistencies at this stage can significantly impact the quality of outputs in subsequent steps. Key aspects to consider during flight planning for aerial imagery capture include flight height, flight path, and image overlap ratios:

1. **Objective:** To design flight parameters for high-resolution data acquisition, ensuring sufficient coverage and overlap for accurate 3D reconstruction.
2. **Input:**
   - Area of interest (AOI)
   - Aerial imagery and/or LiDAR acquisition requirements
3. **Output:** Optimized flight plans with defined altitudes, overlaps, and imaging conditions.
4. **Tool:**
   - Pre-flight planning software (e.g., DJI Pilot, Pix4Dcapture)
   - UAVs or LiDAR-equipped aircraft
5. **Workflow (Process):**
   - Identify the AOI and define resolution needs.
   - **Flight Height:**
     1. The aerial imagery capture height should be carefully determined based on the geometric characteristics of the built environment, particularly the building heights in the area.
   - **Flight Paths:**
     1. Flight paths should follow a systematic grid pattern to ensure comprehensive coverage and optimal image overlap.
     2. To improve balancing accuracy, an additional diagonal grid flight path is also recommended.
   - **Imagery overlap ratios:**

1. The recommended minimum overlap ratios should be:

Forward overlap: 80%

Side overlap: 60%

2. Adhering to these overlap ratios is essential for achieving accurate and high-quality photogrammetric outputs.

- Simulate flight paths and test visibility/coverage.
- Perform data acquisition during favorable weather conditions.
- Close collaboration with the surveying team is crucial to ensure all parameters are strictly followed. These requirements must be explicitly stated in contracts and verified during data checks to avoid issues later in the workflow.

5.1.2 Ground Control Points (GCPs)

1. **Objective:** To provide spatial referencing for aligning and georeferencing imagery and point clouds accurately.
2. **Input:**
    - Surveyed GCP coordinates (latitude, longitude, elevation)
    - Aerial imagery
3. **Output:** Georeferenced spatial data with centimeter-level accuracy.
4. **Tool:**
    - GNSS surveying equipment
    - Reference markers visible in aerial imagery
5. **Workflow (Process):**
    - Place GCPs evenly across the AOI, ensuring visibility from above.
    - The GCPs should be evenly distributed around the edge of the area and some points should also be evenly distributed within the area. The GCPs should be evenly distributed around the edge of the area and some points should also be evenly distributed within the area. In addition, the GCPs should match the reference system, i.e. the actual coordinates of the city of Belgrade. This is usually only possible with GCPs or reference points that also have coordinates in the Belgrade system.
    - When collecting GCPs, operators should photograph their exact locations from multiple angles to avoid missing information during geometric corrections.
    - Survey GCP locations using GNSS equipment with high precision.
    - Cross-check GCP coordinates with base stations or correction data.
    - Incorporate GCP data during photogrammetry or LiDAR processing.
    - Missing GCP’s can cause errors in the subsequent tasks.

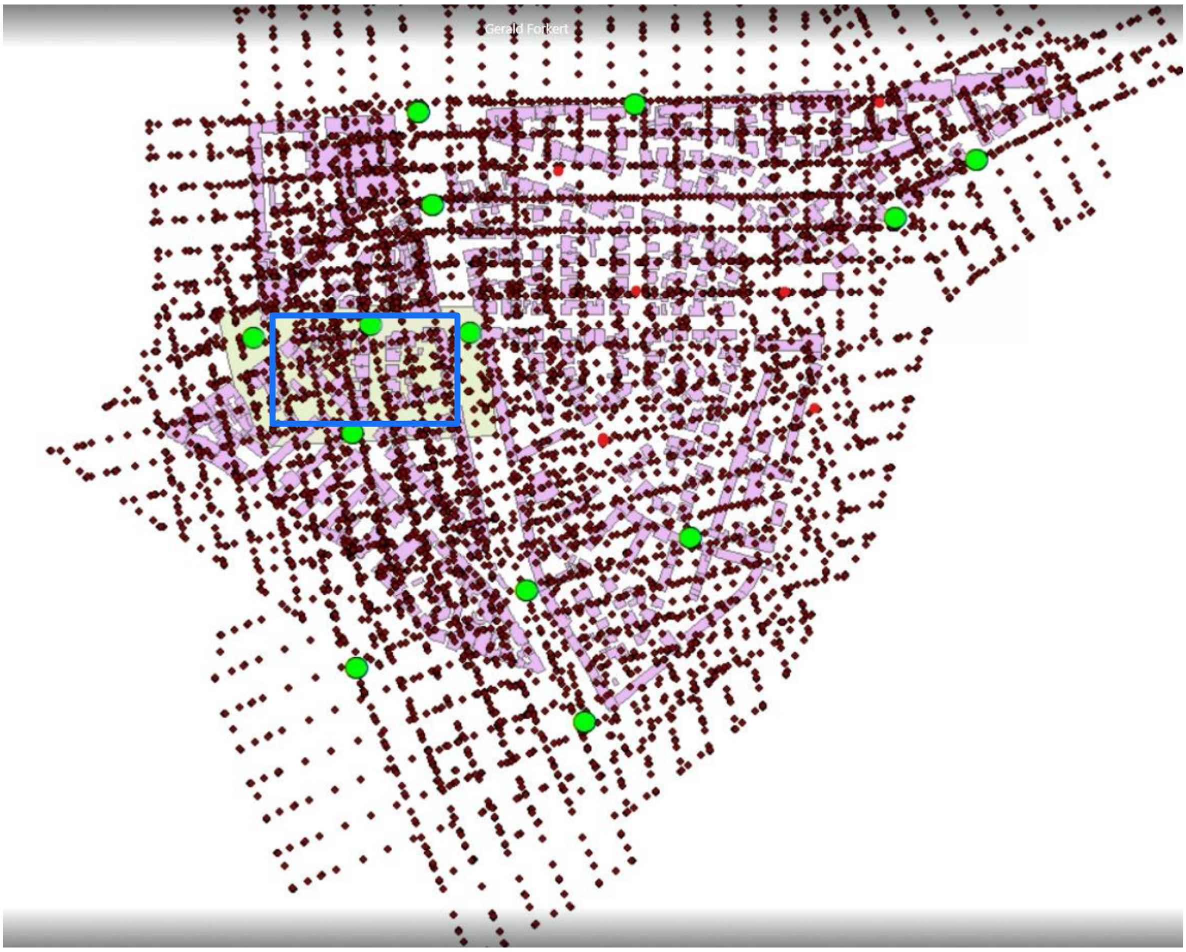


Figure 5 The screenshot from the Pix4D Project showcasing the ground control points

In the Figure 5, ground control points are colored in green, proposal locations for missing ground control points are marked in red. Small multiple points show the locations of aerial imagery. The test area, to be modeled within this workflow is selected within the best georeferenced area, according to the availability of the GCP's and aerial imagery. The selected test area is marked in blue.

