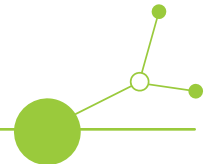


ZEB4ZEN

D.3.3.3. Digital-twin joint report



Version 1

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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, digitalisation is not only a documentation exercise, but a practical foundation for planning, prioritising 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 link geometric representations (3D models and spatial data) with harmonised 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 one specific software, 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. ANNEX I: ZAMOSC

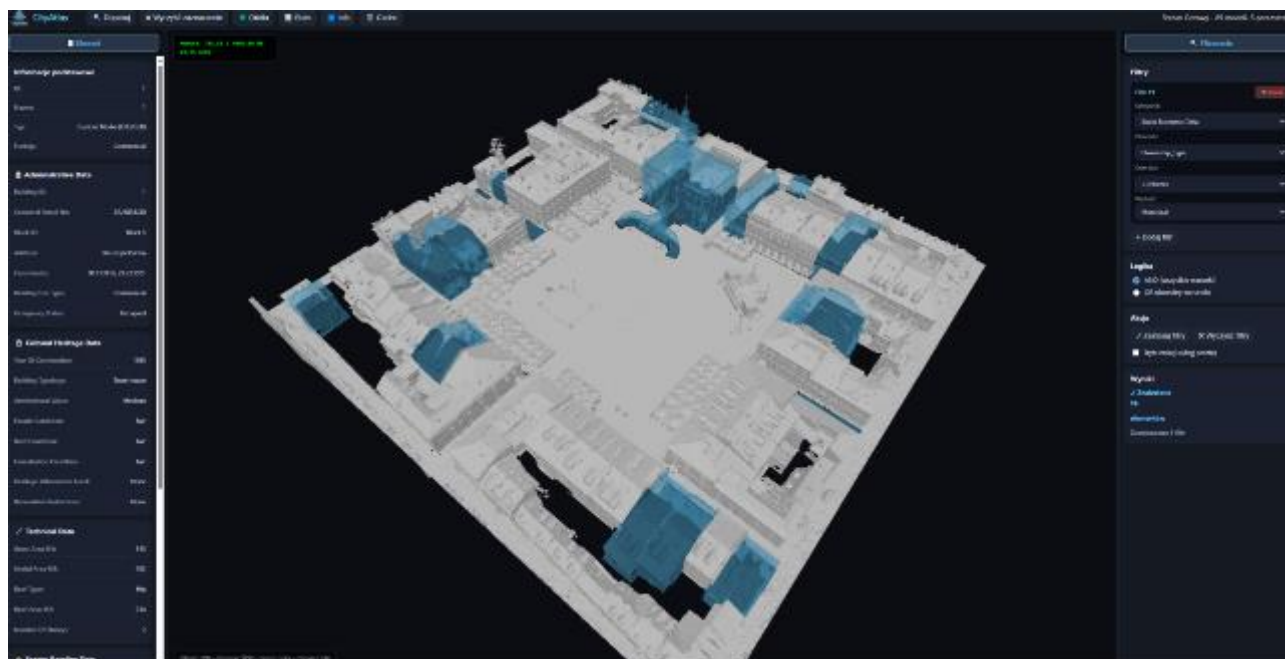
1. Digital twin environment used

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, CO₂ 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.

```
buildings_parameters.json
169   "Ownership_Type": "Municipal",
170   "Physical_Condition_Ratings": "Satisfactory",
171   "Energy_Poverty_Risk": "Medium_risk"
172 },
173 },
174 "Kolegiacka": {
175   "Administrative_Data": {
176     "Building_ID": "Kolegiacka",
177     "Cadastral_Parcel_No": "2A/2545/54",
178     "Block_ID": "Block_1",
179     "Address": "Dc. uzupelnienia",
180     "Coordinates": "50.714681, 23.259800",
181     "Building_Use_Type": "Residential",
182     "Occupancy_Status": "Vacant"
183   },
184   "Cultural_Heritage_Data": {
185     "Year_of_Construction": "1869",
186     "Building_Typology": "Town_house",
187     "Architectural_Value": "High",
188     "Facade_condition": "Poor",
189     "Roof_condition": "Fair",
190     "Penetration_condition": "Good",
191     "Heritage_Valorization_Level": "Medium",
192     "Renovation_Restrictions": "Moderate"
193   },
194   "Technical_Data": {
195     "Gross_Area_m2": 480,
196     "Useful_Area_m2": 375,
197     "Roof_type": "Hip",
198     "Roof_area_m2": 202,
199     "Number_of_Stories": 4
200   },
201   "Energy_Baseline_Data": {
202     "Heating_System_Type": "Gas_boiler",
203     "Installed_Heating_Capacity_kW": 40,
204     "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.

