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DIGITALIZATION OF SCANNED NEIGHBOURHOODS

A. INTRODUCTION

The ZEB4ZEN project aims to support the decarbonization of Europe's historic urban districts by developing and applying digital tools to guide energy-efficient and heritage-sensitive renovation strategies. One of the key components of this effort is the development of digital twins of pilot neighbourhoods, enriched with detailed spatial, architectural, and energy-related data.

This deliverable (D.3.3.1) focuses on the systematic digitalization of cultural heritage buildings within each pilot area. The purpose is to ensure that energy and environmental modeling accounts for the heritage value and architectural character of each building, enabling context-sensitive renovation strategies.

The digitalization process was performed by:

- Compiling and structuring attribute data (administrative, heritage, and energy)
- Preparing spatial layers and aligning them with tabular data
- Creating building-level and block-level representations in QGIS
- Creating public lightning representations in QGIS
- Calculating relevant energy KPIs and aggregating data where applicable
- Visualizing results for interpretation and decision-making

The approach was applied consistently across pilot sites, with adjustments made to suit local data availability and heritage classifications.

B. METHODOLOGY

1. Methodological Background

The approach to defining EE/RES measures at the neighbourhood level is based on an integrated, cross-scalar methodology developed within the ZEB4ZEN project. This framework builds upon the detailed modelling and energy flow assessment conducted at the building level (see Deliverables D.3.1.2 and D.1.2.1) and extends it toward the scale of an entire historic neighbourhood, where buildings, infrastructure, mobility, and public services interact as one urban ecosystem.

1.1. From Building to Neighbourhood Scale

While building-level analysis focuses on the thermal performance, systems efficiency, and RES potential of individual units, neighbourhood-scale planning introduces additional complexity, including:

- Shared energy infrastructure (e.g. district heating, public lighting)

- Common energy generation systems (e.g. shared PV, energy communities)
- Integrated mobility planning (e.g. electrification of transport and charging infrastructure)

To capture these dynamics, the framework aggregates building-level data (e.g. energy demand, CO_2 emissions, investment needs) to the block and district levels, and overlays spatial, technical and regulatory constraints using GIS-based tools.

1.2. Key Analytical Steps

The following methodological steps were applied to structure and quantify EE/RES measures at the neighbourhood scale:

- Spatial mapping of building typologies and functions (residential, public, mixed-use)
- Definition of standard intervention packages per typology (e.g. thermal envelope retrofit, heating system change)
- Simulation of three renovation scenarios (baseline, District Heating-based, HP-based)
- Assessment of shared RES potential, including rooftop PV and off-site PV via energy communities
- Integration of public infrastructure measures (LED street lighting, mobility electrification)
- Calculation of aggregated KPIs (final energy, primary energy, emissions, investment)
- GIS-based visualisation and block-level analysis

1.3. Integration with Digital Tools

The methodology relies heavily on spreadsheet-based energy modelling, integrated with spatial data through QGIS. This allows linking building attributes (e.g. floor area, orientation, usage) with energy flows and identifying spatial clusters with the highest decarbonisation potential. It also enables visual outputs for communication and planning purposes. All building-level and block-level data are geo-referenced and visualized in a GIS environment. This enables planners to assess spatial patterns of consumption, locate renewable generation hubs, and prioritize interventions based on technical potential and heritage restrictions.

1.4. KPI Aggregation and Evaluation

Key performance indicators such as primary energy demand, CO_2 emissions, investment cost per m^2A_k, and emission reduction potential are calculated for each scenario at the neighbourhood level. This supports decision-making and long-term strategic planning. This methodological structure ensures consistency across different thematic areas (buildings, transport, lighting, infrastructure), allowing for flexible adaptation to other heritage districts with similar constraints.

C. MODEL IMPLEMENTATION: CALCULATION STRUCTURE, GIS INTEGRATION, AND PHASED DEPLOYMENT

1. Excel-Based Energy Model Structure and Calculations

An Excel-based energy model was developed as the core analytical tool for evaluating energy efficiency (EE) and renewable energy supply (RES) measures in the Zvijezda zero-emission neighbourhood plan. This model integrates detailed building-level data (e.g. floor areas, usage type, construction, heritage status) with energy performance parameters to calculate current and future energy use. All available data sources – including GIS-derived building geometries and heights, audit and survey information, and national databases – were consolidated to assign each building a set of characteristics and baseline energy demandsfile-lamgukqckifnb5csy9mrtsfile-lamgukqckifnb5csy9mrts. Using these inputs, the model computes annual energy demand for each building across multiple end-uses and fuels, capturing the full energy balance at building level. Key demand components include:

- Electricity demand (lighting, appliances, and any electric heating or cooling) in kWh/year,
- Thermal energy demand for space heating and hot water, broken down by fuel type (e.g. firewood biomass, natural gas, fuel oil, coal, district heat) in kWh/year,
- Space cooling demand (if applicable) in kWh/year, attributed to electricity,
- Total final energy use per building as the sum of all fuels (in MWh/year).

For each building, the model applies appropriate conversion factors and emission factors to quantify annual CO_2 emissions (in tons) resulting from its energy usefile. The baseline scenario reflects current conditions where many buildings have high heating demands (due to little or no insulation) and use a mix of outdated heating systems and fuels (predominantly wood, some gas, fuel oil, and resistive electricity heating)file. These granular calculations are aggregated by building block: the spreadsheet groups buildings into their respective urban blocks (Zvijezda has ~29 blocks encompassing ~235 buildingsfile). For each block, the model automatically sums up the total annual energy demand by fuel type, total electricity use, and total emissions. This yields a block-level energy and emissions profile which is easier to visualize and analyze for planning than individual building data.

Energy Supply and Scenario Calculations: In addition to energy demand, the model accounts for on-site energy supply measures and fuel switching in scenario analyses. Users can define specific EE/RES interventions for each building or block – for example, adding insulation, installing efficient windows, upgrading lighting, switching heating systems, or adding solar panels – by adjusting relevant parameters in the spreadsheet. The model then recalculates energy demand and supply for a future scenario with those measures implemented. For instance, improved insulation and window replacement reduce a building's space heating demand (kWh/m^2) by a given percentage, which the model applies to lower the annual heating energy for that building. If a building is converted from an individual fossil-fuel boiler to a renewable district heating system (CTS), the model zeroes out the building's fuel oil or gas use and instead counts the required heat delivered as "district heat" energy (with an emission factor reflecting the renewable source). Likewise, if a building switches to a heat pump, its heating fuel demand is replaced by additional electricity demand (computed based on heat pump COP, so that electricity use = heat demand / COP). On-site renewable generation (such as photovoltaic panels on roofs) is represented on the supply side: the model allows input of PV capacity per building and calculates the annual PV electricity production (kWh/year) using typical yield factors. This local production can offset a portion of the building's grid electricity consumption in the scenario. All these changes are captured at building level and then aggregated by block to show how each

block's total energy profile shifts – e.g. a block's biomass and oil use might drop to zero if all its buildings connect to geothermal district heating, while its electricity use might increase if heat pumps are used instead, and a new PV generation column will show output from installed solar capacity.

Investment Costs and KPIs: The Excel model also incorporates an investment calculation module. Each EE/RES measure is assigned a unit cost (e.g. insulation cost per m^2, heat pump cost per kW, PV cost per kWp, etc.), allowing the model to estimate the capital investment needed per building and per block for the chosen scenario. For example, if Block 5 has 10 buildings being insulated (with a total of 5,000 m^2 of façade), plus 3 heat pumps and 200 kW of PV installed, the model will sum the costs for all those measures to give an overall investment figure for Block 5. Summing across all blocks yields the total neighbourhood investment for that scenario. With both baseline and scenario data in place, the model computes key Key Performance Indicators (KPIs) to quantify impacts. These include:

- Reduction in energy use – e.g. final energy savings in MWh/year and as a percentage of the baseline, often normalized per m^2 to gauge intensity improvements. The model can report both final energy (at site) and primary energy (accounting for energy supply chain), in line with EU nearly zero-energy building metrics.
- CO_2 emissions reduction – the drop in annual CO_2 emissions (tons/year) compared to baseline, and percentage reduction towards climate targets.
- Renewable energy share – the fraction of the final energy consumption supplied by renewable sources (%). For instance, if solar PV and geothermal heat cover a large part of the demand, the RES share rises accordingly.
- Renovated building area – total floor area or envelope area renovated (m^2) in the scenario, indicating the scale of intervention.
- Installed RES capacity – such as total PV capacity (kWp) installed in the neighbourhood or number of buildings connected to district heating.
- Cost and economic indicators – total investment cost and potential economic metrics like payback period or cost per kWh saved (the model can be used to derive simple payback if annual energy cost savings are estimated, as an additional KPI).

All these outputs are organized by building block and for the entire district, giving a clear quantitative basis to compare scenarios. Built-in summary tables and charts in the Excel workbook illustrate the results – for example, stacked bar charts show each block's energy demand by source in baseline and in the scenario, highlighting the reduction in fossil fuels and increase in renewable supply. In summary, the Excel model provides a transparent calculation structure where one can trace inputs (building data, measures) through to outputs (energy, emissions, costs, KPIs), ensuring the methodology is traceable and adjustable as needed. This level of detail and flexibility is critical for a historic district like Zvijezda, where planners must balance energy targets with building-specific constraints.

2. GIS Integration for Spatial Visualization and Planning

To effectively use the model results in urban planning and decision-making, the Excel dataset is closely integrated with GIS (Geographic Information System) spatial layers. Each building and block in the model is referenced by a unique ID that corresponds to geospatial features in the Zvijezda district map. A geospatial data layer of the 29 urban blocks and all buildings was prepared, containing attributes such as block number, building addresses, floor areas, and heritage protection status.