5.1.3 Balancing Aerial Imagery

1. **Objective:** To ensure uniform image quality, color balance, and alignment for seamless processing into 3D point clouds.
2. **Input:**
    - Raw aerial images
    - Flight metadata (camera parameters, altitude, etc.)
3. **Output:** Balanced and georeferenced imagery ready for point cloud generation.
4. **Tool:**
    - Photogrammetry software (e.g., Pix4D, Agisoft Metashape)
5. **Workflow (Process):**
    - Remove distortions using camera calibration data.
    - Stitch images to create orthophotos or mosaics.
    - Export georeferenced imagery for further processing.

5.1.4 Point Cloud Generation

Point cloud generation is the process of creating a set of 3D points representing the surface of the surveyed area and objects within it. This is typically achieved through photogrammetric processing of overlapping aerial images or from the LiDAR scan data. The generated point cloud serves as the primary data source for subsequent 3D modeling and analysis.

1. **Objective:** To produce dense 3D point clouds that accurately represent the AOI, including all building elements.
2. **Input:**
   - Balanced aerial imagery (for photogrammetry)
   - LiDAR scan data
3. **Output:** Accurate point clouds of the AOI. Optimal point cloud density for this workflow is 20 points per square meter. The density of the point cloud does not have to be higher than that as this increases the computational load and creates discrepancies in the available softwares.
4. **Tool:**
   - Photogrammetry software (e.g., Agisoft Metashape, Pix4D)
   - LiDAR processing tools (e.g., CloudCompare, LAStools, DJI Terra)
5. **Workflow (Process):**
   - Process imagery or LiDAR data to generate raw point clouds.
   - Filter noisy points and refine the dataset.
   - Align and georeference the point cloud using GCPs.
   - This process involves several key steps within photogrammetric software (such as Pix4Dmapper or Agisoft Metashape):
     1. Image Matching: Identifying corresponding points across multiple overlapping images.
     2. Bundle Adjustment: Simultaneously refining the camera positions and orientations and the 3D positions of the matched points. This creates a geometrically consistent point cloud.
     3. Dense Matching: Generating a highly detailed point cloud by interpolating between the matched points.
   - The density and accuracy of the resulting point cloud are influenced by factors such as:
     1. Image overlap (as specified in section 1.1)
     2. Image quality (resolution, sharpness)
     3. GCP accuracy (as specified in section 1.2)
   - Export for classification and further processing.

5.1.5 Point Cloud Classification

Classified point clouds are vital for certain steps in LOD3 production, such as **Digital Terrain Model (DTM) Generation.** Surveying teams must deliver accurate classifications to streamline downstream workflows. Accurate classification streamlines downstream workflows and improves the quality of derived products like DTMs.

1. **Objective:** To classify point clouds into distinct layers such as ground, buildings, and vegetation for detailed modeling.
2. **Input:**

- Raw point clouds
- GCP data

3. **Output:** Classified point clouds with labeled building elements. 3 different classification suffice for this workflow. 1. Ground points, 2. Vegetation**,** 3. Buildings.
4. **Tool:**
    - Classification software (e.g., CloudCompare, TerraScan)
    - Machine learning models for semantic segmentation
5. **Workflow (Process):**
    - Apply automated classification algorithms to the point cloud. Automated algorithms: Many photogrammetric and point cloud processing software packages (e.g., Pix4Dmapper, Agisoft Metashape, Terrasolid, CloudCompare) offer automated classification tools based on geometric and radiometric properties of the points.
    - Identify and label features such as buildings, ground, vegetation, etc.
    - Refine classifications manually in complex or ambiguous areas. In most cases, manual refinement of the automated classification may be necessary to ensure accuracy, especially in complex urban environments.
    - Export classified point clouds for DTM creation or direct modeling.

5.1.6 Digital Terrain Model (DTM) Generation

1. **Objective:** To create a bare-earth model by removing non-ground points, ensuring a reliable surface for aligning building geometries.
2. **Input:**
    - Classified point clouds
3. **Output:** A triangulated digital terrain model (DTM) representing the ground surface.
4. **Tool:**
    - DTM generation software (e.g., QGIS, ArcGIS, Agisoft Metashape, Pix4D, FME)
    - Interpolation tools (e.g., triangulated irregular networks, rasterization)
5. **Workflow (Process):**
    - Filter classified point clouds to isolate ground points.
    - Apply interpolation techniques to generate a continuous ground surface.
    - Validate and refine the DTM to ensure accuracy.
    - Export the DTM for use in LOD3 modeling workflows.

5.1.7 Photogrammetric Restitution

1. **Objective:** To precisely identify and draw the building geometries in 3D CAD using Stereo imagery
2. **Input:** Balanced stereo aerial imagery
3. **Output:** 3D CAD Drawing of the area with different layers for different building models.
4. **Tool:** Complete 3D Photogrammetric Workstation with 3D screen, 3D mouse, and an expert operator, and a 3D CAD Software such as MicroStation Software.
5. **Process:**

The operator loads stereo images of the area of interest (AOI) onto a 3D workstation and utilizes specialized equipment—3D glasses, a 3D monitor, and a 3D mouse—for precise restitution. Using MicroStation, the operator manually traces the 3D CAD representation of the AOI, organizing the geometries into designated layers for subsequent processing. Multiple layers are specifically assigned for roof structures. Based on these layers, the geometries are automatically generated using FME software.

6. **Challenges:**

The required level of detail significantly impacts the speed of restitution. For instance, if façade details are needed, the operator must invest additional time to finalize the 3D drawing. As a reference, drawing an LOD2 building with roof overhang typically takes around three minutes per building. But this value can differ significantly depending on the complexity of the building.