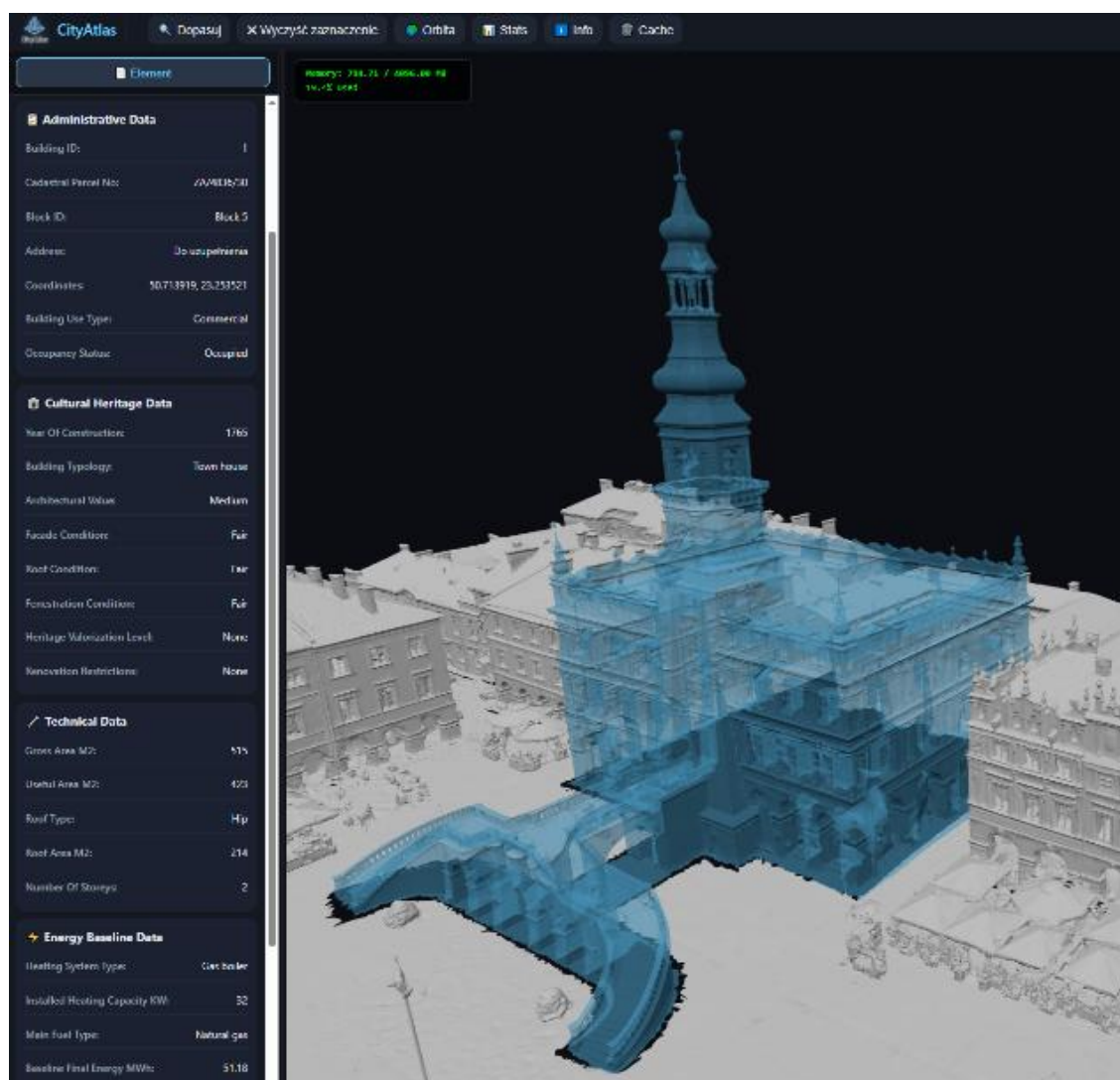
This approach provides a robust baseline for scaling and collaboration, as data corrections or metadata updates can be executed in the spreadsheet/JSON layer without requiring manual rework of the 3D model (provided that identifiers remain stable).