The outputs from the Excel model (energy demand, emissions, etc. by block or building) are linked or imported into the GIS environment for visualization. This linkage can be done by exporting summary tables

from Excel and joining them to the block polygons in GIS via the block ID. The result is a digital energy map of the neighbourhood. Using the GIS integration, planners can create thematic maps that illustrate the baseline and scenario data spatially. For example, one map layer might show baseline CO_2 emissions intensity by block, using color shading to indicate which blocks are currently responsible for higher emissions (as was done in Figure 1: Building blocks CO_2 emissions – Baseline scenario of the plan)

Another set of map layers can depict the simulated effects of measures at block level, such as coloring each block by its percentage energy reduction or labeling blocks with their selected heating solution (e.g. blocks connected to the central district heating versus blocks using heat pumps).

Because the GIS contains not only energy data but also information on urban context (building footprints, streets, heritage landmarks, etc.), it provides a rich platform to combine spatial context with energy performance. Planners can visually identify clusters of high energy consumption, proximity to infrastructure (for example, which blocks are near the planned geothermal district heating pipeline route), and any spatial patterns that might inform implementation (such as grouping adjacent blocks in a single project phase). In practical terms, the GIS-integrated model serves as a "digital twin" of the neighbourhood's energy system.

Users can click on a specific block or building in the map and retrieve its data from the model – for instance, viewing a popup of Block 10 that lists the number of buildings, baseline energy use by fuel, planned measures (insulation, PV, etc.), scenario energy use, CO_2 reduction, and investment cost for that block. This improves the transparency and communicability of the plan: city officials and stakeholders can readily see where and how interventions will take place. Moreover, having georeferenced data enables further analysis, such as checking the correlation of energy performance with building age or verifying that proposed PV installations correspond to roofs with sufficient sun exposure (using GIS solar maps). It also allows layering of additional criteria – for example, overlaying the energy reduction map with a heritage protection map to ensure that the most sensitive historic zones are receiving appropriate retrofit strategies. The GIS integration is crucial for scenario assessment and comparison. Different scenario results (which are generated in the Excel model as separate datasets, e.g. one scenario with centralized heating and another with decentralized heat pumps) can be loaded as separate map layers. This way, one can visually compare Scenario A and Scenario B – for instance, seeing that in Scenario A (geothermal district heating) the blocks are uniformly green (low emissions) but require a new pipeline network, whereas in Scenario B (heat pumps) certain blocks might still have slightly higher emissions due to remaining fossil backup or less PV. The spatial approach helps convey these differences to decision-makers. Additionally, by integrating the model with the city's GIS, the plan's data can be kept up to date ("live") – as real projects get implemented, the GIS attributes can be updated (e.g. marking a building as renovated and updating its post-renovation consumption), which can then feed back into the Excel model for monitoring purposes. In essence, the combination of Excel's calculation power with GIS's visualization and data management capacity creates a powerful planning toolkit for moving Zvijezda towards a zero-emission future.

3. Phased Deployment Strategy and Temporal Scenario Implementation

Implementing all proposed measures across an entire neighbourhood is a multi-year endeavor, especially in a historically protected area. The model supports phased implementation planning by incorporating a timeline dimension into the scenario calculations. In the Excel structure, each building or block can be assigned a specific year or phase when retrofitting measures are executed. This is facilitated by an annual timeline from the present (2025) through a target horizon (e.g. 2030, 2040, up to 2050) across the spreadsheet columns. For each year, the model can reflect the cumulative effect of measures implemented up to that point. In practical terms, this means if Block 15 is scheduled to be renovated in 2025, the model will apply the reduced energy demand and new heating system for Block 15 starting in the 2025 column

onward. Blocks not yet renovated will continue to show baseline energy consumption until their assigned intervention year. By stepping through the years, the spreadsheet generates an annual progression of energy demand and emissions for each block and for the whole district, illustrating how the neighbourhood's energy profile improves over time (rather than jumping straight from baseline to final scenario). Planners can use this to verify interim targets: for example, they can check that by 2030 a certain percentage of emissions reduction is achieved with the first set of renovations, and that the trajectory continues toward the 2050 zero-emission goal.

Prioritization criteria can be tested in the model to develop an optimal phasing sequence. One common approach is to prioritize buildings or blocks by energy savings potential – the model can identify which blocks have the highest baseline consumption or the largest expected reduction if retrofitted, and these can be scheduled in earlier phases to maximize early gains in energy and CO_2 reduction. Another criterion is heritage and technical constraints: since the Zvijezda core is under strict cultural protection, some interventions (external façade insulation, window replacements, etc.) require careful design and approvals. Blocks with the most significant monuments or complex heritage constraints might be planned in later phases, allowing more time for developing tailor-made solutions (or awaiting new technologies) while ensuring easier sites are addressed first. The model's dataset explicitly tags each building with its heritage status or protection level, so planners can filter or sort the implementation schedule accordingly.

The annual columns allow planners to assign, say, 5–6 blocks per year over a decade, rather than all 29 blocks in one year, reflecting realistic construction capacity and funding flows. This also helps align the plan with funding availability (e.g. municipal budgets or EU funding rounds) – the model can compute the investment required each year, which can then be matched with expected financing. By reviewing the yearly investment profile from the model, the phasing can be adjusted to avoid peaks that exceed budget or workforce limits. Similarly, phasing can be used to coordinate infrastructure roll-out: for example, if a new district heating network (CTS) is part of the scenario, the model can group blocks by their geographic proximity so that the network extension happens sequentially. Blocks along the same branch of the network would be scheduled in the same phase to streamline construction, which can be visualized in GIS and verified that contiguous areas are handled together. The phased deployment output of the model provides a clear roadmap: it details which blocks (and how many buildings, what measures) are improved each year, along with the resulting annual energy savings and emissions cut.

The Excel model ensures all relevant metrics (energy, CO_2, cost, renewables) are quantified for each part of the neighbourhood; the integration with GIS enables these results to be seen in their spatial context and communicated clearly to stakeholders.

D. ANNEXES

1. ANNEX I: KARLOVAC PILOT (ZVIJEZDA) DIGITALIZATION

1.1. SCOPE OF DIGITALIZATION

The following actions were carried out for each pilot:

1. Data Collection and Structuring

Tabular data was compiled in Excel spreadsheets containing:

- Administrative information (building ID, location, use)
- Cultural heritage attributes (construction date, typology, valorization)
- Energy data (heating needs, final/primary energy, CO_2 emissions)
- Public Lightning data

2. Spatial Referencing

Data was linked to spatial layers using:

- Parcel number as a key for building-level joins
- Block name for aggregations at district level
- Geo-location coordinates

3. QGIS Integration

CSV files were prepared and joined with building and block polygon layers in QGIS, allowing for rich geovisualization and comparative analysis.

4. Key Performance Indicators (KPIs)

At the block level, aggregated indicators were calculated:

- Energy needs by energy source and end use,
- CO_2 emissions,

1.2. DATA VISUALIZATION AND INTERPRETATION IN QGIS

QGIS was used to visualize both levels of data:

- Building Level (Detailed View):
- Shows administrative, architectural, and basic energy data
- Used for identifying individual heritage and energy characteristics
- Block Level (Aggregated View):
- Focuses on aggregated KPIs relevant for strategic planning
- Visualized through thematic mapping (e.g. choropleth styles)

1.3. METHODOLOGY FOR DIGITAL TWIN DEVELOPMENT AND SPATIAL DATA INTEGRATION

1.4. Digitalization of Buildings in Zvijezda

1.4.1. Step 1: Tabular Data Structuring and Conversion to QGIS-Ready Format

Two main Excel files were prepared to contain the building-level data:

- ***Zvijezda_Buildings_RES.xlsx*** – *residential buildings*
- ***Zvijezda_Buildings_NON_RES.xlsx*** – *non-residential buildings*

Each file includes:

- Administrative data (building ID, address, cadastral parcel number)
- Descriptive heritage data (construction date, typology, architectural value, protection level)
- Basic technical data (surface area, heated volume, occupancy)
- Energy-related values (energy consumption, installed heating power)

The linking key to spatial data was the cadastral parcel number, which exists both in the attribute table and in the polygon shapefile.