The process requires a dedicated photogrammetric workstation, which includes a 3D screen, 3D glasses, a 3D mouse, 3D CAD software, and, most importantly, a skilled photogrammetry operator. These requirements make the process costly and resource-intensive.

Due to these challenges, this protocol prioritizes semi-automated solutions for LOD3 geometry reconstruction instead of relying solely on conventional photogrammetric restitution.

5.1.8 CityGML LOD 2 Model Generation

1. **Objective:** To generate the initial LOD2 models for validation and data check.
2. **Input:** 3D CAD Data from Photogrammetric Restitution, Aerial Imagery (if texture is required), Digital Terrain Model (for the height of the buildings.)
3. **Output:** CityGML LOD2 Dataset
4. **Tool:** FME Workbench, CityGRID Bundle

5: Process:

The CityGRID software bundle, in addition to its built-in capabilities, is accompanied by a dedicated FME Workbench designed for LOD2 model generation. The flexible structure of FME Workbench allows users to apply parametric adjustments tailored to different cases, enabling automated LOD2 production.

The workflow follows a structured approach. Extract the external footprint of the roof faces from the CAD drawing. Use this footprint to extrude the façade geometry, initially extruding it to approximately 30 meters. In the next step, the extruded geometry is trimmed to match the minimum elevation value of the DTM, ensuring accurate height representation.

By utilizing FME Workbench, the CAD layers are systematically assigned to facilitate automatic geometry construction, ensuring efficient and precise generation of LOD2 models.

5.2 Geometric Modelling of the LOD3 Roof Details

This section outlines the process of generating detailed 3D city models, specifically focusing on incorporating roof details into LOD2 models to achieve LOD3 roof geometries. It describes the use of raw and processed data, such as aerial imagery and point cloud data, for this purpose. The workflow leverages a semi-automated approach facilitated by the CityGRID Shaper program, which combines automated algorithms with manual refinements for enhanced precision.

The semi-automated methodology relies on the CityGRID Shaper program's ability to detect and recommend geometric structures. After importing the point cloud and aerial imagery, the software identifies potential planar shapes, referred to as "alpha shapes," and suggests a primary alpha shape to the operator. With a single click, the operator selects the appropriate shape, and the roof geometry is generated automatically.

Subsequent refinements focus on adding smaller roof features, such as dormers, terraces, flat roofs, and chimneys. Extrusion geometries and other detailed elements are incorporated to achieve a more comprehensive LOD3 representation.

The objective of this step is to maximize the creation of detailed roof geometries within the Shaper program. Since the program automates much of the process, it significantly reduces the effort required for geometry production compared to fully manual methods. Following chapters provide the guide for a Shaper Project.

5.2.1 Setting a CityGRID Shaper Project

A CityGRID Shaper project is initialized by integrating point cloud data, and aerial imagery to facilitate efficient roof geometry generation. The Shaper tool processes these inputs, ensuring accurate visualization and efficient model production.

The project setup includes:

- Importing and aligning point cloud data to define roof structures.
- Incorporating aerial imagery for enhanced visual reference and texture application.

Once the data is prepared, the CityGRID Shaper environment provides a structured workflow for semi-automated LOD3 roof modeling.

5.2.2 Modeling the roof shapes

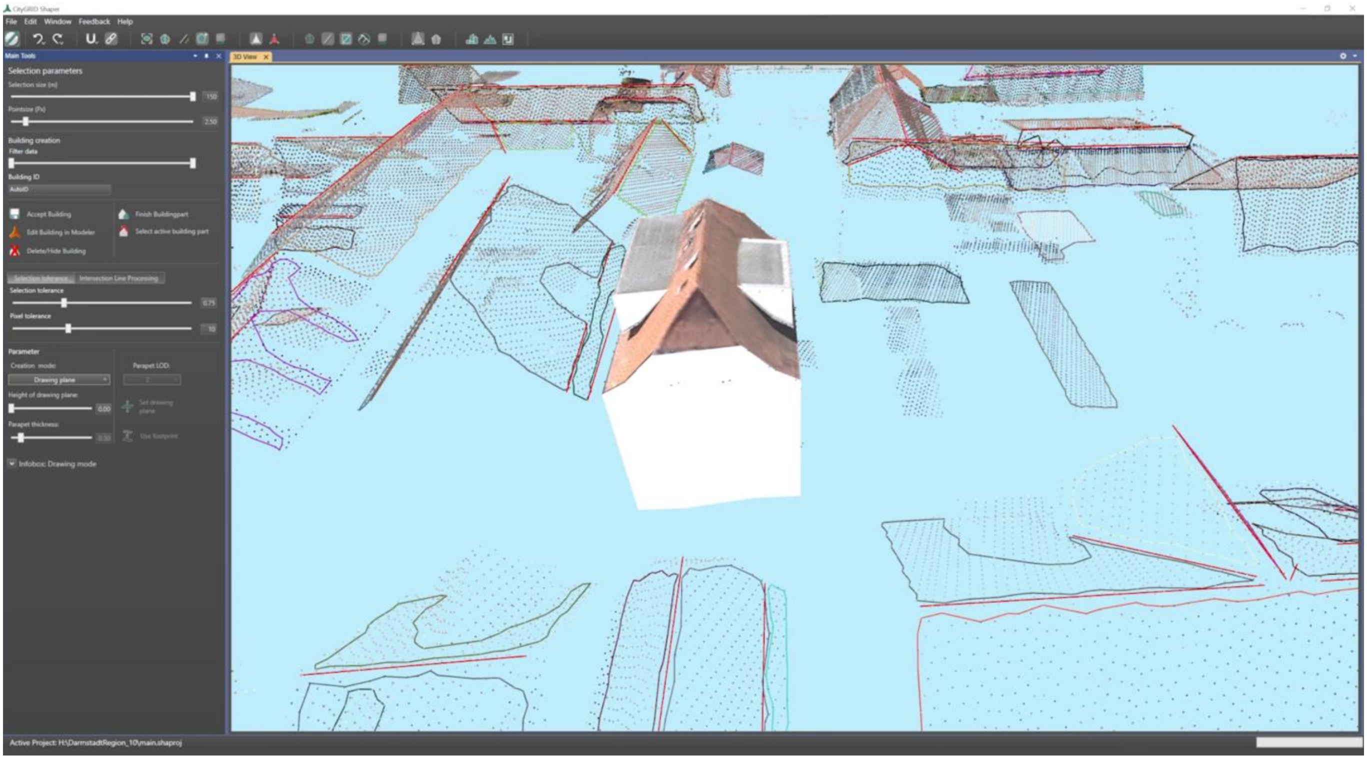
Once the CityGRID Shaper project is set up, the software automatically detects potential roof structures using its alpha shape algorithm. The program then suggests possible roof geometries to the operator, who can:

- Accept the recommended shape.
- Modify the detected geometry for improved accuracy.
- Reproduce or manually refine the shape if needed.