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.



C. 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.

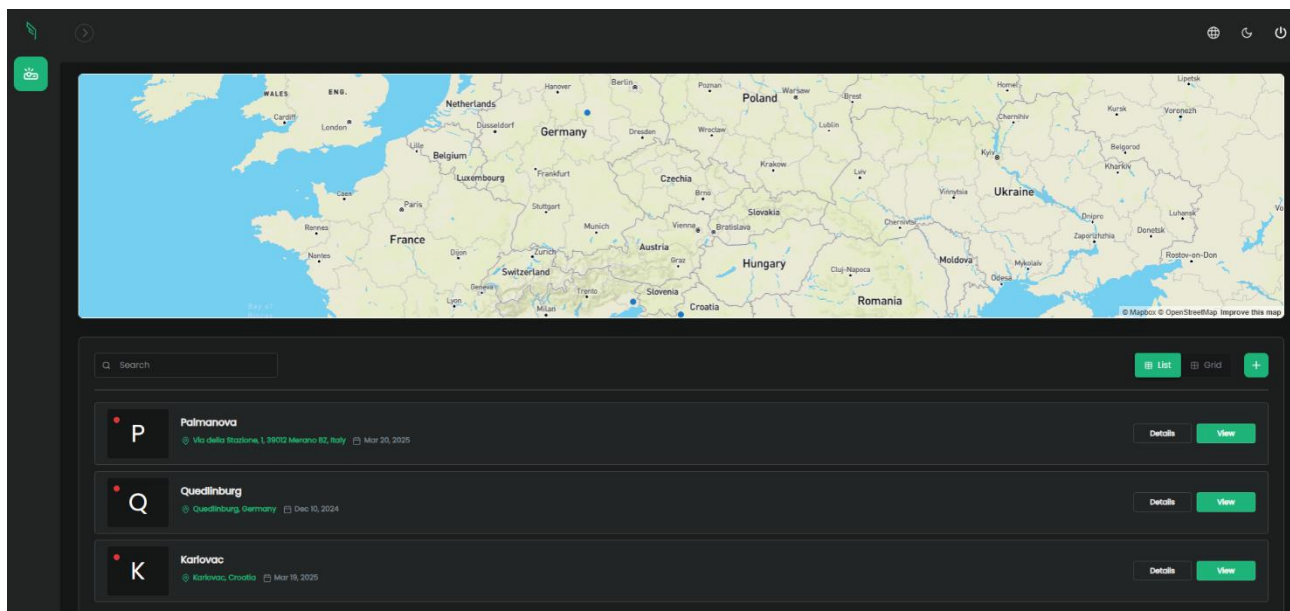


Figure 1: Project Overview in Dronoviewer

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

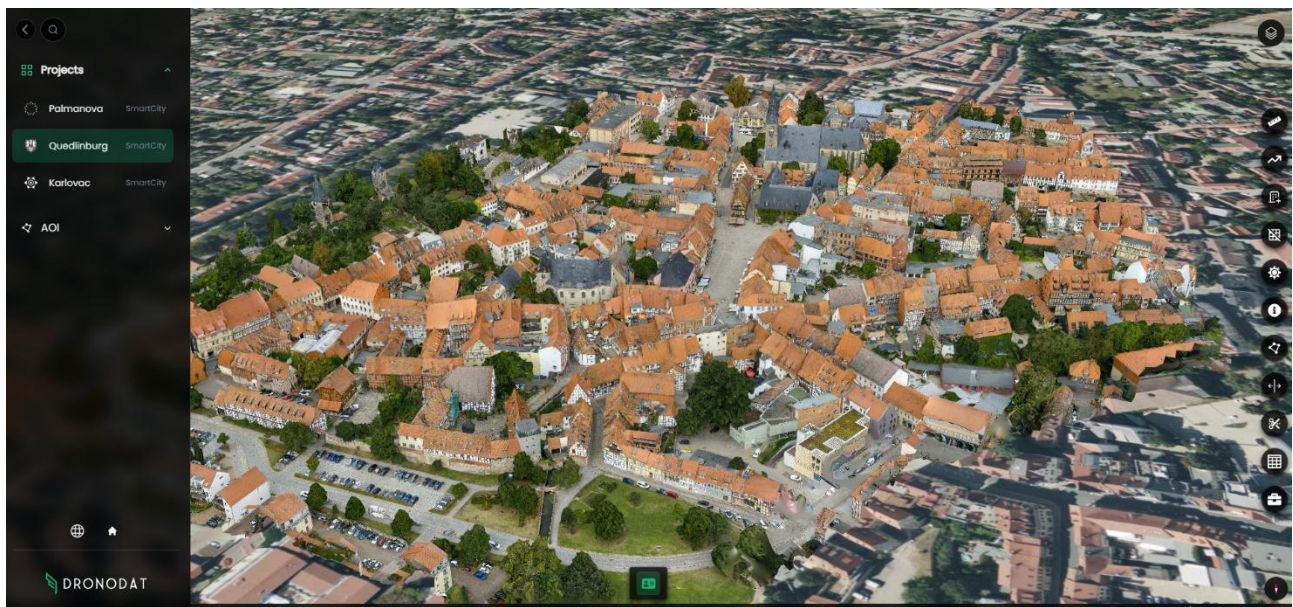


Figure 3: Quedlinburg in the Dronoviewer



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, CO₂ 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.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Building_ID	Block_ID	Administrative_Cadastral_Parcel_No	Administrative_Building_Use_Type	Administrative_Str	Administrative_S	Administrativ	Administrative	Administrative	Administrative	Administrative_Occupancy_Status		
2	1	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 486	Residential and Commercial Building	Blasistraße	1	06484	Quedlinburg	11.14097	51.78861	partially vacant		
3	5	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 484	Residential and Commercial Building	Blasistraße	2	06484	Quedlinburg	11.14097	51.78861	in use		
4	8	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 1306	Residential and Commercial Building	Blasistraße	3	06484	Quedlinburg	11.14079	51.7886	in use		
5	11	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 1305, 879	Residential and Commercial Building	Blasistraße	4	06484	Quedlinburg	11.14067	51.7886	in use		
6	14	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 316	Residential and Commercial Building	Blasistraße	5	06484	Quedlinburg	11.14054	51.78857	in use		
7	18	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 880	Residential and Commercial Building	Blasistraße	6	06484	Quedlinburg	11.14043	51.78856	in use		
8	20	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 137 / 98	Special Building	Blasistraße	06_K	06484	Quedlinburg	11.14042	51.78869	in use		
