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D.3.3.3. Digital-twin joint report

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EXECUTIVE SUMMARY

Historic neighbourhoods face a double challenge: they need to reduce energy consumption and emissions while conserving protected buildings and the historic urban setting. The information needed to make decisions is often scattered across surveys, cadastral and heritage records, energy assessments and technical documents. A 3D model alone is not sufficient, and a detailed building information model for every building would be disproportionate for neighbourhood-scale planning.

ZEB4ZEN developed a common neighbourhood digital-twin solution that connects spatial representations with structured heritage, technical and energy information. It combines the results of A1.4 (neighbourhood scanning, digitalisation and the transnational protocol) and A3.3 (heritage enrichment, selective detailed modelling and the joint synthesis). The solution is a transferable data-and-workflow architecture implemented using local toolchains, not a single proprietary software product.

Four pilot implementations demonstrate how the common approach is applied: Karlovac, Palmanova and Quedlinburg use GIS and Dronoviewer-related workflows, while Zamość uses CityAtlas with segmented OBJ geometry and structured JSON metadata. Together, they demonstrate the feasibility of linking spatial data to building attributes and providing an interactive basis for heritage-sensitive planning. Particular functions differ by site and are documented in the evidence matrix and pilot annexes.

The joint solution enables users to locate buildings, inspect relevant information, compare and filter records and use spatial and energy evidence in planning. It supports—not replaces—engineering design, conservation approval, investment evaluation and formal adoption of measures. Detailed BIM/BEM can be added selectively where a specific building intervention requires it

DIGITAL-TWIN JOINT REPORT

A. INTRODUCTION

Work Package 3 (WP3) "Cultural heritage and historic neighbourhood preservation" supports the ZEB4ZEN ambition to enable deep energy renovation and neighbourhood-level energy transition in historic areas while preserving cultural heritage values. In this context, digitalization is not only a documentation exercise but also a practical foundation for planning, prioritizing, and communicating renovation actions, as well as for integrating energy-related information with heritage constraints and the spatial logic of historic urban fabrics.

Deliverable D.3.3.3 consolidates and presents the jointly developed neighbourhood digital-twin solution focused on cultural heritage, tested across the four pilot neighbourhoods. The deliverable aggregates and systematises the results of A1.4 and A3.3 by combining: (i) geometric and spatial documentation of pilot neighbourhoods (laser scanning, photogrammetry, 3D models and spatial layers) and (ii) heritage-focused data integration workflows that connect geometry with structured metadata required for renovation planning. The resulting joint solution provides a replicable approach to linking geometric representations (3D models and spatial data) with harmonized building and neighbourhood datasets (administrative, cultural heritage, technical, energy baseline, and socio-economic parameters), thereby supporting decision-making towards zero-emission neighbourhood objectives.

Across pilots, partners followed a shared methodological logic consisting of four core stages:

1. establishing a reliable geometric baseline for the pilot neighbourhood;
2. defining and applying a consistent object identification scheme (IDs enabling unambiguous linkage between geometry and metadata);
3. integrating structured datasets into a digital-twin environment (GIS-based or web-based); and
4. enabling interactive exploration through object-level inspection (object cards) and analytical operations (queries, filtering and scenario comparisons where available).

While the implementation environments differ between pilots (e.g., QGIS-based workflows in Karlovac versus a browser-based 3D platform in Zamość), the use of common principles – structured data schemas, traceable identifiers, and QA/QC checks for geometry–attribute consistency – ensures comparability, interoperability and transferability across cities. In this sense, the "digital twin solution" is defined not by a specific software tool, but by a consistent data-and-workflow architecture that can be implemented using different toolchains depending on local capacity and data availability.

In addition to documenting the tested solution, D.3.3.3 outlines the requirements for upscaling the digital twin approach to other historic neighbourhoods and cities. Upscaling needs include:

- standardisation of minimum metadata schemas and identifiers,
- repeatable QA/QC procedures ensuring consistency between geometry and attributes,
- guidance on minimum survey requirements and acceptable tolerances for neighbourhood-scale use,

- and recommendations for progressive enrichment of the digital twin with additional layers (public lighting, public spaces, mobility, and energy-efficiency measures scenarios) to support broader planning, monitoring and stakeholder engagement.

B. Territorial challenge and scope

In a historic neighbourhood, the feasibility of an energy measure depends not only on energy demand but also on the building's heritage status, physical condition, construction, location, ownership and the relationship with the surrounding urban fabric. Conventional energy audits and standalone maps can identify individual needs but do not consistently connect these dimensions. This makes it difficult for municipalities to compare interventions, explain conservation constraints and organise coherent neighbourhood-scale action.

The solution addresses this gap by providing a spatially referenced, traceable information base that can be explored at the building and aggregated to the neighbourhood scale. It supports municipalities, energy planners, conservation professionals and researchers in evaluating where further investigation or an energy measure may be appropriate.

C. Definition of the jointly developed solution

The final ZEB4ZEN solution is a neighbourhood digital-twin package consisting of: (i) a spatial baseline; (ii) a structured information model for buildings and neighbourhood elements; (iii) persistent links between geometry and records; (iv) data validation and integration procedures; and (v) an interactive interface for inspection and planning. The package is documented through the common protocol and the four working pilot representations. It can be implemented with a GIS-based workflow or a browser-based 3D viewer without requiring every city to adopt identical software.

Common architecture and data flow

Layer	Function and data flow
1. Spatial acquisition	Survey and existing geospatial data → point clouds, 3D meshes, building and block polygons. Select higher-detail capture where heritage significance or the intervention requires it.
2. Information model	Building_ID, Block_ID, Pilot_City and structured administrative, heritage, technical, energy and socio-economic fields → validated tabular records.
3. Integration	Match spatial objects to records using stable identifiers via GIS joins or OBJ–JSON mapping. Document coordinate system, mapping rules and missing records.

4. Analysis	Use linked attributes for building inspection, filtering and aggregation. Import externally calculated energy indicators and measure/scenario data where available.
5. Interaction	Present the baseline and relevant information in a 3D/GIS viewer; visualise measures and compare information where implemented.
6. Maintenance	Retain source datasets, versions and ID mappings; update records without rebuilding all geometry where possible. Check access and backups.