In cases where the CityGRID Shaper functionalities are insufficient for detailed roof modeling, users can switch to Autodesk 3ds Max via the CityGRID 3ds Max Modeler Extension:

1. Switch to the 3ds Max environment for advanced geometry editing.
2. Apply refinements, such as intricate roof details and complex extrusion geometries.
3. Return to CityGRID Shaper to finalize the LOD3 model.

For further details on advanced functionalities and workflow optimizations, users should refer to the official documentation.



Selection size (m): 150
Pointsize (Px): 2.50
Building ID: AutoID
Selection tolerance: 0.75
Pixel tolerance: 10
Creation mode: Drawing plane
Parapet LOD: 2
Height of drawing plane: 0.00
Parapet thickness: 0.30

Active Project: H:\DarmstadtRegion_10\main.shaproj

Figure 6 Screenshot from a CityGRID Shaper project showcasing the alpha shapes and possible roof lines

5.2.3 Modelling the chimney geometries

The creation of LOD3 chimney objects follows a workflow similar to that of facade elements, using the CityGRID Shaper's 3ds Max extension and the FME Workbench. This ensures that chimney geometries are accurately modeled and structured according to the CityGML data model, maintaining a parent-child relationship with the roof elements.

1. Integration of Chimneys: Once the target building is imported into the Autodesk 3ds Max environment, chimney geometries are defined and processed as follows.

- Defining Chimney Objects: Chimneys are treated as exclusion objects, with their geometries defined based on height data and designated as exclusion data types. This ensures their precise placement and semantic clarity in the roof structure.
- Establishing Parent-Child Relationships: In accordance with the CityGML data structure, chimney objects are assigned as sub-objects under the roof layer. This hierarchical organization ensures that the chimneys are properly linked to the roof and correctly recognized in the dataset.

- FME Workbench Automation: Using a predefined FME Workbench, chimney objects are automatically generated and integrated into the roof structure. The workflow ensures accurate geometry creation and seamless inclusion of chimneys in the CityGML model.

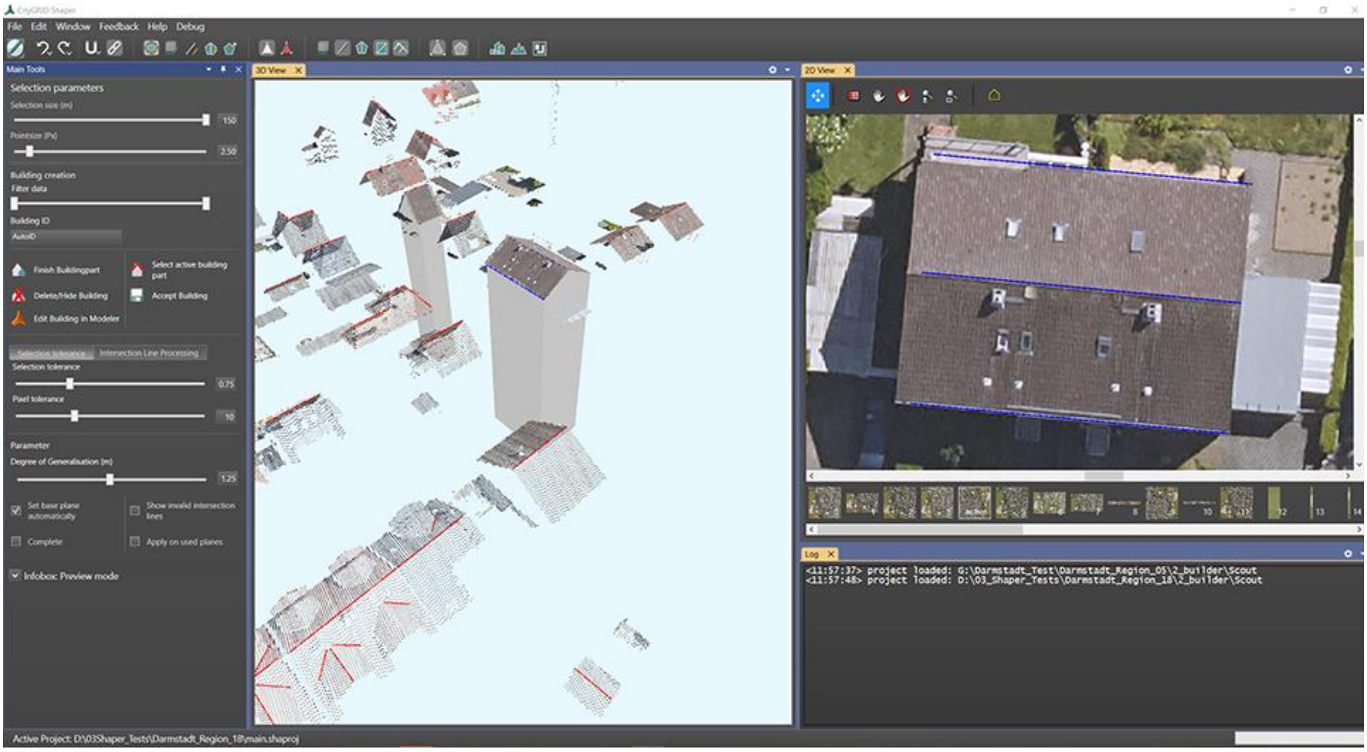
2. Process Application

- This process is applied to all chimneys within the building, ensuring consistency and compatibility with the CityGML schema.

3. Tools Used

- CityGRID Shaper (3ds Max Extension)
- FME Workbench
- CityGRID Modeler

This workflow ensures that chimney objects are modeled and integrated efficiently, leveraging automation to minimize manual efforts while maintaining high accuracy and semantic consistency within the CityGML LOD3 dataset.