9	22	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 881	Residential and Commercial Building	Blasistraße	7	06484	Quedlinburg	11.1402	51.78856	partially vacant		
10	28	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 882	Residential and Commercial Building	Blasistraße	8	06484	Quedlinburg	11.13997	51.78853	partially vacant		
11	29	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 883	Residential and Commercial Building	Blasistraße	9	06484	Quedlinburg	11.13986	51.78853	in use		
12	31	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 884	Residential and Commercial Building	Blasistraße	10	06484	Quedlinburg	11.13965	51.78845	in use		
13	36	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 885	Residential and Commercial Building	Blasistraße	11	06484	Quedlinburg	11.13935	51.78844	in use		
14	41	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 886	Residential and Commercial Building	Blasistraße	12	06484	Quedlinburg	11.13923	51.78847	vacant		
15	44	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 137 / 560, 2207 / 137	Residential and Commercial Building	Blasistraße	14	06484	Quedlinburg	11.13903	51.78844	in use		
16	50	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 390	Residential Building	Blasistraße	15	06484	Quedlinburg	11.13882	51.78853	in use		
17	51	BLOCK 16	Gemarkung Quedlinburg, Flur 37, Flst. 223	Residential and Commercial Building	Blasistraße	16	06484	Quedlinburg	11.13869	51.78852	in use		
18	56	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 728	Residential and Commercial Building	Blasistraße	17	06484	Quedlinburg	11.139	51.78866	in use		
19	59	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 729	Residential and Commercial Building	Blasistraße	18	06484	Quedlinburg	11.1392	51.78864	partially vacant		
20	60	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 861	Residential and Commercial Building	Blasistraße	19	06484	Quedlinburg	11.1393	51.78861	in use		