What makes this one solution?

The common deliverable is the method and information structure that makes a neighbourhood model usable for heritage-sensitive energy planning. Local implementation choices are adaptations of that structure. CityAtlas demonstrates automatic object-to-record matching and attribute queries; the Dronoviewer/GIS workflow demonstrates spatially referenced data, visualisation and measurement. Both implement the principle of relating an identifiable spatial object to relevant attributes. A common data structure and documented mappings make the approach transferable; they do not imply that the platforms have identical functions or that an automated cross-platform exchange has been independently tested.

D. Common information model and integration rules

The transnational protocol D.1.4.3 specifies a minimum data baseline. The following consolidated implementation specification translates that protocol and the pilot experience into a practical starting point for replication. The field names below are a recommended common mapping; only Building_ID, Block_ID, and Pilot_City are explicitly named in the protocol. Local field names may be retained if a mapping is documented.

Layer	**Function and data flow**
Identification & geometry	Building_ID (unique within pilot), Block_ID, Pilot_City; polygon or segmented 3D object, coordinates / CRS, address or cadastral reference.
Administrative	Building use and occupancy category; administrative or cadastral identifiers.
Heritage	Protection designation, heritage value, relevant restrictions, construction period and source of classification.
Technical	Useful floor area (m^2), heating system type, available condition, construction or envelope characteristics.
Energy & cost	Baseline energy consumption/demand with reference year and basis; CO_2 emissions, costs and source. Use consistent units (MWh/year, tCO_2/year, €).
Socio-economic	Available ownership and relevant aggregated indicators; omit or restrict sensitive personal information.

Measures & scenarios	Measure ID, affected building/block, description, assumptions, expected energy, CO_2 and cost effects where assessed; label baseline, scenario and realised results separately.

Integration and quality assurance

The core acceptance checks are: (1) each spatial object has a traceable identifier; (2) identifiers are unique and correctly matched to attribute records; (3) required fields and units are checked; (4) geometry, coordinates and selected numerical values are plausible; and (5) data sources, dates, assumptions and missing values are documented. The Zamość OBJ–JSON workflow implements identifier-based matching; the GIS pilots use spatial/attribute joins. Where the local input uses cadastral references or addresses, a mapping to the common identifier is retained.

High-resolution data are used selectively: the intended use determines survey coverage and accuracy. A neighbourhood viewer need not provide construction-level detail. BIM, thermal imagery or detailed point clouds can enrich individual heritage buildings where the intervention warrants it. The technical source and limitations should remain visible to users.

E. Functionalities and validation of the joint solution

The original D.3.3.3 describes a range of capabilities. The matrix below separates documented pilot demonstrations from additional functionality that should not be assumed to be uniformly operational. It provides a traceable answer to the AF requirement for testing in four pilot neighbourhoods.

Function	**Documented pilot evidence**	Interpretation
Spatial visualisation	All four: navigable 3D representations; original D.3.3.3 figs. 2–4 and Zamość Annex I.	Common baseline demonstrated.
Geometry–attribute linkage	Zamość: segmented OBJ, Building_ID, JSON object cards. Other pilots: GIS building layers with structured attributes.	Common principle demonstrated through different implementations.
Inspection and querying	Zamość: object cards and AND/OR queries; QGIS workflows enable attribute selection and mapping.	Interactive attribute inspection / GIS analysis documented; not identical interfaces.
Measure visualisation	Karlovac: renewable-energy measures tool (original fig. 6).	Specific example; not evidence of every measure in every pilot.
Spatial measurement	Quedlinburg: roof/area measurement tool (original fig. 7).	Specific example; no claim of certified survey accuracy.

Neighbourhood context	Palmanova: 3D insula and linked GIS building/heritage/energy records, including public lighting.	Spatial context for off-site REC measure; not a detailed building BIM or evidence of PV operation.
Advanced decision support	AHP in Quedlinburg; protocol describes scenario/KPI links and MCA.	Methodological integration / intended extension; no uniform validation of predictive modelling, automatic compliance or live optimisation.

Validation logic for replication

For a new deployment, test model navigation; select representative buildings and compare their displayed attributes with the source data; verify unmatched/duplicate IDs; check a filter or spatial query against a known set of records; and test any scenario or measurement feature against its documented inputs. Record the date, version, tester, expected result, observed result and limitations. The evidence in the pilot annexes illustrates the existing functions; this acceptance procedure is proposed for subsequent deployments, not a claim of additional tests already performed.

F. Integration of the four pilot experiences

The four cases address distinct needs within the same heritage-sensitive planning problem. Their contribution to the joint solution is not simply the existence of four models: each demonstrates a complementary aspect of the architecture and informs the common transfer rules.

Pilot	**Specific contribution**	**Lesson incorporated into the common solution**
Karlovac (Zvijezda)	Neighbourhood 3D/GIS baseline, building attributes, City Administration BIM/BEM and measure visualisation.	Use a neighbourhood baseline with selective detailed building models. Link intervention information to a spatial context; separate detailed design from neighbourhood screening.
Palmanova (historic insula)	Drone-derived 3D context; residential/non-residential datasets linked to QGIS building polygons via cadastral references; lighting layer.	Use local cadastral references and a documented ID mapping. For off-site energy generation, a neighbourhood model and dedicated investment design can be proportionate; BIM is

		not required for every consumer building.
Zamość (Rynek Wielki)	Photogrammetry/TLS, segmented OBJ, spreadsheet-to-JSON conversion, CityAtlas object cards and filters; detailed heritage renovation case.	Stable object IDs and automated matching permit repeatable updates and queries. Use heritage metadata alongside energy/technical attributes.
Quedlinburg (blocks 1, 16, 17)	3D visualisation, metadata and spatial measurement; AHP approach for weighting energy, cost and heritage criteria.	Include local decision criteria and visual/spatial effects. Make model size and access suitable for browser use; reserve sophisticated analysis for documented functions.