Selection parameters

Selection size (m) 150

Pointsize (Px) 2.50

Building creation

Filter data

Building ID

AutoID

Selection tolerance 0.75

Pixel tolerance 10

Parameter

Degree of Generalisation (m) 1.25

☑ Set base plane automatically

☐ Show invalid intersection lines

☐ Complete

☐ Apply on used planes

☑ Infobox Preview mode

```
<11:57:37> project loaded: G:\Darmstadt_Test\Darmstadt_Region_05\2_builder\Scout
<11:57:48> project loaded: D:\03_Shaper_Tests\Darmstadt_Region_18\2_builder\Scout
```

Active Project: D:\03Shaper_Tests\Darmstadt_Region_18\main.shaproj

Figure 7 Screenshot from a CityGRID Shaper project showcasing the alpha shapes and possible roof lines

5.3 Geometric Modelling of the LOD3 Facade Details

5.3.1 Modeling the window and door geometries

The CityGRID Shaper’s 3ds Max extension is used to model the LOD3 facade details, including doors and windows. This workflow ensures that facade elements are structured according to the CityGML data model, maintaining a parent-child relationship between walls and their respective sub-objects.

1. Integration of Doors and Windows

Once the target building is imported into the Autodesk 3ds Max environment, the door and window geometries are defined using the Boolean object type. The key considerations in this process include:

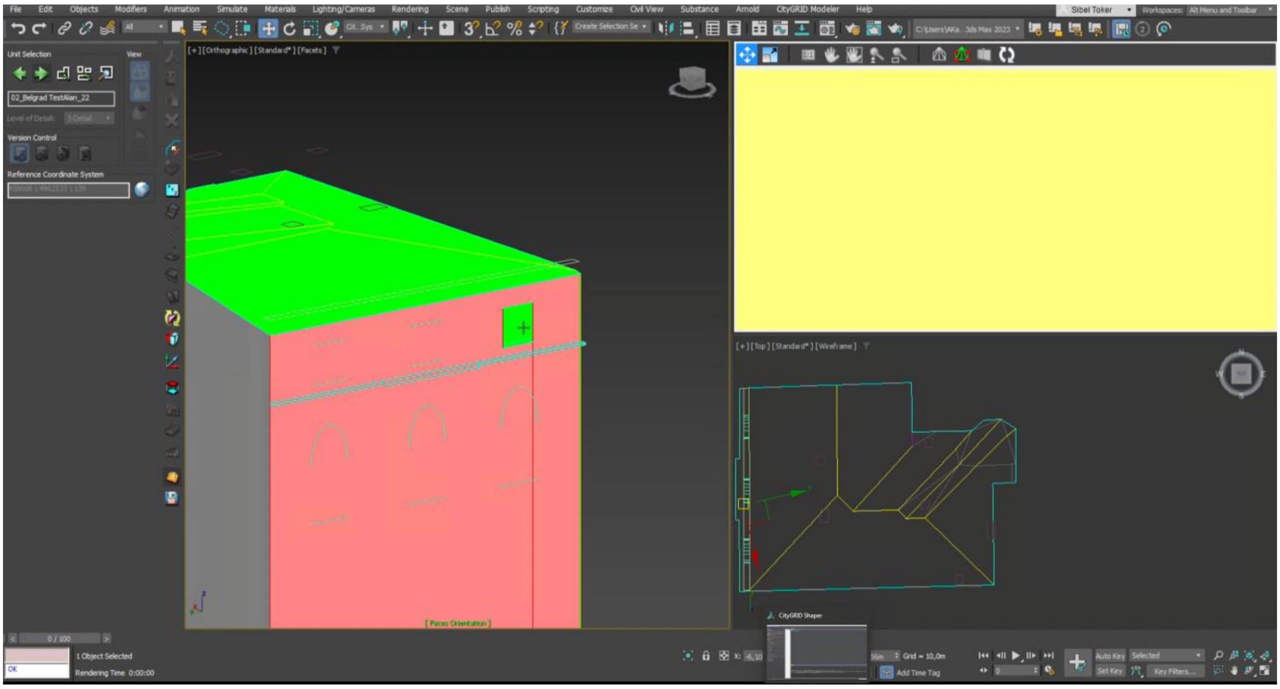
- Defining Boolean Objects: Doors and windows are created as Boolean objects to allow proper subtraction and integration within the facade geometry.
- Establishing Parent-Child Relationships: In accordance with the CityGML data structure, Boolean layers are placed by software as sub-objects under the wall layer, ensuring they are correctly recognized as components of the facade.
- Once the geometries are created, the CityGRID Modeler extension processes the Boolean objects and assigns them as sub-objects of the respective walls. This ensures that the CityGML dataset correctly interprets the facade elements within the hierarchical data structure.

2. Process Application

This process is applied to all doors and windows within the building to ensure consistency across the dataset.