A	B	C	E	G	H	I	J	L	M	N	O	X
No.	BLOCK	Cadastral Number	Legislative Building Typology	Heritage Val.	Dating	Floors	Total Gross Area [m2]	Ak [m2]	Qh,nd [kWh/m2]	E (Other Energy Needs) [kWh/m2]	Building Condition Classification	Heating Mode
1	BLOCK 1	1101	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	950	788,50	98,95	127,75	Good condition	Local heating
2	BLOCK 1	1092	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	792	601,92	241,90	127,75	Moderate condition	Unknown
3	BLOCK 1	1091	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	720	547,20	241,90	127,75	Moderate condition	Local heating
4	BLOCK 1	1090	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	760	615,60	178,50	127,75	Moderate condition	Local heating
5	BLOCK 1	1100	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP1K	788	598,88	241,90	127,75	Demolished	Unknown
6	BLOCK 1	1104/3	Residential building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P1K	275	209,00	241,90	127,75	Bad condition	Local heating
7	BLOCK 1	1104/1	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	228	173,28	241,90	127,75	Bad condition	Local heating
8	BLOCK 1	1103	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	220	167,20	241,90	127,75	Bad condition	Local heating
9	BLOCK 1	1102	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	1161	882,36	241,90	127,75	Good condition	Local heating
10	BLOCK 1	1099	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	1135	783,15	113,39	127,75	Moderate condition	Local heating
11	BLOCK 1	1098	Residential building	EXPRESSIVE	FIRST HALF OF THE 19TH CENTURY.	P1K	791	569,52	244,77	127,75	Moderate condition	Local heating
12	BLOCK 1	1097	Residential building	ARCHITECTURAL AMBIENT	18th century	P2K	749	494,34	94,04	127,75	Moderate condition	Local heating
13	BLOCK 1	1096	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	599	386,84	241,90	127,75	Moderate condition	Unknown
14	BLOCK 1	1095	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	702	547,56	175,84	127,75	Moderate condition	Local heating
15	BLOCK 1	1094_1	Residential building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	PK	140	106,40	241,90	127,75	Moderate condition	Unknown
16	BLOCK 1	1094	Residential building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	PK	448	340,48	241,90	127,75	Moderate condition	Unknown
17	BLOCK 1	1089	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	1422	1.066,50	197,08	127,75	Moderate condition	Local heating, Central heating
20	BLOCK 2	1270_1	Residential building	ARCHITECTURAL AMBIENT	18th century	P2K	735	558,60	241,90	127,75	Bad condition	Unknown
21	BLOCK 2	1270	Residential building	ARCHITECTURAL AMBIENT	18th century	P2K	739	561,64	241,90	127,75	Bad condition	Unknown
22	BLOCK 2	1271	Residential building	ARCHITECTURAL AMBIENT	FIRST HALF OF THE 19TH CENTURY.	P2K	1036	787,36	241,90	127,75	Good condition	Unknown
23	BLOCK 2	1273_1	Family house	LOWER AMBIENT	FIRST HALF OF THE 20TH CENTURY	PK	115	87,40	241,90	127,75	Bad condition	Local heating
24	BLOCK 2	1273	Family house	AMBIENT	18th century	PK	100	76,00	241,90	127,75	Bad condition	Local heating
25	BLOCK 2	1274/1	Family house	LOWER AMBIENT	SECOND HALF OF THE 20TH CENTURY.	PK	128	107,52	300,08	127,75	Bad condition	Unknown
26	BLOCK 2	1274/2	Family house	LOWER AMBIENT	SECOND HALF OF THE 20TH CENTURY.	PK	95	71,25	225,93	127,75	Bad condition	Local heating
28	BLOCK 3	1112	Residential building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P1K	488	370,88	163,37	127,75	Moderate condition	Local heating
29	BLOCK 3	1111	Residential building	AMBIENT	FIRST HALF OF THE 20TH CENTURY	P1K	390	296,40	241,90	127,75	Moderate condition	Unknown
30	BLOCK 3	1118	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	639	401,92	226,79	127,75	Bad condition	Unknown
31	BLOCK 3	1117	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	782	594,32	241,90	127,75	Bad condition	Unknown
32	BLOCK 3	1113	Residential building	ARCHITECTURAL AMBIENT	FIRST HALF OF THE 19TH CENTURY.	P1K	548	416,48	241,90	127,75	Moderate condition	Local heating
35	BLOCK 4	1083	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	1095	832,20	241,90	127,75	Moderate condition	Local heating
37	BLOCK 5	992/1_1	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	SECOND HALF OF THE 19TH CENTURY.	P3K	3269	2.484,44	241,90	127,75	Great condition	Unknown (Central heating)
40	BLOCK 6	1264	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP1K	1071	835,38	241,90	127,75	Good condition	Central heating
41	BLOCK 6	1283	Residential building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP1K	1348	1.024,48	241,90	127,75	Moderate condition	Local heating
42	BLOCK 6	1281/1	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	228	189,24	148,46	127,75	Moderate condition	Central heating
43	BLOCK 6	1280	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	759	576,84	241,90	127,75	Good condition	Unknown
44	BLOCK 6	1279/1	Family house	LOWER AMBIENT	SECOND HALF OF THE 20TH CENTURY.	P1K	235	178,60	241,90	127,75	Good condition	Local heating
45	BLOCK 6	1278/1	Family house	LOWER AMBIENT	SECOND HALF OF THE 20TH CENTURY.	P1K	378	287,28	241,90	127,75	Good condition	Local heating
46	BLOCK 6	1277/1	Residential building	LOWER AMBIENT	SECOND HALF OF THE 20TH CENTURY.	P1K	518	393,68	241,90	127,75	Good condition	Unknown
47	BLOCK 6	1279/2	Family house	LOWER AMBIENT	SECOND HALF OF THE 20TH CENTURY.	P1K	240	182,40	241,90	127,75	Good condition	Unknown
48	BLOCK 7	1268	Residential building	ARCHITECTURAL AMBIENT	18th century	P1K	470	357,20	241,90	127,75	Very bad condition	Local heating
49	BLOCK 7	1267	Residential building	ARCHITECTURAL AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P1K	360	273,60	241,90	127,75	Very bad condition	Local heating

Figure 1: Data Spreadsheet by Residential Buildings, Zvijezda

No.	BLOCK	Cadastral Number	Legislative Building Typology	Heritage Val.	Dating	Floors	Total Gross Area [m2]	Ak/A	Ak [m2]	Qh,nd [kWh/m2]	E (Other Energy Needs) [kWh/m2]	Building Condition Classification	Heating Mode
18	BLOCK 1	1105	Office and administrative building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	1872	0,76	1.422,72	241,90	152,00	Good condition	Unknown (Local heating)
19	BLOCK 1	1093	Office and administrative building	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PoP2K	4495	0,76	3.416,20	241,90	152,00	Good condition	Central heating
27	BLOCK 2	1272	Schools	ARCHITECTURAL AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P1K	1872	0,76	1.422,72	241,90	152,00	Great condition	Central heating
33	BLOCK 3	1116	Office and administrative building	AMBIENT	FIRST HALF OF THE 20TH CENTURY	P2K	3469	0,75	2.601,75	28,51	152,00	Great condition	Central heating
34	BLOCK 3	1115	Other non-residential buildings	EXPRESSIVE	16th and 17th centuries	P1K	1208	0,76	918,08	241,90	152,00	Under Renovation / Construction	Central heating
36	BLOCK 5	992/1_2	Schools	EXPRESSIVE	16th and 17th centuries	P2K	5898	0,76	4.482,48	241,90	152,00	Moderate condition	Central heating
39	BLOCK 5	992/1	Schools	NOT INCORPORATED IN THE HISTORICAL MATRIX	FIRST HALF OF THE 20TH CENTURY	PK	784	0,76	595,84	241,90	152,00	Moderate condition	Central heating
51	BLOCK 7	1265_1	Schools	ARCHITECTURAL AMBIENT	18th century		1293	0,76	982,68	241,90	152,00	Moderate condition	Central heating
52	BLOCK 7	1265_3	Schools	ARCHITECTURAL AMBIENT	18th century		390	0,76	296,40	241,90	152,00	Moderate condition	Central heating
53	BLOCK 7	1265_2	Schools	ARCHITECTURAL AMBIENT	18th century		790	0,76	600,40	241,90	152,00	Moderate condition	Central heating
54	BLOCK 7	1265	Schools	ARCHITECTURAL AMBIENT	18th century	PoP1K	420	0,76	319,20	241,90	152,00	Moderate condition	Central heating
58	BLOCK 8	1120/2	Other non-residential buildings	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	PK	182	0,76	138,32	241,90	152,00	Bad condition	Unknown
59	BLOCK 8	1120/1	Other non-residential buildings	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	VP	182	0,76	138,32	241,90	152,00	Bad condition	Unknown
60	BLOCK 8	1119/4	Office and administrative building	UNFITTED DESIGN	SECOND HALF OF THE 20TH CENTURY.	PoP1K	1614	0,89	1.436,46	85,06	152,00	Good condition	Central heating
61	BLOCK 8	1122	Office and administrative building	ARCHITECTURAL AMBIENT	18th century	P1K	1212	0,76	921,12	241,90	152,00	Under Renovation / Construction	Central heating
63	BLOCK 9	1073	Commerce	ARCHITECTURAL AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P1K	823	0,72	592,56	141,40	152,00	Moderate condition	Local heating
64	BLOCK 9	1071	Office and administrative building	ARCHITECTURAL AMBIENT	18th century	P1K	2377	0,76	1.806,52	241,90	152,00	Under Renovation / Construction	Unknown
72	BLOCK 10	1067	Office and administrative building	EXPRESSIVE	16th century	P1K	283	0,96	271,68	27,83	152,00	Great condition	Central heating
75	BLOCK 10	1060	Office and administrative building	ARCHITECTURAL AMBIENT	18th century	P1K	873	0,76	663,48	241,90	152,00	Moderate condition	Unknown
126	BLOCK 13	1243	Commerce	ARCHITECTURAL AMBIENT	18th century	PK	172	0,76	130,72	241,90	152,00	Moderate condition	Local heating
133	BLOCK 13	1155/2	Other non-residential buildings	ARCHITECTURAL AMBIENT	18th century	PK	87	0,76	66,12	241,90	152,00	Moderate condition	Local heating
139	BLOCK 13	1247/3	Office and administrative building	ARCHITECTURAL AMBIENT	18th century	P1K - PK	526	0,76	399,76	241,90	152,00	Moderate condition	Unknown (Local heating)
143	BLOCK 14	1262	Office and administrative building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P2K	1676	0,76	1.273,76	241,90	152,00	Bad condition	Unknown
144	BLOCK 14	1263_1	Office and administrative building	ARCHITECTURAL AMBIENT	SECOND HALF OF THE 19TH CENTURY.	P1K	1558	0,74	1.152,92	198,56	152,00	Moderate condition	Unknown
145	BLOCK 14	1263	Office and administrative building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	PK	246	0,74	182,04	198,56	152,00	Moderate condition	Unknown
146	BLOCK 14	1264	Office and administrative building	ARCHITECTURAL AMBIENT	18th century	PoP2K	2876	0,76	2.185,76	241,90	152,00	Bad condition	Central heating
147	BLOCK 15	1124/2	Office and administrative building	AMBIENT	SECOND HALF OF THE 19TH CENTURY.	VP	84	0,76	63,84	241,90	152,00	Bad condition	Unknown
148	BLOCK 15	1124/3	Other non-residential buildings	AMBIENT	FIRST HALF OF THE 20TH CENTURY	VP	74	0,76	56,24	241,90	152,00	Moderate condition	Unknown
149	BLOCK 15	1124/4	Other non-residential buildings	UNFITTED DESIGN	FIRST HALF OF THE 20TH CENTURY	VP	70	0,76	53,20	241,90	152,00	Moderate condition	Unknown
150	BLOCK 15	1124/5	Other non-residential buildings	LOWER AMBIENT	FIRST HALF OF THE 20TH CENTURY	VP	313	0,76	237,88	241,90	152,00	Moderate condition	Unknown
151	BLOCK 15	1124/1_1	Other non-residential buildings	EXPRESSIVE	16th and 17th centuries	VPK - P1K- P2K	3880	0,76	2.948,80	241,90	152,00	Under Renovation / Construction	Unknown
152	BLOCK 15	1124/1	Other non-residential buildings	EXPRESSIVE	16th and 17th centuries	VPK	115	0,76	87,40	241,90	152,00	Under Renovation / Construction	Unknown
153	BLOCK 16	1026/1	Schools	EXPRESSIVE	18th century	P-P2K	4071	0,76	3.093,96	37,35	152,00	Under Renovation / Construction	Central heating
178	BLOCK 18	1251_1	Other non-residential buildings	ARCHITECTURAL AMBIENT	FIRST HALF OF THE 19TH CENTURY.	P2K	1145	0,76	870,20	241,90	152,00	Moderate condition	Unknown
179	BLOCK 18	1251	Other non-residential buildings	ARCHITECTURAL AMBIENT	SECOND HALF OF THE 20TH CENTURY.	P2K	1071	0,76	813,96	241,90	152,00	Moderate condition	Unknown
184	BLOCK 19	1130	Other non-residential buildings	ARCHITECTURAL AMBIENT	FIRST HALF OF THE 19TH CENTURY.	P1K - P2K	2090	0,76	1.588,40	241,90	152,00	Bad condition	Unknown
186	BLOCK 20	1079	Other non-residential buildings	EXPRESSIVE	18th century	P2K	6881	0,76	5.229,56	241,90	152,00	Very bad condition	Unknown
192	BLOCK 21	1023_1	Other non-residential buildings	ARCHITECTURAL AMBIENT	18th century	VP	368	0,76	279,68	241,90	152,00	Great condition	Unknown
193	BLOCK 21	1023_2	Other non-residential buildings	ARCHITECTURAL AMBIENT	18th century	P1K	850	0,76	646,00	241,90	152,00	Great condition	Unknown
194	BLOCK 21	1023_3	Other non-residential buildings	ARCHITECTURAL AMBIENT	18th century	PoP1K	385	0,76	292,60	241,90	152,00	Great condition	Unknown