Concrete results and added value

The project documentation records four pilot digital representations and structured data workflows, a common transnational protocol and the demonstrated pilot functions listed in Section 4. This provides a shared spatial-information foundation that makes it easier to inspect buildings, relate heritage constraints to energy evidence and communicate possible measures. The practical added value is the ability to work from a common spatial reference while retaining local data and technical choices.

The digital twin supports preparation of heritage strategies and energy action plans, but the report does not claim quantified energy savings attributable to the software, automatic conservation approval, or formal adoption by all municipalities. Those outcomes require separate evidence. The pilot investments and the WP4 VR tools are related applications, not additional copies of O3.2

G. Transfer and upscaling: implementation guide

The solution can be replicated in other historic neighbourhoods by using the common architecture rather than copying a specific pilot viewer. The minimum viable deployment should provide a spatial baseline, linked building records and a usable interface. Additional precision, analysis and scenarios are added only where justified by planning needs and available data.

Step	Action and required inputs	Acceptance / output
1. Define scope	The municipality and conservation/energy staff define boundaries, use cases, heritage restrictions, and priority buildings.	Agreed scope, source inventory, responsible data steward.

	Inventory existing GIS, surveys and data permissions.	
2. Capture and prepare	Reuse cadastral polygons and existing models; commission drone/photogrammetry/TLS only where needed. Segment objects and simplify models for browser access.	Georeferenced geometry, coverage and accuracy statement, stable ID map.
3. Harmonise attributes	Prepare common data categories and units; collect baseline data in the energy, heritage, and technical fields. Map local IDs and document estimates/gaps.	Structured spreadsheet/CSV, schema and mapping table.
4. Integrate and validate	Use QGIS joins or equivalent OBJ/JSON mapping; run completeness, uniqueness, match and plausibility checks.	Linked model and records; QA log and corrected dataset.
5. Configure and test	Select the GIS/viewer environment, configure inspection/filtering, and enable optional measures/analysis. Test with municipal and heritage users.	Accessible pilot model, test record and user guidance.
6. Release and maintain	Publish permitted views; keep source files, access permissions, backups and version history; assign update responsibility and budget.	Release package, access route and maintenance arrangement.

Actions needed to scale beyond a first neighbourhood

Standardise the schema and IDs across additional districts, define survey quality proportionate to intended use, automate repeatable data conversion and validation, and optimise model size for web access. Prioritise the next neighbourhoods by heritage constraints and available information. Extend the baseline with measure libraries, scenario data, monitoring indicators and BIM only where justified. Provide training for planners and conservation staff, and allocate ongoing resources for hosting, data stewardship and updates.

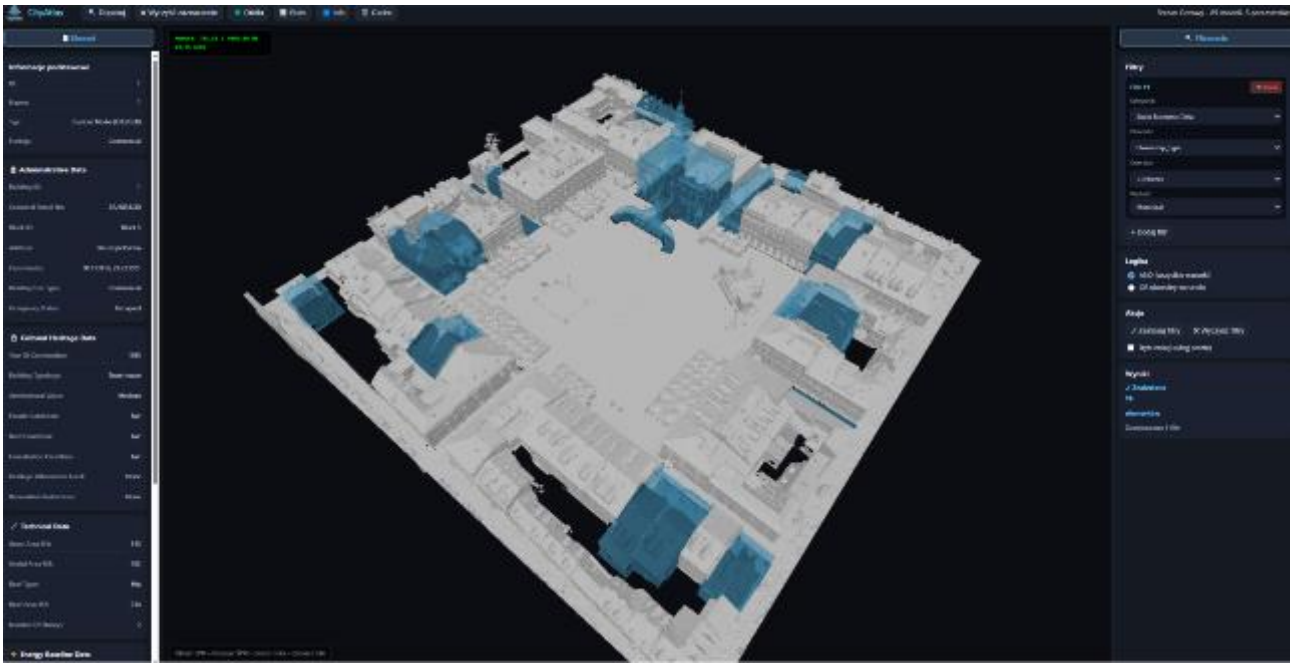
H. ANNEX I: ZAMOSC

1. Digital twin environment used

The Zamość pilot implements the neighbourhood digital twin using the custom web platform CityAtlas. CityAtlas integrates:

- an interactive 3D model viewer (OBJ-based),
- a structured attribute data layer (JSON-based),
- and a user interface supporting both object-level inspection and neighbourhood-scale filtering/analysis.

The platform is designed to operate in a browser-based environment and to serve as a practical decision-support interface for stakeholders (municipality, heritage authorities, designers and researchers) working in a heritage-sensitive urban context.



2. Inputs from A1.4 (data acquisition and spatial documentation)

The geometric baseline for the pilot neighbourhood was produced using an integrated survey workflow combining photogrammetry and terrestrial laser scanning (TLS).

The documented area covers the historic centre around Rynek Wielki (Great Market Square) and adjacent historic blocks and streets within the UNESCO-listed old town ensemble.