3. Tool Used

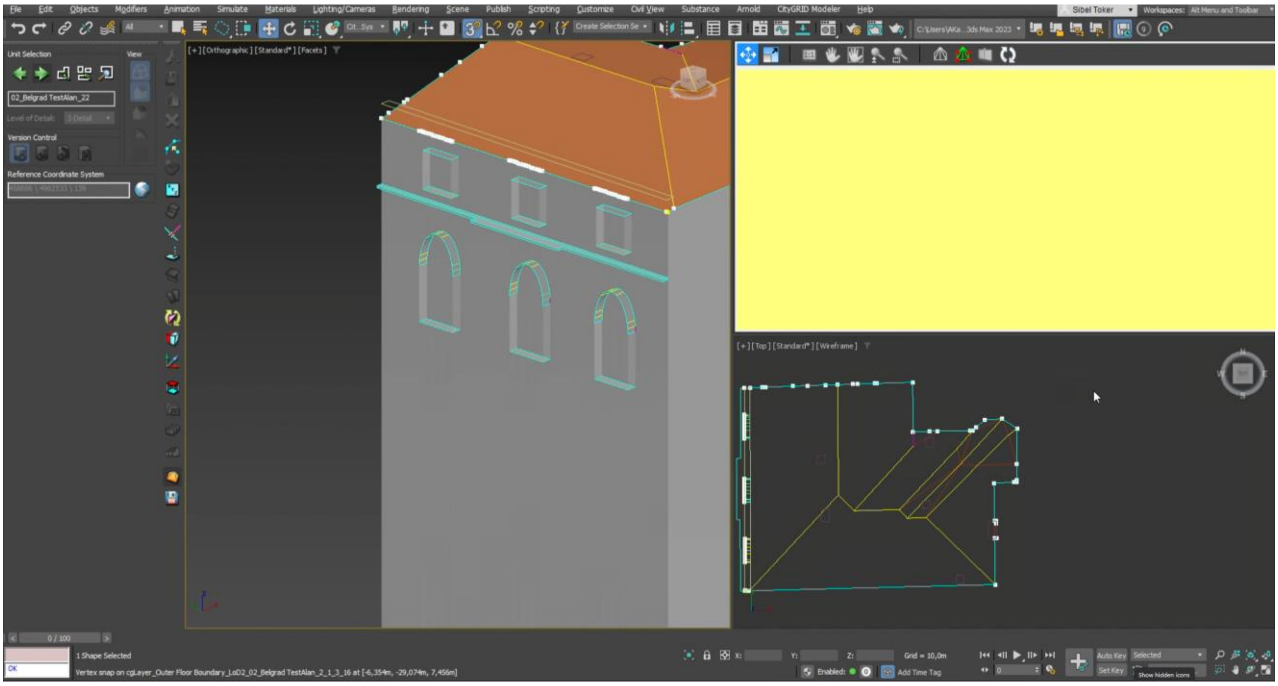
- CityGRID Shaper (3ds Max Extension)
- CityGRID Modeler



1 Object Selected

Rendering Time 0:00:00

Figure 8 CityGrid Modeler Window Geometry Creation



1 Shape Selected

Vertex snap on cgLayer_Outer Floor Boundary_LoD2_02_Belgrad TestAlan_2_1_3_16 at [-6,354m, -29,074m, 7,456m]

Figure 9 CityGRID Modeler Window Geometry Creation

5.3.2 Modeling the balcony geometries

Balcony geometries in the LOD3 facade modeling process are created using 3D solid extrusion in 3ds Max and integrated as sub-objects of the wall layer in accordance with the CityGML data structure.

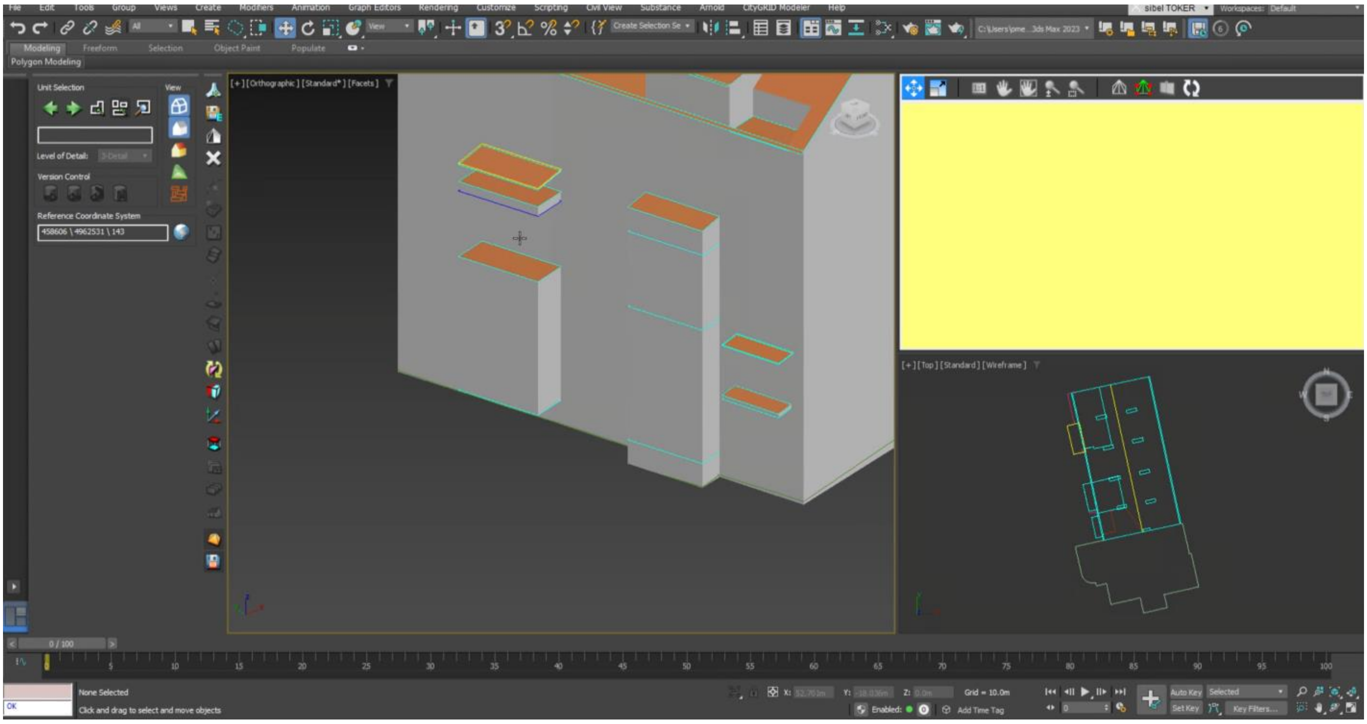
1. Creating Balcony Geometries
2. Defining the Balcony Volume:
   - A 3D solid extrusion is used to generate the balcony geometry, ensuring that the shape accurately represents the real-world structure.
   - The extrusion extends outward from the facade, with appropriate height and depth adjustments.
3. Establishing Parent-Child Relationships:
   - The balcony geometry is assigned as a sub-object under the wall layer, maintaining consistency with the CityGML hierarchy.
   - This ensures that the balcony remains linked to the main building structure within the dataset.

Once the balcony geometry is created, the CityGRID Modeler extension processes it and assigns it as a child element of the wall, similar to doors and windows. This ensures that the CityGML dataset correctly interprets the balcony within the hierarchical data structure.

- Process Application

This process is applied to all balconies in the building, ensuring that they are properly integrated into the CityGML model.