Figure 2: Data Spreadsheet by Non-Residential Buildings, Zvijezda

The Excel files were edited and converted into QGIS-compatible .csv format.

1.4.2. Step 2: Linking to Spatial Data in QGIS

In QGIS, each .csv table was joined to its corresponding building polygons using the **cadastral parcel number** as the key. This allowed for:

- Full visualization of each building's attributes
- Mapping by architectural category, historical period, or energy characteristics
- Integration with cadastral ortho-photo basemaps and other reference layers

The building polygons for the Zvijezda district were provided by the City of Karlovac. These spatial datasets were subsequently adapted to ensure compatibility with the prepared attribute tables. **A crucial step in this process was defining a reliable key identifier to enable the join between spatial geometries** (polygon shapefiles) and the attribute data (Excel or .csv tables). In this case, the cadastral parcel number served as the primary linking field, allowing for accurate and consistent integration of building-level administrative, heritage, and energy-related information within the QGIS environment.

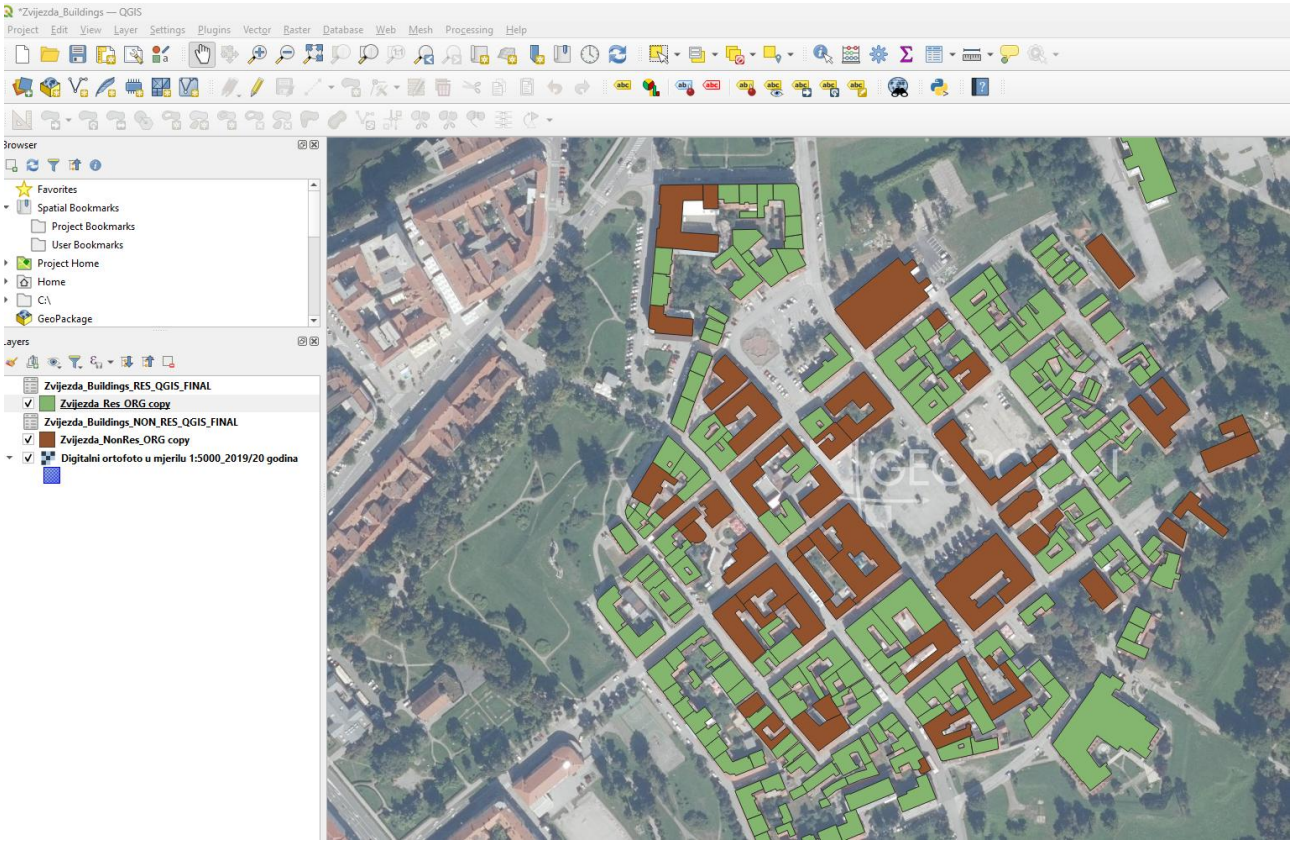


Figure 3: QGIS interface - visualization of residential and non-residential building polygons in QGIS

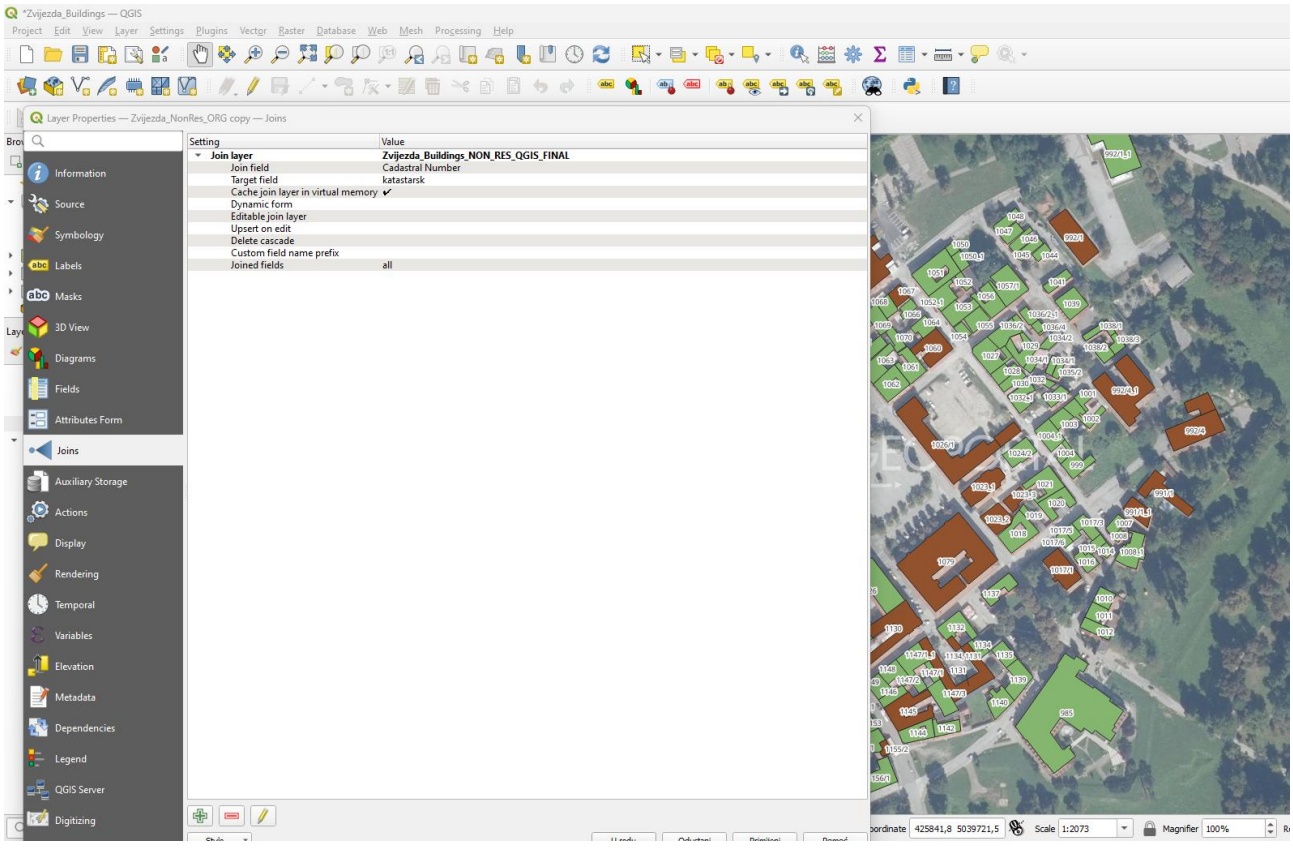


Figure 4: QGIS interface - linking polygons and building data speadsheets with buildings data (cadastral numbers)