Key outputs of the acquisition and processing stage include:

- a high-resolution, metric 3D model of buildings and relevant public-space elements,
- exported as one or more OBJ files representing the pilot area,
- with the model segmented into discrete objects representing building units or logical groups aligned with existing administrative / urban subdivisions (e.g., cadastral parcels or block logic).

This segmentation is a critical prerequisite for digital-twin functionality, as it enables object-level linking of geometry to metadata and supports later aggregation, prioritisation and comparative analysis at neighbourhood scale.



3. Inputs from A3.3 (heritage-focused integration and structured metadata)

To enable heritage-focused planning use cases, building-level metadata were collected and harmonised in a structured spreadsheet (e.g., “Metadata Buildings”) and organised into five main categories:

- Administrative data (IDs, addresses, parcels, blocks, coordinates, use/occupancy),
- Cultural heritage data (protection status, heritage value, constraints, condition assessments),
- Technical data (areas, storeys, volumes, key construction/roof characteristics),
- Energy baseline data (systems, energy demand/consumption, cost proxies, CO_2 indicators),
- Socio-economic data (ownership and selected indicators relevant for renovation planning).

A project-developed conversion workflow (Python-based) transforms the spreadsheet into a structured JSON format consistent with the CityAtlas data schema (e.g., buildings_parameters.json).

This ensures that the same metadata logic can be reliably re-used and extended, while enabling automated loading and validation in the digital twin environment.



```
        "Ownership_Type": "Municipal",
        "Physical_Condition_Ratings": "Satisfactory",
        "Energy_Poverty_Risk": "Medium_risk"
      }
    },
    "Kolegiacka": {
      "Administrative_Data": {
        "Building_ID": "Kolegiacka",
        "Cadastral_Parcel_No": "ZA/2545/54",
        "Block_ID": "Block_1",
        "Address": "Do uzupełnienia",
        "Coordinates": "50.714681, 23.259800",
        "Building_Use_Type": "Residential",
        "Occupancy_Status": "Vacant"
      },
      "Cultural_Heritage_Data": {
        "Year of Construction": "1869",
        "Building_Typology": "Town_house",
        "Architectural_Value": "High",
        "Facade_condition": "Poor",
        "Roof_condition": "Fair",
        "Fenestration_condition": "Good",
        "Heritage_Valorization_Level": "Medium",
        "Renovation_Restrictions": "Moderate"
      },
      "Technical_Data": {
        "Gross_Area_m2": 480,
        "Useful_Area_m2": 375,
        "Roof_type": "Hip",
        "Roof_area_m2": 202,
        "Number_of_Storeys": 4
      },
      "Energy_Baseline_Data": {
        "Heating_System_Type": "Gas boiler",
        "Installed_Heating_Capacity_kW": 40,
        "Main_Fuel_Type": "Electricity",
```

4. Integration approach (IDs, linking logic, QA/QC)

The integration of geometry (OBJ) and structured attributes (JSON) relies on a consistent identifier scheme:

- Building_ID is assigned to each segmented OBJ object and to the corresponding JSON record.

During scene initialisation in CityAtlas, each 3D object is automatically linked to its metadata record by matching Building_ID. The integration logic supports built-in QA/QC by design:

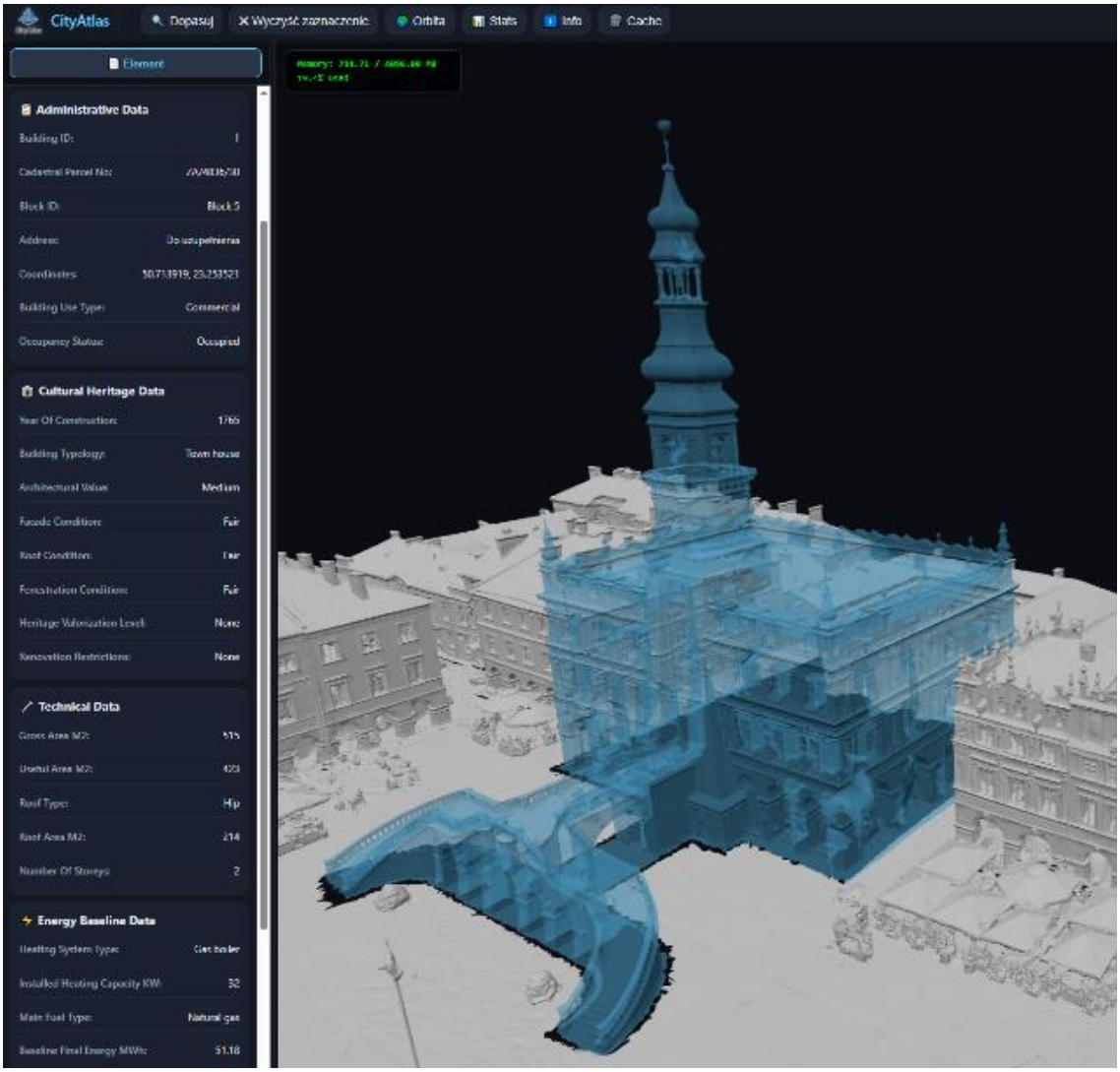
- missing IDs, duplicates, or mismatches between geometric objects and metadata records can be detected,
- enabling ongoing consistency checks and data cleaning during iterative dataset updates.