- Tools Used
- CityGRID Shaper (3ds Max Extension)
- CityGRID Modeler



None Selected

Click and drag to select and move objects

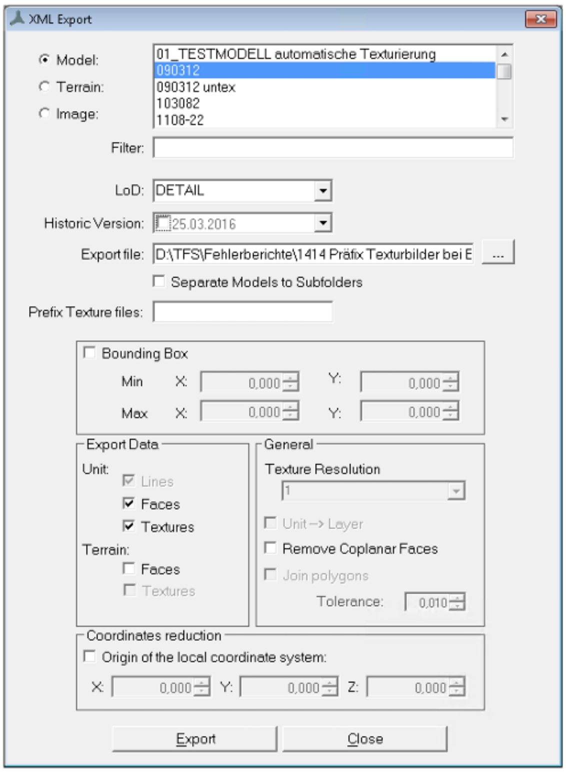
Figure 10 CityGRID Modeler Balcony Geometry Creation

5.3.3 Export as CityGML LOD3

Once the LOD3 facade detailing process is completed, the project data is exported using the Administrator module, which is part of the CityGRID bundle. This module allows exporting the dataset in various formats according to project requirements.

Additionally, to comply with data protection regulations, the generated LOD3 dataset can also be exported as LOD2 with a lower resolution. This ensures controlled data dissemination while maintaining flexibility in data usage.

For further details on export settings and additional options, please refer to the official tutorial documentation.



● Model:
○ Terrain:
○ Image:

01_TESTMODELL automatische Texturierung
090312
090312 untex
103082
1108-22

Filter:

LoD: DETAIL

Historic Version: ☐ 25.03.2016

Export file: D:\TFS\Fehlerberichte\1414 Präfix Texturbilder bei E

☐ Separate Models to Subfolders

Prefix Texture files:

☐ Bounding Box
Min X: 0,000 Y: 0,000
Max X: 0,000 Y: 0,000

Export Data
Unit:
☑ Lines
☑ Faces
☑ Textures
Terrain:
☐ Faces
☐ Textures

General
Texture Resolution: 1
☐ Unit --> Layer
☐ Remove Coplanar Faces
☐ Join polygons
Tolerance: 0,010

Coordinates reduction
☐ Origin of the local coordinate system:
X: 0,000 Y: 0,000 Z: 0,000