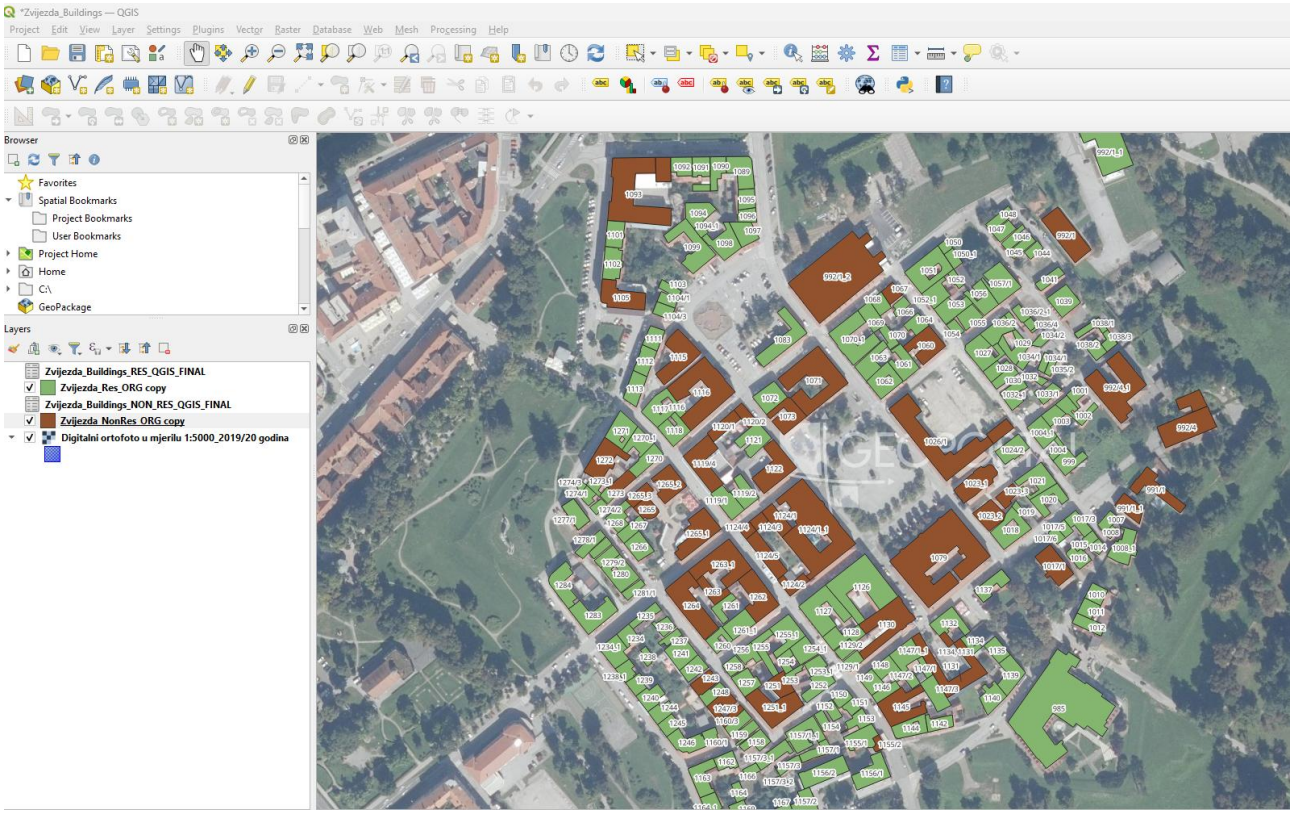


Figure 5: QGIS interface - spatial display of data from attribute tables (cadastral numbers)

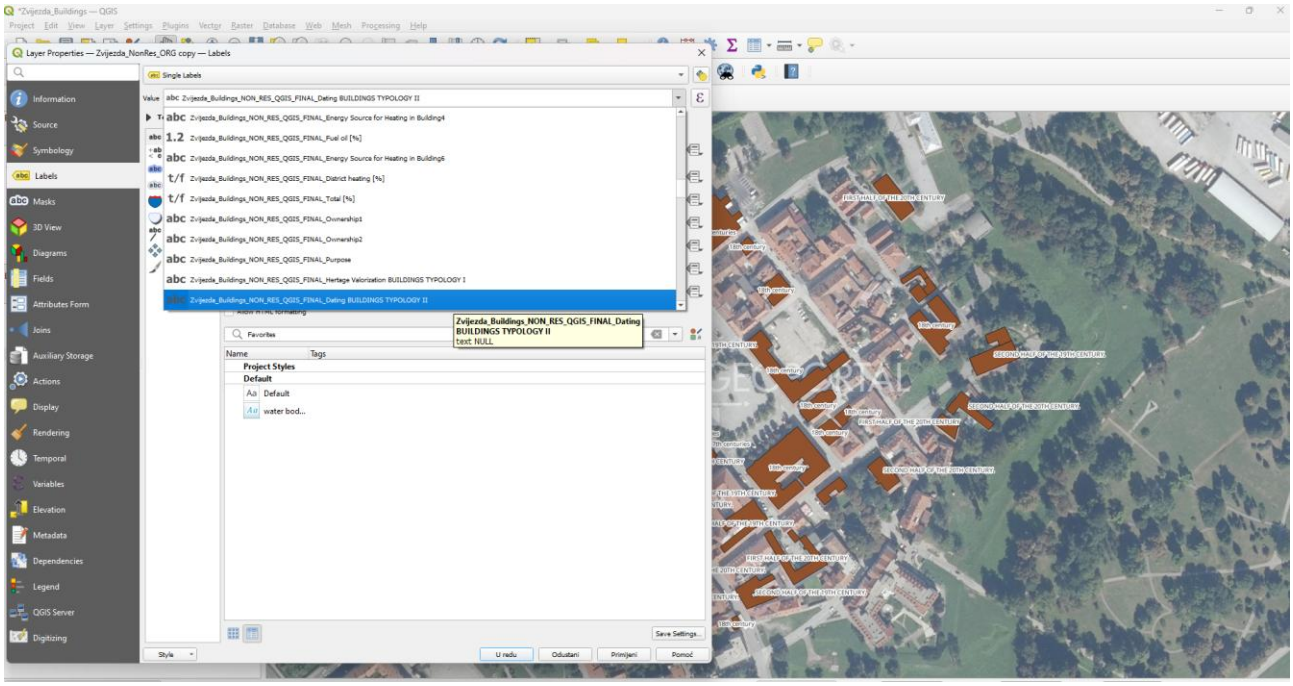


Figure 6: QGIS interface - selecting data for spatial display from attribute tables (dating of Non Residential Buildings)

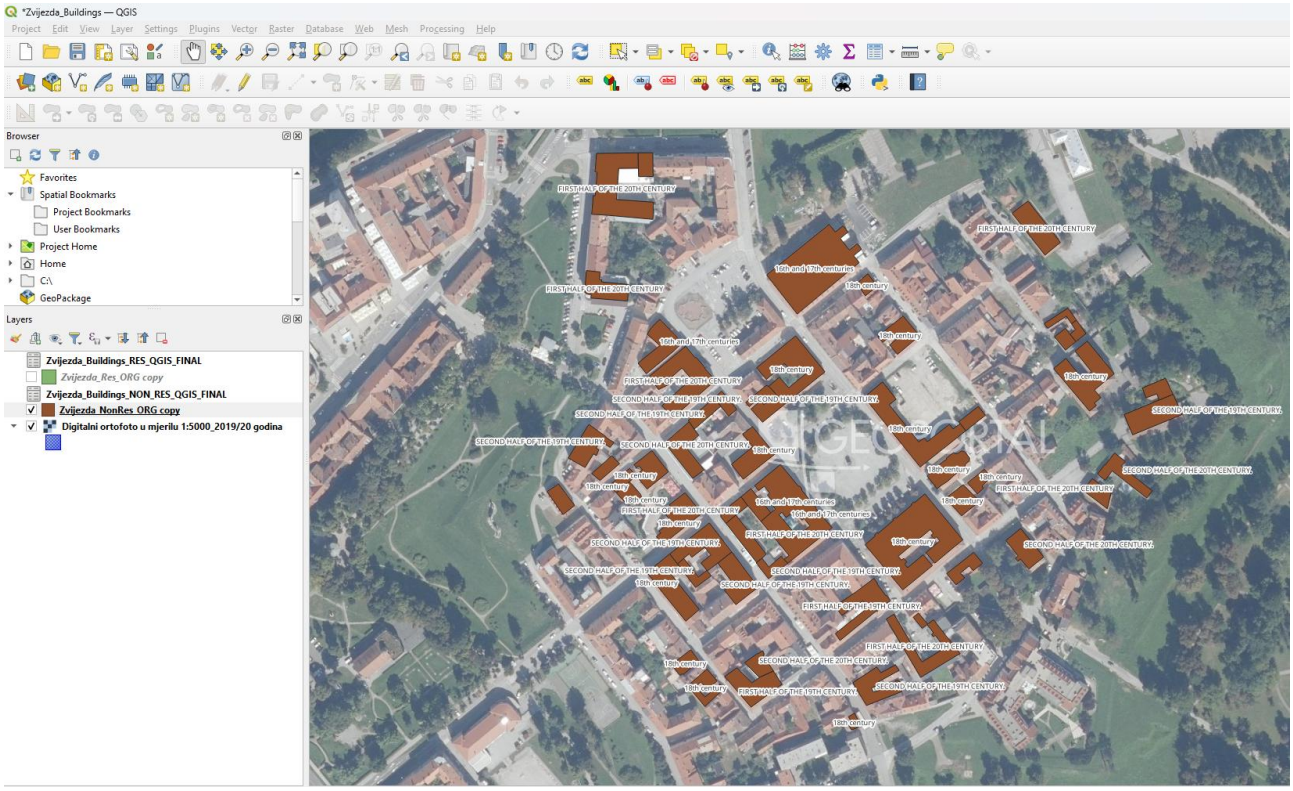


Figure 7: QGIS interface - spatial display from attribute tables (dating of Non Residential Buildings)

1.4.3. Step 3: Aggregation at Block Level – KPI Layer

Data was aggregated and summerized in excel spreadsheets at the level of blocks — groups of buildings defined spatially. For this, the ***Zvijezda_Blocks_Baseline.xlsx*** file was prepared.