This approach provides a robust baseline for scaling and collaboration, as data corrections or metadata updates can be executed in the spreadsheet/JSON layer without requiring manual rework of the 3D model (provided that identifiers remain stable).

Recommended QA/QC checks applied (or recommended for upscaling):

- ID completeness check (every OBJ object has a Building_ID; every JSON entry has a matching object),
- uniqueness check (no duplicated Building_IDs in either geometry or metadata),
- schema completeness check (required categories and minimum fields present),

- plausibility checks for selected numeric fields (e.g., gross floor area > 0, year of construction within plausible range).



5. Tested functionalities (digital twin “solution”)

The Zamość pilot validates a set of core digital twin functionalities enabling practical heritage-sensitive analysis and prioritisation:

(1) Object inspection – “object cards” (left panel)

Clicking on a building opens a structured object card presenting the full metadata organised into the five standard categories. This enables rapid review of combined heritage, technical and energy baseline characteristics for individual buildings.

(2) Queries and filtering – neighbourhood-scale selection (right panel)

Users can build selection rules by choosing a category, parameter, operator and value threshold, and can combine multiple conditions using AND/OR logic. Matching objects are highlighted in the 3D view, supporting comparative analysis and prioritisation. Example use cases include selecting:

- buildings with high baseline energy indicators combined with high heritage value,
- buildings with elevated risk indicators (e.g., energy poverty proxy) and poor technical condition,
- buildings with specific heating system types or size classes relevant for renovation planning.

(3) Comparative neighbourhood analysis (building-by-building logic)

Although implemented in a web-based 3D environment rather than a conventional GIS, the approach supports systematic building-by-building comparison across the entire pilot area, enabling a practical prioritisation workflow for planning renovation actions and stakeholder discussions.

6. Outcomes

The Zamość pilot delivered a functional neighbourhood digital-twin component for the historic centre around Rynek Wielki by linking a segmented OBJ geometry baseline with a harmonised building metadata dataset. The pilot demonstrates that a browser-based 3D environment can successfully implement the core digital twin principles (structured schema, stable identifiers, automated linking and QA/QC, object cards and filtering) typically associated with GIS workflows, while improving accessibility for non-GIS stakeholders.

The established digital twin provides a practical basis for subsequent WP3/WP4 activities, including:

- heritage-sensitive retrofit strategy development,
- preparation of neighbourhood action plans,
- and stakeholder workshops supporting communication of priorities and scenarios.

I. ANNEX II: QUEDLINBURG, KARLOVAC & PALMANOVA

1. Digital twin environment used

For the pilot cities of Quedlinburg, Karlovac and Palmanova, the digital twin environment was created in cooperation with Dronodat. The digital twin environment combines a detailed 3D model viewer generated from drone data, a structured attribute layer for integrating additional urban and energy-related information, and a browser-based user interface which enables analyses at both the broad-scale and detailed levels. This allows stakeholders to explore, analyse and compare urban scenarios directly within an accessible online environment.