Figure 11 CityGRID Administrator Export Window

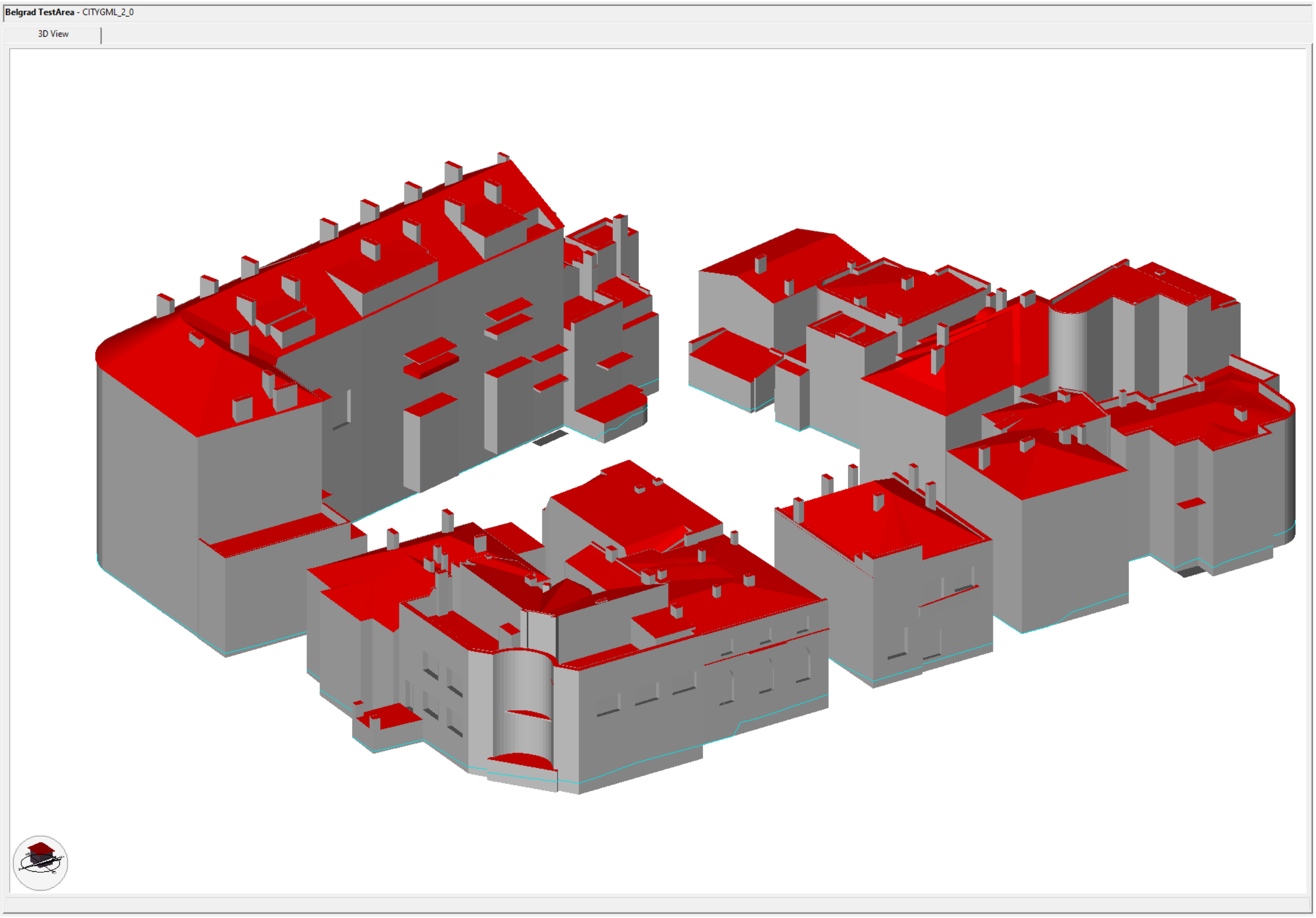
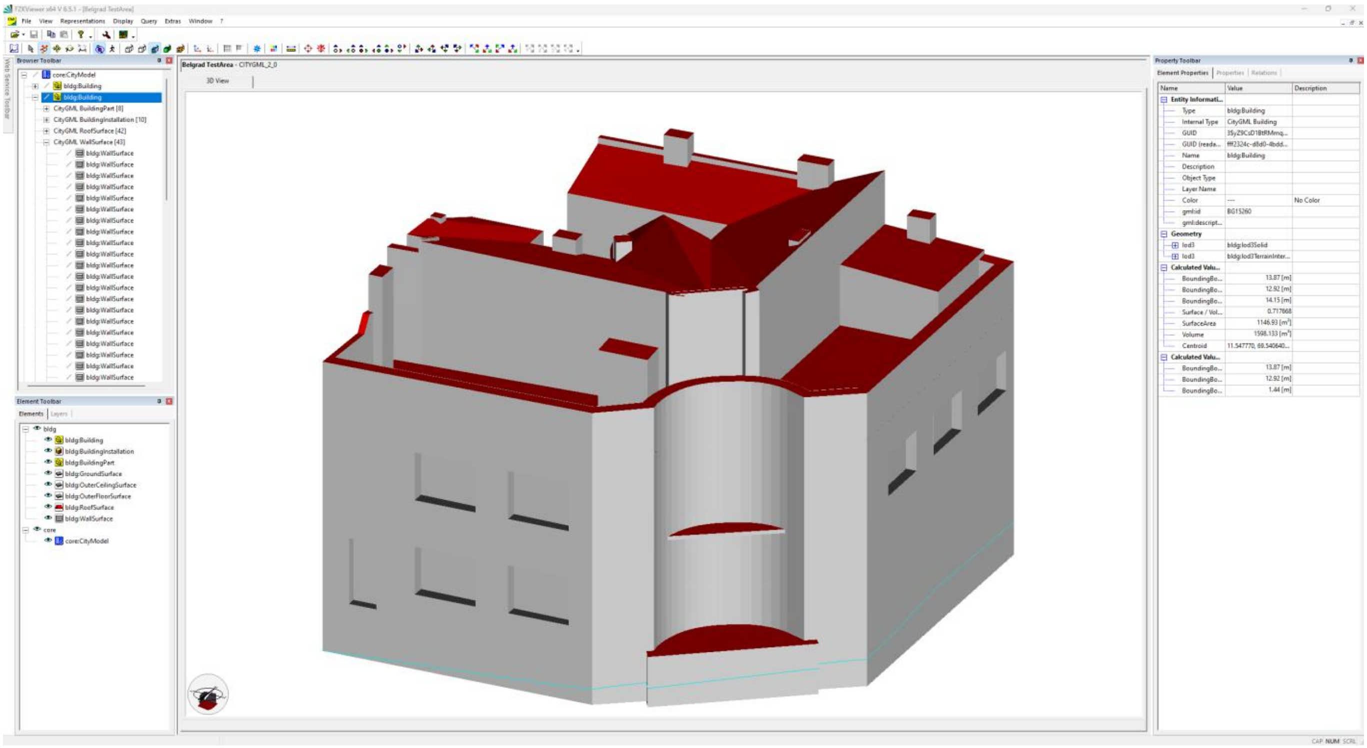


Figure 12 Test Area CityGML LOD3 Result



Name	Value	Description
Entity Informati...		
Type	bldg:Building	
Internal Type	CityGML Building	
GUID	3SyZ9CsD1BtRMmq...	
GUID (reada...	fff2324c-d8d0-4bdd...	
Name	bldg:Building	
Description		
Object Type		
Layer Name		
Color	---	No Color
gml:id	BG15260	
gml:descript...		
Geometry		
lod3	bldg:lod3Solid	
lod3	bldg:lod3TerrainInter...	
Calculated Valu...		
BoundingBo...	13.87 [m]	
BoundingBo...	12.92 [m]	
BoundingBo...	14.15 [m]	
Surface / Vol...	0.717668	
SurfaceArea	1146.93 [m²]	
Volume	1598.133 [m³]	
Centroid	11.547770, 69.540640...	
Calculated Valu...		
BoundingBo...	13.87 [m]	
BoundingBo...	12.92 [m]	
BoundingBo...	1.44 [m]	

Figure 13 Sample Building from Test Area CityGML LOD3 Result. Windows, balconies, chimneys are modeled in relevant categories.

6 Conclusions

The D4.1 Protocol for Spatial Data Acquisition and Geometry Reconstruction offers a practical, semi-automated approach for upgrading CityGML Level of Detail 2 (LOD2) to Level of Detail 3 (LOD3). This protocol integrates point cloud data, aerial imagery, and tools like CityGRID to create detailed 3D city models with enhanced features such as windows, doors, balconies, and chimneys. By combining automation with manual refinement, it ensures both flexibility and accuracy in producing high-quality urban models.

Developed as part of the CIRC-BOOST project, the protocol aligns with circular economy principles by enabling better resource management, material tracking, and sustainability assessments in the built environment. While focused on the Belgrade use case, the methodology is designed to adapt to diverse urban contexts and datasets, providing a scalable solution for similar applications.

Fully automated solutions for LOD3 creation are not yet achievable due to the complexity of detailed facade modeling. This protocol addresses these limitations by focusing on a realistic balance between existing technologies and manual interventions, ensuring practical and effective results. The workflows were validated through expert consultations and previous implementations, such as in Hamburg, to ensure reliability.

The D4.1 Protocol provides a solid foundation for advancing urban modeling while recognizing that further refinement and innovation will always be necessary. It is a step forward in supporting smarter, more sustainable cities through actionable and reproducible methods.

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