21	62	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 862	Residential and Commercial Building	Blasistraße	20	06484	Quedlinburg	11.13943	51.7886	in use		
22	63	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 1858 / 137	Residential and Commercial Building	Blasistraße	21	06484	Quedlinburg	11.13956	51.78865	in use		
23	69	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 1808 / 137	Residential Building	Blasistraße	23	06484	Quedlinburg	11.13991	51.78882	in use		
24	71	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 1807 / 137	Residential Building	Blasistraße	24	06484	Quedlinburg	11.14	51.78887	in use		
25	73	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 1890 / 137, 1889 / 137	Residential and Commercial Building	Blasistraße	25	06484	Quedlinburg	11.14005	51.78894	in use		
26	75	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 373	Residential and Commercial Building	Blasistraße	26 a	06484	Quedlinburg	11.1403	51.78914	in use		
27	76	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 950 / 137	Outbuilding / Garage	Blasistraße	26	06484	Quedlinburg	11.14011	51.78904	in use		
28	77	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 137 / 574	Residential and Commercial Building	Blasistraße	27	06484	Quedlinburg	11.14048	51.78913	in use		
29	79	BLOCK 17	Gemarkung Quedlinburg, Flur 37, Flst. 864	Residential and Commercial Building	Blasistraße	28	06484	Quedlinburg	11.14044	51.78909	partially vacant		

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.

Renewable energy measures											
All											
9	1002	BLOCK 22	1002	192	2045	0	71342	82039	3608	3	0
10	1002	BLOCK 22	1002	192	2045	0	71342	82039	3608	3	0

Figure 6: Renewable energy measures tool in use in Karlovac

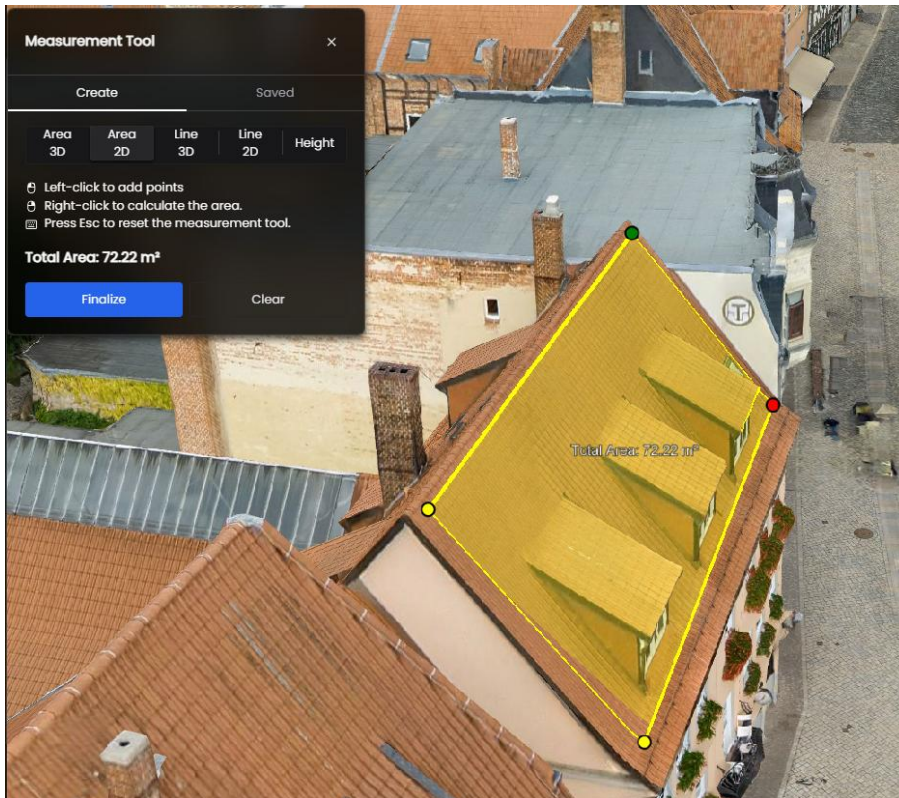


Figure 7: Measurement tool in use in Quedlinburg

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.



D. 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.