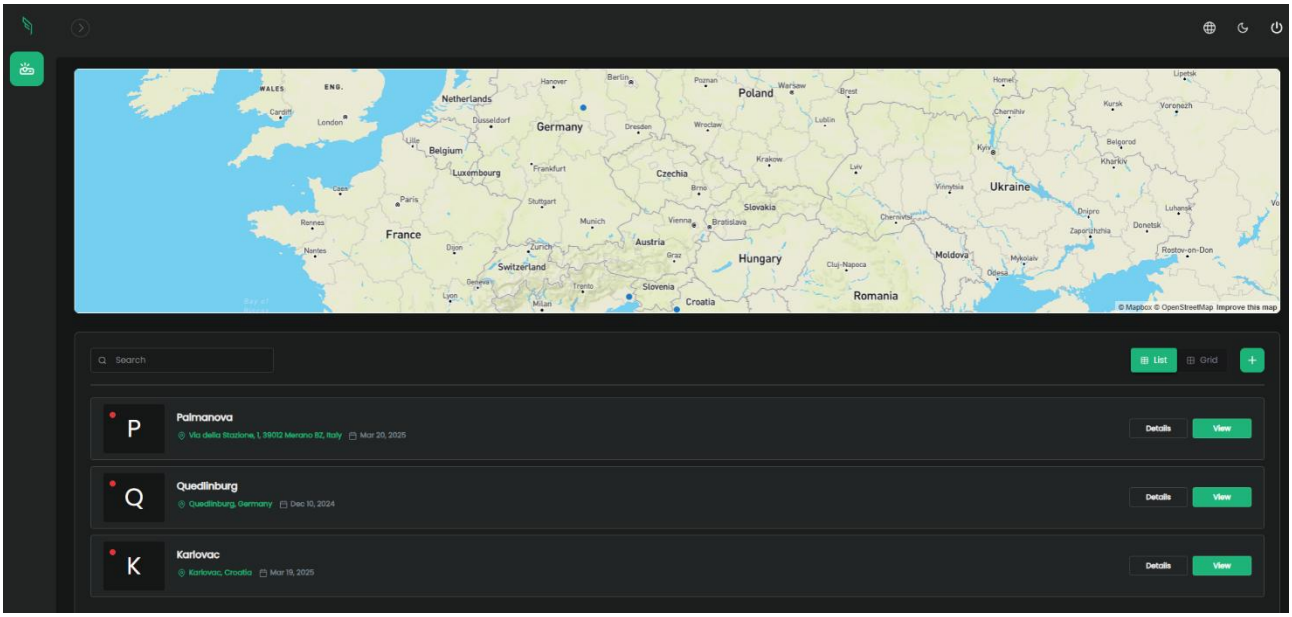


Figure 1: Project Overview in Dronoviewer

2. Data Acquisition and Spatial Documentation

The data acquisition and spatial documentation process formed the basis for the development of the digital twin environments in the pilot cities. High-resolution spatial data were collected through drone-based surveys, LiDAR technologies, satellite imagery and additional surveying methods. These technologies enabled the creation of detailed 2D and 3D representations of buildings, streets, open spaces and other relevant urban structures.

The following pilot areas were digitally documented:

- Karlovac: the historical zone of Zvijezda
- Quedlinburg: Blocks 1, 16 & 17 within the historic old town area

The spatial documentation process was further complemented by the integration of GIS-based datasets such as raster and vector data, CityGML models and other georeferenced urban information.



Figure 2: Palmanova in the Dronoviewer



Figure 3: Quedlinburg in the Dronoviewer



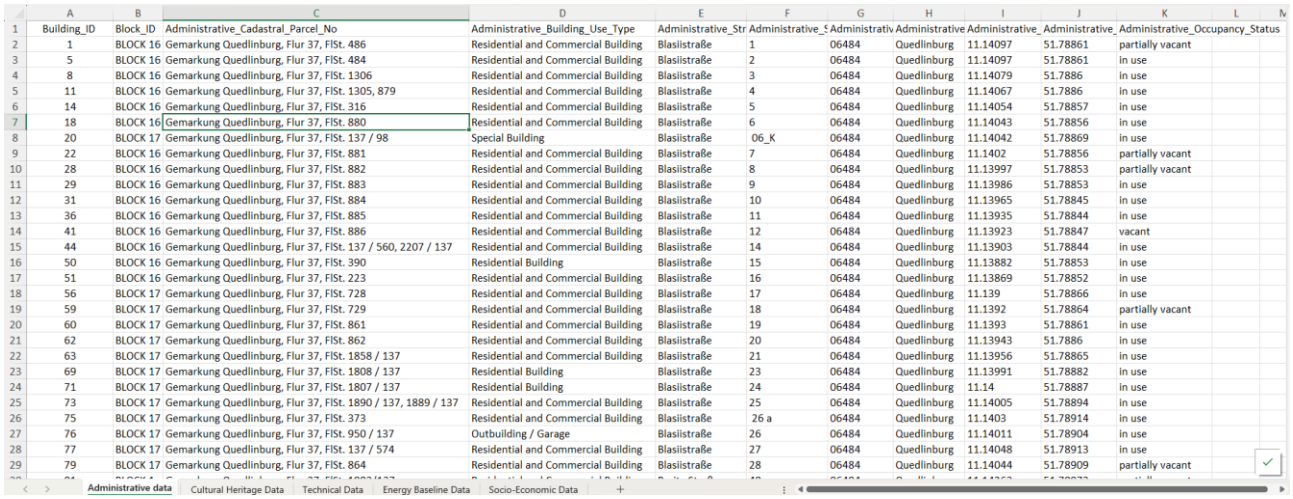
Figure 4: Karlovac in the Dronoviewer

3. Heritage-focused Integration and Structured Metadata

To enable heritage-focused planning use cases, building-level metadata were collected and organised into five main categories:

- Administrative data (IDs, addresses, parcels, blocks, coordinates, use/occupancy),
- Cultural heritage data (protection status, heritage value, constraints, condition assessments),
- Technical data (areas, storeys, volumes, key construction/roof characteristics),
- Energy baseline data (systems, energy demand/consumption, cost proxies, CO_2 indicators),
- Socio-economic data (ownership and selected indicators relevant for renovation planning).

These datasets were subsequently imported into QGIS and linked to the geospatial building outlines using coordinate-based references. This enabled the integration of attribute data with the spatial representation of individual buildings, allowing all information to be visualised, queried and analysed directly within the map environment.