BLOCK	Ak [m2]	Electricity Other [kWh/y]	Electricity Cooling and Ventilation [kWh/y]	Electricity Heating [kWh/y]	Natural Gas Heating [kWh/y]	Wood Biomass Heating [kWh/y]	Fuel Oil Heating [kWh/y]	District Heating [kWh/y]	Electricity DWH [kWh/y]	Natural Gas DHW [kWh/y]	Fuel Oil DHW [kWh/y]	District Heating DHW [kWh/y]	Electricity Cooking [kWh/y]	Natural Gas Cooking [kWh/y]	PRODUCTION Electricity [kWh/y]	TOTAL ENERGY [kWh/y]	TOTAL ELECTRICITY [kWh/y]	HEATING AND DHW Power [kW]
BLOCK 1	13.718	387.391	13.074	122.262	1.142.155	1.371.676	176.639	0	145.005	60.775	0	0	35.729	35.729	0	3.490.435	703.461	1.509
BLOCK 2	3.672	107.125	3.761	34.959	225.286	382.374	34.020	0	21.500	32.136	0	0	4.545	13.561	0	859.268	171.891	365
BLOCK 3	5.600	199.565	8.504	22.980	163.255	351.898	140.389	55.202	27.978	31.388	6.977	0	8.370	8.370	0	1.024.875	267.397	400
BLOCK 4	832	15.628	191	0	0	270.415	0	0	15.841	0	0	0	3.349	3.349	0	308.773	35.009	143
BLOCK 5	7.563	278.227	12.150	71.404	986.768	0	0	0	51.819	34.067	0	0	19.995	0	11.613	1.454.430	433.596	572
BLOCK 6	3.668	68.880	843	17.723	181.595	572.408	25.418	139.364	58.852	10.966	0	0	7.276	22.244	0	1.105.570	153.574	503
BLOCK 7	3.215	75.896	5.247	0	63.893	206.429	5.663	550.201	42.823	9.938	0	0	118.520	6.627	0	1.085.238	242.486	439
BLOCK 8	4.387	163.952	8.592	40.437	344.504	284.306	279.292	0	35.074	18.309	0	0	7.053	7.053	0	1.188.572	255.109	501
BLOCK 9	2.913	119.058	5.588	106.828	172.189	338.519	124.461	0	23.129	4.896	0	0	0	4.140	0	898.808	254.603	385
BLOCK 10	4.604	123.363	4.489	259.042	148.081	749.267	47.193	0	61.773	20.209	0	0	11.650	17.877	0	1.442.945	460.317	643
BLOCK 11	3.634	68.245	836	38.595	236.619	659.411	33.385	0	33.562	35.611	0	0	6.049	23.198	0	1.135.510	147.286	519
BLOCK 12	2.121	39.834	488	44.398	68.917	434.498	75.092	0	40.376	0	0	0	8.536	8.536	0	720.673	133.631	332
BLOCK 13	16.546	326.721	5.028	474.509	375.974	2.721.183	415.498	0	280.119	28.007	0	0	54.402	73.963	0	4.755.403	1.140.778	2.148
BLOCK 14	5.641	234.528	11.126	199.066	182.704	339.601	176.220	243.097	52.554	0	0	16.612	3.407	3.407	0	1.462.320	500.680	605
BLOCK 15	3.447	157.200	7.860	238.392	221.119	260.722	221.119	0	26.200	0	0	0	0	0	0	1.132.612	429.652	484
BLOCK 16	3.094	141.085	7.054	34.325	0	0	0	0	23.514	0	0	0	0	0	0	205.977	205.977	29
BLOCK 17	2.961	55.596	681	89.130	51.447	588.176	58.827	0	56.352	0	0	0	11.913	11.913	0	924.037	213.673	422
BLOCK 18	4.743	134.250	4.543	320.992	154.510	614.942	202.422	0	71.033	0	0	0	12.311	12.311	0	1.527.315	543.129	682
BLOCK 19	5.634	148.400	4.552	279.235	122.528	434.529	725.723	0	89.074	0	0	0	16.279	16.279	0	1.836.599	537.540	826
BLOCK 20	5.230	238.468	11.923	299.613	360.294	424.824	360.294	0	39.745	0	0	0	0	0	0	1.735.159	589.748	742
BLOCK 21	2.987	88.761	3.184	83.931	119.749	480.752	107.811	0	42.918	0	0	0	7.116	7.116	0	941.338	225.910	418
BLOCK 22	1.498	28.127	344	67.359	42.245	309.372	8.964	0	28.510	0	0	0	6.027	6.027	0	496.975	130.368	228
BLOCK 23	8.155	231.371	7.855	300.181	197.565	1.220.222	177.526	0	121.865	0	0	0	21.077	21.077	0	2.298.739	682.349	1.009
BLOCK 24	391	7.350	90	22.424	12.944	69.950	8.629	0	7.450	0	0	0	1.575	1.575	0	131.987	38.890	61
BLOCK 25	2.057	63.748	2.393	42.580	32.547	184.784	227.858	0	28.454	0	0	0	4.511	4.511	0	591.386	141.685	258
BLOCK 26	3.669	167.318	8.366	0	531.298	0	0	0	27.886	0	0	0	0	0	0	734.868	203.570	280
BLOCK 27	6.117	114.876	1.407	0	1.685.792	0	0	0	116.439	0	0	0	24.616	24.616	0	1.967.747	257.339	901
BLOCK 28	2.192	56.408	1.669	130.520	74.603	350.527	62.791	0	35.221	0	0	0	6.533	6.533	0	724.805	230.351	327
BLOCK 29	2.706	123.410	6.171	155.053	186.456	219.851	186.456	0	20.568	0	0	0	0	0	0	897.966	305.202	384

Figure 8: Data Spreadsheet by Blocks, Zvijezda

In the next step of spatial data preparation, individual building polygons were grouped into larger spatial units referred to as **blocks**.

This aggregation was carried out directly within the QGIS environment by merging building footprints based on their assigned block identifiers. The grouping reflected both physical contiguity and functional planning

units. Once merged, each block was represented as a single polygon geometry, allowing for the calculation and visualization of aggregated indicators (e.g., total energy demand, CO_2 emissions). **The key identifier for aggregation is the block name** (e.g. BLOCK 1, BLOCK 2...), which matches with the spatial layer of blocks in QGIS.

For each block, key performance indicators (KPIs) were computed, such as:

- Total final energy consumption
- CO_2 emissions (absolute and per m^2)
- Installed heating/DHW power
- Energy demand per square meter

These indicators summarize the energy footprint of entire zones, supporting scenario comparisons and retrofit prioritization.