Building_ID	Block_ID	Administrative_Cadastral_Parcel_No	Administrative_Building_Use_Type	Administrative_Str	Administrative_	Administrativ	Administrative	Administrative_	Administrative_	Administrative_Occupancy_Status
1	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 486	Residential and Commercial Building	Blasiistraße	1	06484	Quedlinburg	11.14097	51.78861	partially vacant
5	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 484	Residential and Commercial Building	Blasiistraße	2	06484	Quedlinburg	11.14097	51.78861	in use
8	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 1306	Residential and Commercial Building	Blasiistraße	3	06484	Quedlinburg	11.14079	51.7886	in use
11	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 1305, 879	Residential and Commercial Building	Blasiistraße	4	06484	Quedlinburg	11.14067	51.7886	in use
14	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 316	Residential and Commercial Building	Blasiistraße	5	06484	Quedlinburg	11.14054	51.78857	in use
18	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 880	Residential and Commercial Building	Blasiistraße	6	06484	Quedlinburg	11.14043	51.78856	in use
20	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 137 / 98	Special Building	Blasiistraße	06_K	06484	Quedlinburg	11.14042	51.78869	in use
22	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 881	Residential and Commercial Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	partially vacant
28	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 882	Residential and Commercial Building	Blasiistraße	8	06484	Quedlinburg	11.13997	51.78853	partially vacant
29	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 883	Residential and Commercial Building	Blasiistraße	9	06484	Quedlinburg	11.13986	51.78853	in use
31	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 884	Residential and Commercial Building	Blasiistraße	10	06484	Quedlinburg	11.13965	51.78845	in use
36	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 885	Residential and Commercial Building	Blasiistraße	11	06484	Quedlinburg	11.13935	51.78844	in use
41	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 886	Residential and Commercial Building	Blasiistraße	12	06484	Quedlinburg	11.13923	51.78847	vacant
44	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 137 / 560, 2207 / 137	Residential and Commercial Building	Blasiistraße	14	06484	Quedlinburg	11.13903	51.78844	in use
50	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 390	Residential Building	Blasiistraße	15	06484	Quedlinburg	11.13882	51.78853	in use
51	BLOCK 16	Gemarkung Quedlinburg, Flur 37, FISt. 223	Residential and Commercial Building	Blasiistraße	16	06484	Quedlinburg	11.13869	51.78852	in use
56	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 728	Residential and Commercial Building	Blasiistraße	17	06484	Quedlinburg	11.139	51.78866	in use
59	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 729	Residential and Commercial Building	Blasiistraße	18	06484	Quedlinburg	11.1392	51.78864	partially vacant
60	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 861	Residential and Commercial Building	Blasiistraße	19	06484	Quedlinburg	11.1393	51.78861	in use
62	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 862	Residential and Commercial Building	Blasiistraße	20	06484	Quedlinburg	11.13943	51.7886	in use
63	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 1858 / 137	Residential and Commercial Building	Blasiistraße	21	06484	Quedlinburg	11.13956	51.78865	in use
69	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 1808 / 137	Residential Building	Blasiistraße	23	06484	Quedlinburg	11.13991	51.78882	in use
71	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 1807 / 137	Residential Building	Blasiistraße	24	06484	Quedlinburg	11.14	51.78887	in use
73	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 1890 / 137, 1889 / 137	Residential and Commercial Building	Blasiistraße	25	06484	Quedlinburg	11.14005	51.78894	in use
75	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 373	Residential and Commercial Building	Blasiistraße	26 a	06484	Quedlinburg	11.1403	51.78914	in use
76	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 950 / 137	Outbuilding / Garage	Blasiistraße	26	06484	Quedlinburg	11.14011	51.78904	in use
77	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 137 / 574	Residential and Commercial Building	Blasiistraße	27	06484	Quedlinburg	11.14048	51.78913	in use
79	BLOCK 17	Gemarkung Quedlinburg, Flur 37, FISt. 864	Residential and Commercial Building	Blasiistraße	28	06484	Quedlinburg	11.14044	51.78909	partially vacant

Administrative data | Cultural Heritage Data | Technical Data | Energy Baseline Data | Socio-Economic Data

Figure 5: Sample of metadata for Quedlinburg to be integrated in platform

4. Integration approach

The integration approach for the digital twin of Quedlinburg, Karlovac and Palmanova follows a multi-layered process that combines high-resolution physical modelling with geospatial datasets and structured decision-making methods. The platform combines spatial models with GIS-based datasets. Heritage-focused metadata and structured building information were connected to the spatial and drone-based data through unique building IDs, allowing attribute datasets to be linked directly to individual building objects within the digital twin environment.

Beyond the integration of physical and spatial data, the Quedlinburg digital twin also incorporates a methodological layer through the use of the Analytic Hierarchy Process (AHP). This approach supports decision-making by linking the overall goal of decarbonization with criteria such as energy efficiency, cost-effectiveness, regulatory compliance and the visual impact on heritage sites. Through pairwise comparisons based on the Saaty scale, planners can evaluate and weight different criteria and planning alternatives according to their relative importance. This enables technical, environmental and cultural considerations to be integrated into one coherent decision-making framework.

An additional component of the integration approach is the optimization of the 3D models for browser-based accessibility. A compression algorithm was used to reduce the file size of the digital models significantly while maintaining their visual quality and geometric accuracy. In some cases, models were reduced from several hundred megabytes to only a few megabytes, allowing the platform to remain accessible and interactive on standard computers without requiring specialized hardware.

5. Tested functionalities

The digital twin platform for Quedlinburg, Karlovac and Palmanova provides the following functionalities:

- Browser-based interaction with detailed 3D city models through optimized and compressed datasets that can be accessed on standard computers without specialized hardware.
- Integration and visualization of metadata, heritage-related information and energy-related data directly within the digital twin environment.
- 2D and 3D measurement tools for analysing distances, areas, heights and spatial relationships within the urban environment.
- Visualization of decarbonization measures and retrofitting scenarios over time, including renewable energy systems, insulation measures and district heating infrastructure, with a particular focus on their aesthetic and spatial effects in heritage-sensitive contexts.
- Centimeter-accurate spatial planning to support interventions while respecting preservation requirements and legal constraints.
- Multi-criteria decision-making through the Analytic Hierarchy Process (AHP), enabling the evaluation of planning alternatives based on energy efficiency, cost-effectiveness, environmental impact and visual compatibility with heritage sites.
- Predictive modelling to assess the long-term environmental and economic impacts of proposed interventions and to support the prioritization of decarbonization measures.
- Compliance monitoring to ensure that proposed measures remain in line with preservation guidelines, heritage protection requirements and legal frameworks.

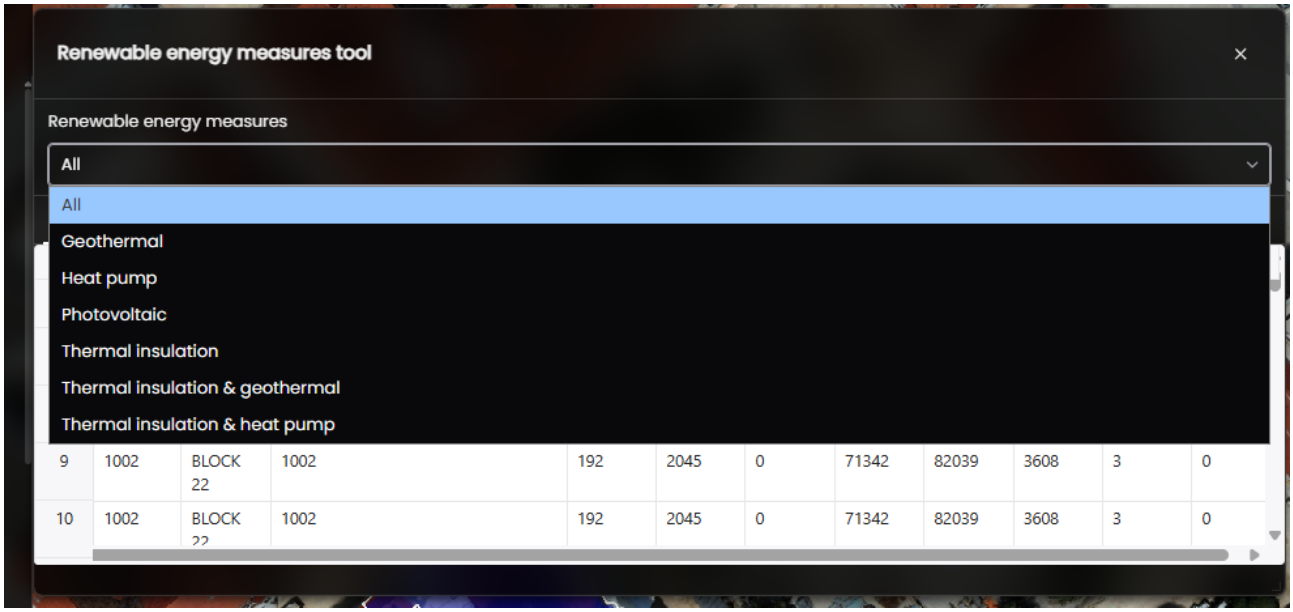


Figure 6: Renewable energy measures tool in use in Karlovac

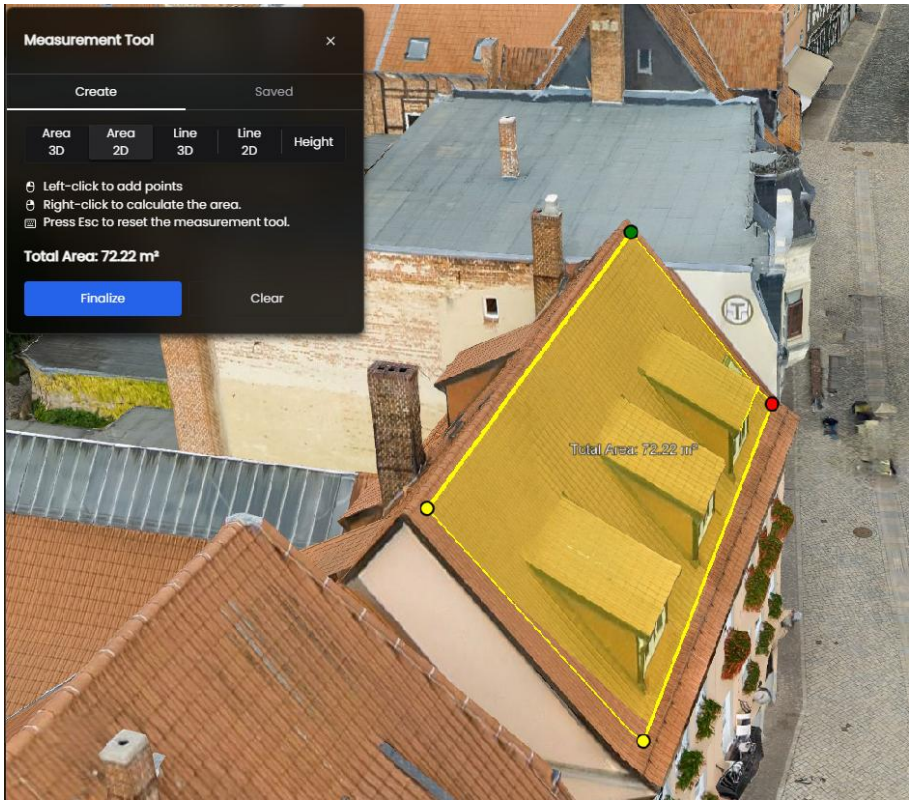


Figure 7: Measurement tool in use in Quedlinburg

6. Outcomes

The outcome of this deliverable is the creation of browser-based digital twin environments for the pilot areas in Quedlinburg, Karlovac and Palmanova. These digital twins combine high-resolution 3D city models with structured metadata, GIS information and energy-related datasets in one integrated platform.

As a result, the deliverable provides a practical basis for subsequent WP3/WP4 activities, including:

- heritage-sensitive retrofit strategy development,
- preparation of neighbourhood action plans,
- and stakeholder workshops supporting communication of priorities and scenarios.

J. CONCLUSION

This deliverable demonstrates that the neighbourhood-scale digital twin concept is technically feasible, methodologically robust, and practically applicable in the context of energy transition in historic urban areas. Across the four pilot sites (Zamość, Quedlinburg, Karlovac and Palmanova), the work confirms that combining high-resolution spatial documentation (e.g. 3D models, LiDAR, photogrammetry) with structured metadata enables an integrated understanding of buildings' technical, energy-related and heritage characteristics. A key strength of the developed approach lies in its interoperability and transferability. Although different software environments were used (such as QGIS-based workflows and browser-based 3D platforms), the application of common principles—consistent object identifiers, harmonised data schemas, QA/QC procedures, and systematic linking of geometry and attributes—ensures comparability across pilot cases. In this sense, the digital twin solution is not defined by a specific tool, but by a coherent data and workflow architecture that can be adapted to different technical contexts.

The pilot implementations demonstrate that digital twins can effectively support decision-making processes, particularly in prioritising renovation measures, analysing intervention scenarios, and balancing energy efficiency objectives with heritage protection requirements. Furthermore, the interactive and visual nature of the digital twin environment enhances communication with stakeholders by making complex data more accessible and facilitating participatory planning processes. For future scaling and replication, the report highlights the need for standardised metadata structures, clearly defined minimum data acquisition requirements, and continuous enrichment of the digital twin with additional thematic layers (e.g. energy systems, mobility, public space). Overall, the developed digital twin approach provides a solid foundation for implementing zero-emission neighbourhood strategies in heritage-sensitive urban contexts and represents a significant step towards integrated, data-driven planning for sustainable urban transformation.