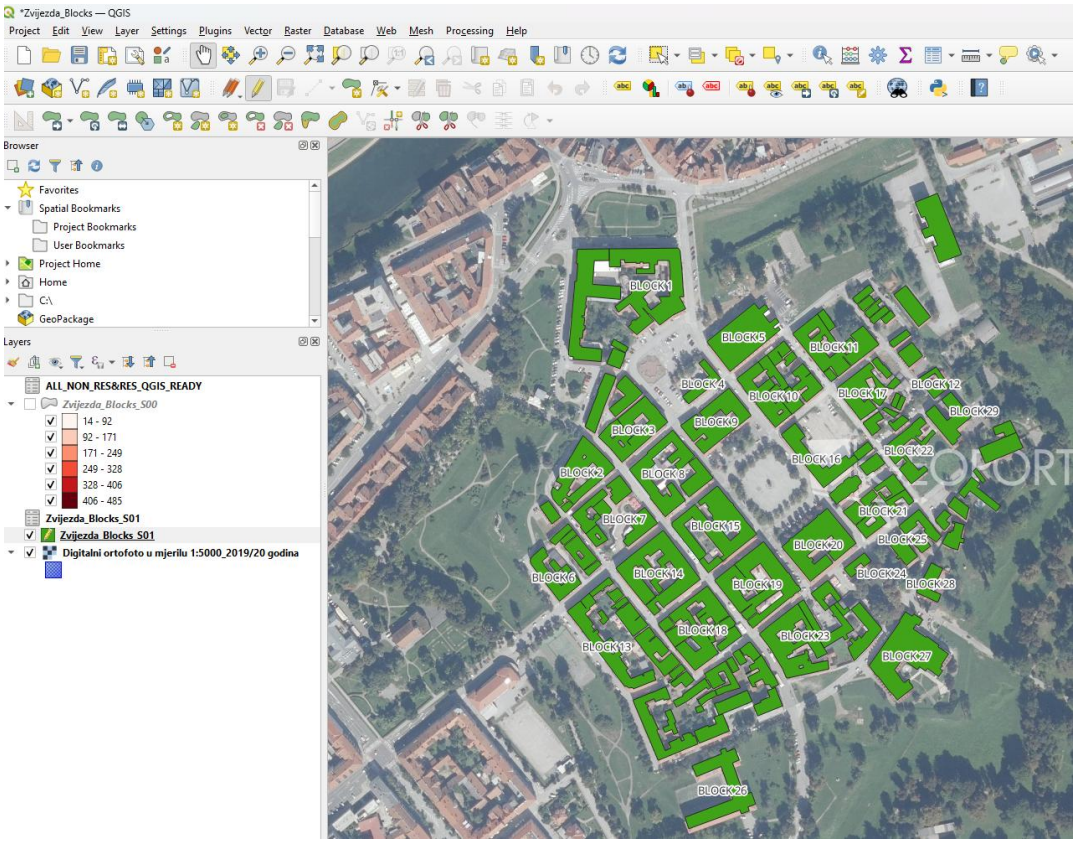


Figure 9: QGIS interface - spatial display of Blocks, Zvijezda

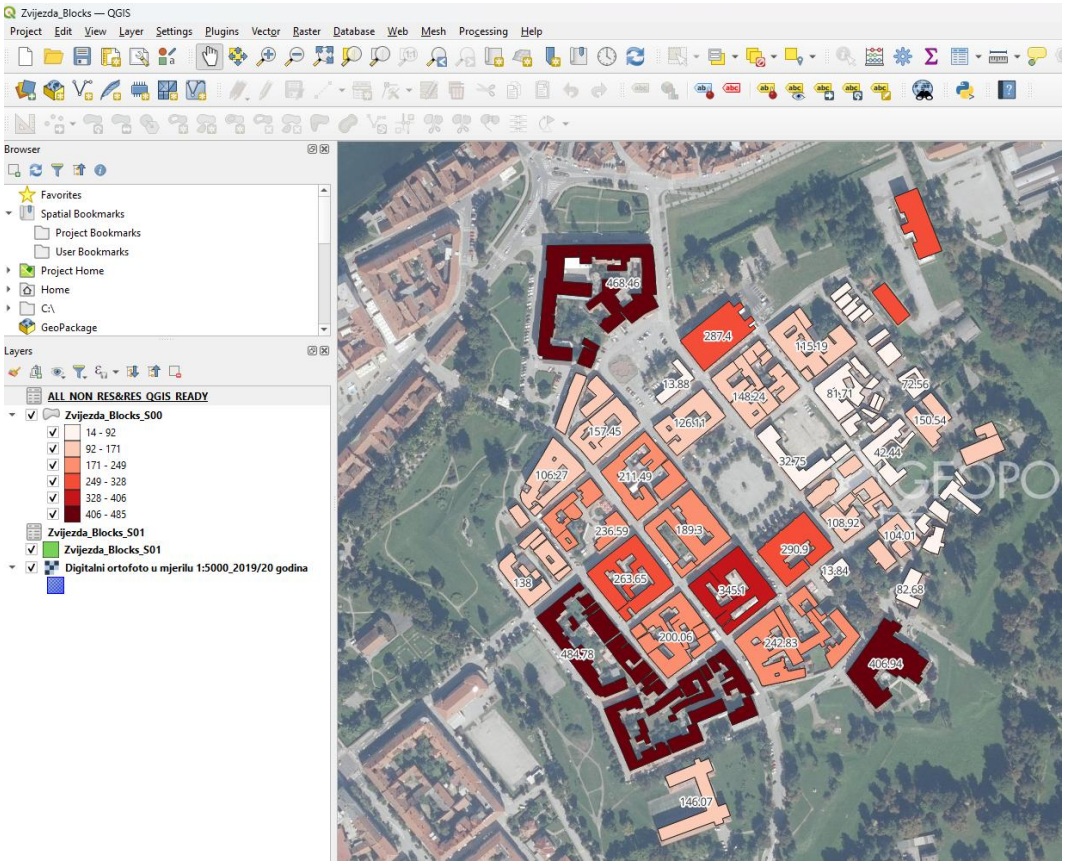


Figure 10: QGIS interface - CO_2 emissions [tCO_2/year] for baseline scenario by Blocks, Zvijezda

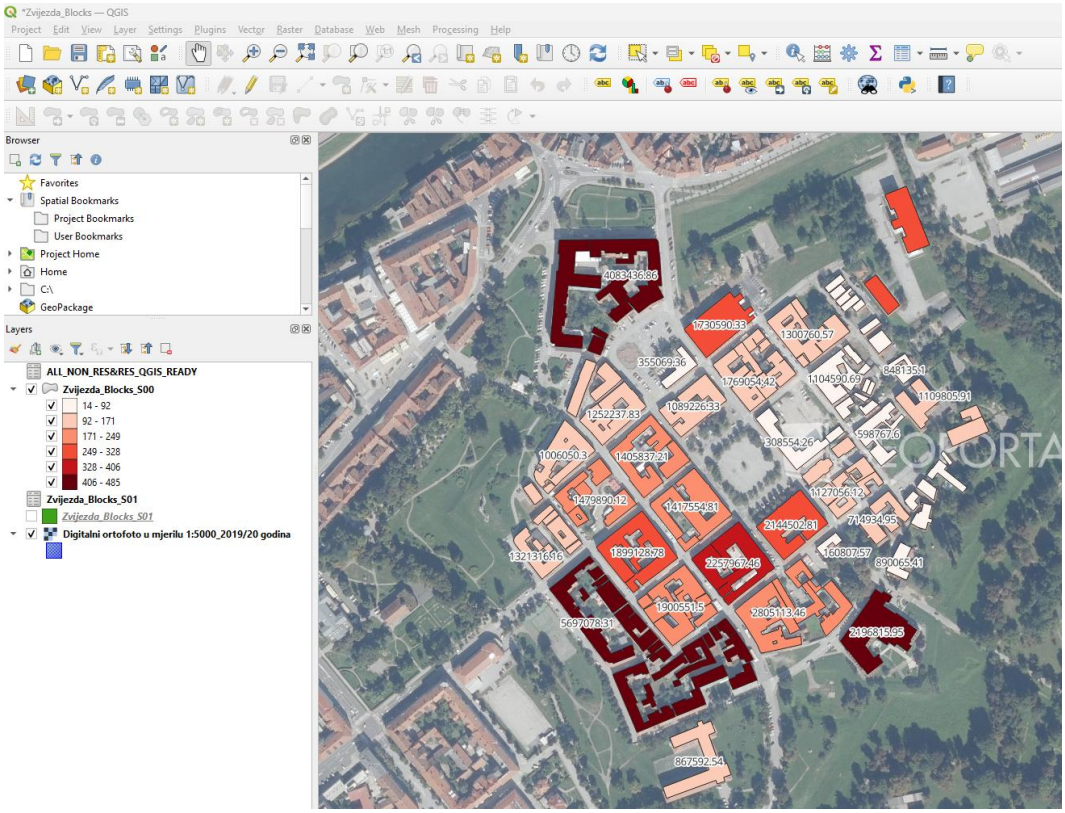


Figure 11: QGIS interface - primary energy needs [kWh/year] for baseline scenario by Blocks, Zvijezda

Based on the actiities within T.1.2, a set of energy efficiency measures (EEMs) was selected and applied to the baseline data. These measures included improvements to the building envelope, heating system upgrades, integration of renewable energy sources (such as photovoltaic panels or geothermal heat pumps) and geothermal district heating. The quantified effects of these EEMs — such as reduced final energy consumption, lower CO_2 emissions, and optimized installed power — were calculated and systematically integrated into new attribute tables. These updated datasets were then visualized in QGIS using the same spatial building and block geometries, allowing direct comparison with the baseline scenario.

This spatialized representation of post-retrofit performance indicators enables stakeholders to assess the impact of proposed measures across the urban heritage fabric and supports evidence-based decision-making for achieving ZEB4ZEN objectives.

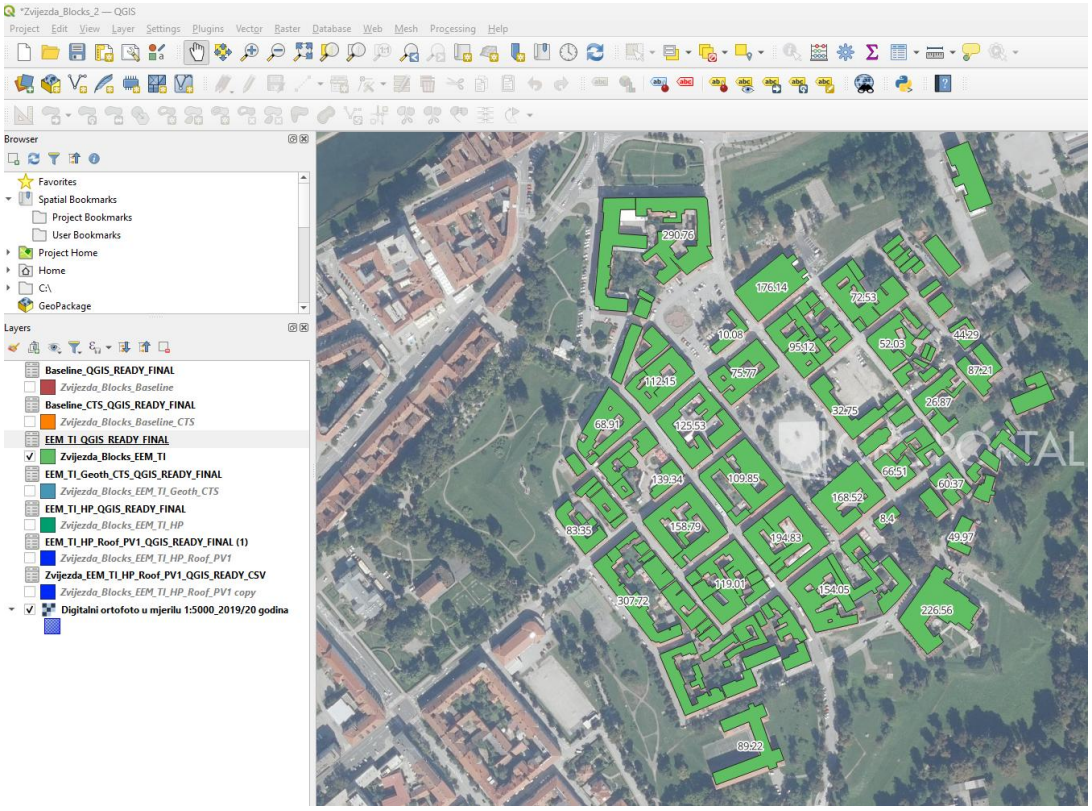


Figure 12: QGIS interface - CO_2 emissions [tCO_2/year], thermal insulation on buildings, by Blocks, Zvijezda

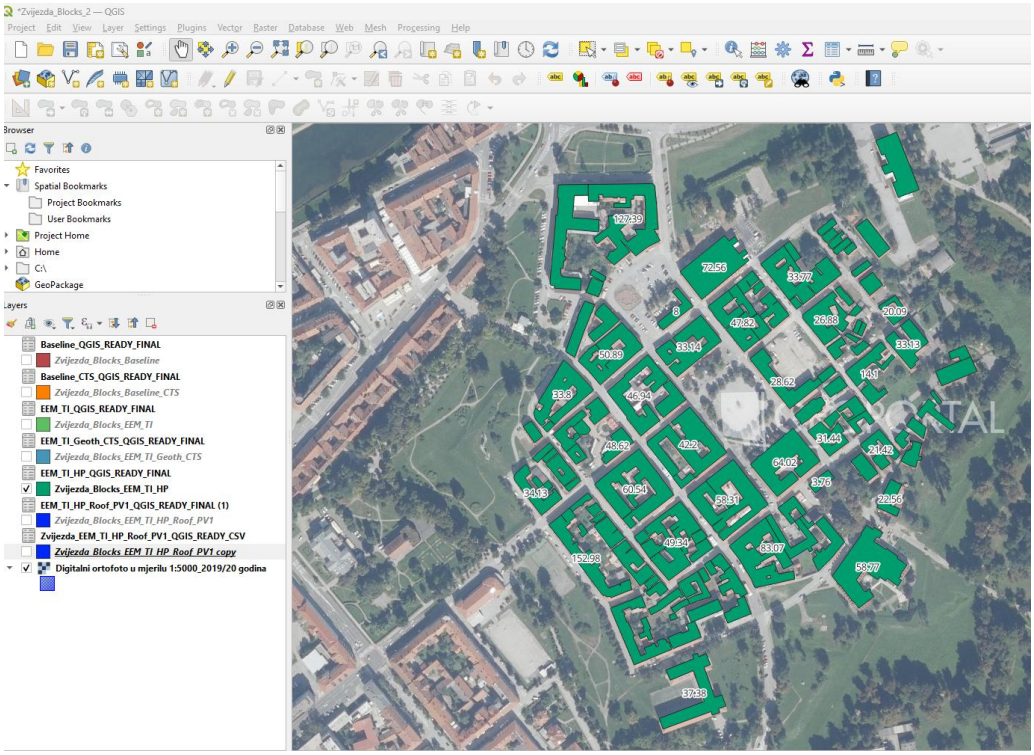


Figure 13: QGIS interface - CO_2 emissions [tCO_2/year], thermal insulation on buildings and heat pumps, by Blocks, Zvijezda

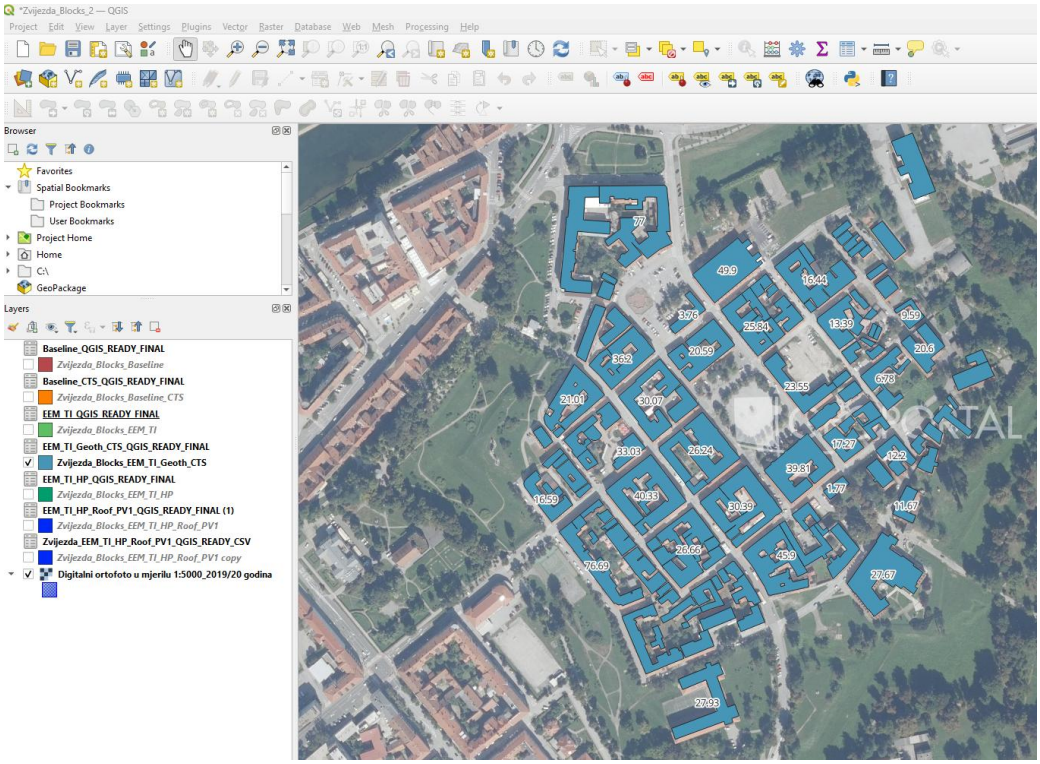


Figure 14: QGIS interface - CO_2 emissions [tCO_2/year], thermal insulation on buildings and Gothermal district heating, by Blocks, Zvijezda

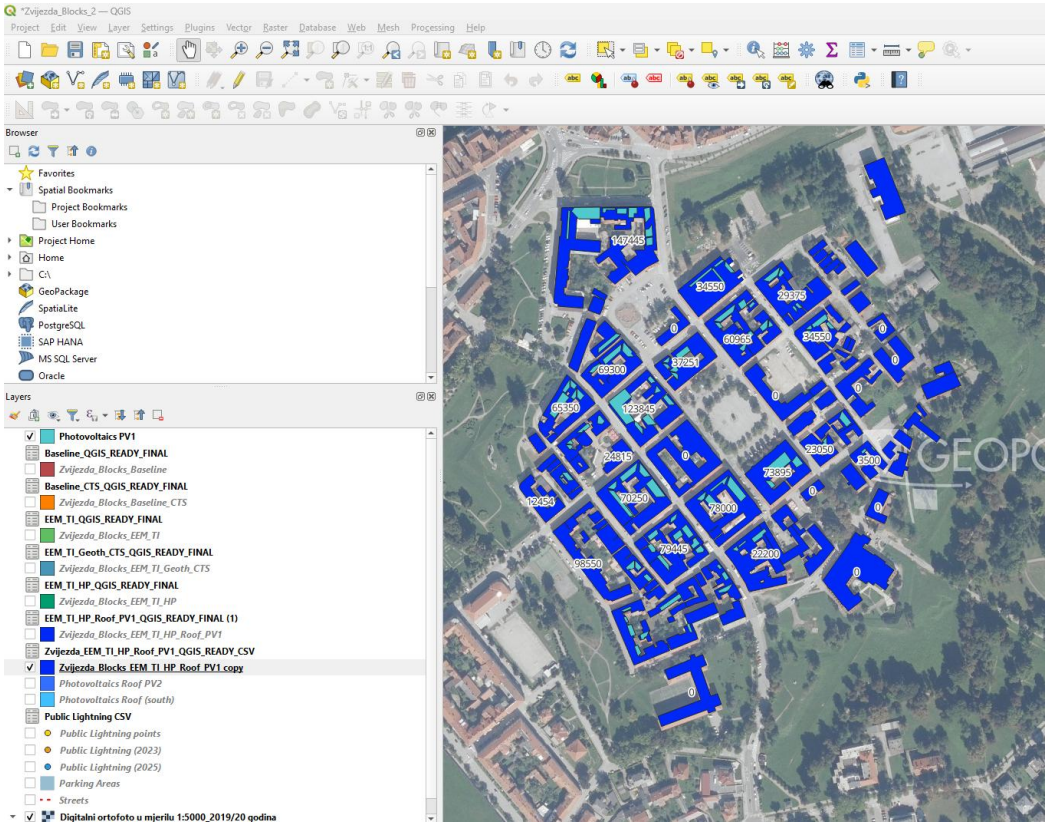


Figure 15: QGIS interface - spatial display of Roof PV and production [kWh/year] by Blocks, Zvijezda

1.5. Digitalization of Public Lightning in Zvijezda

As part of the broader effort to create a comprehensive digital twin of the pilot area, the public lighting infrastructure in Zvijezda, Karlovac, was also thoroughly digitalised. The process began with the preparation and cleaning of an Excel data table (Public Lightning.xlsx) containing detailed information on individual lighting points, creating a list of public lighting in an Excel document (X and Y coordinates must be in separate columns), saving the Excel document in .csv format and importing a new Delimited Text document into GIS with selecting the fields for X and Y coordinates. The data includes:

- *Lighting point ID*
- *Power of the lighting fixture (W)*
- *Type of lighting technology (e.g., LED, Sodium Vapor)*
- *Mounting height*
- *Support type*
- *Energy consumption and estimates (kWh/year)*
- *Reconstruction scenarios data*

ID	GIS label	Street Name	Number of lamps	Lamps Type	Technology - old state	Power - old state [W]	Power - old state (with included losses) [W]	Number of working hours [h]	Electricity consumption - old state [kWh]
667	35	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
670	57	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
671	58	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
673	60	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
674	62	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
675	61	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
680	53	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
681	41	IVANA BANJAVČIĆA	1	LVC 06 NaVT 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
684	42	IVANA BANJAVČIĆA	1	SITECO DL500 MAXI-K 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
685	43	IVANA BANJAVČIĆA	1	LVC 06 NaVT 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
686	44	IVANA BANJAVČIĆA	1	LVC 06 NaVT 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
687	45	IVANA BANJAVČIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
688	46	IVANA BANJAVČIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
690	48	STJEPANA RADIĆA	1	TPK-03 NaVT 400W	HST (High Pressure Sodium)	400	476	4100	1951,6
691	49	STJEPANA RADIĆA	1	TPK-03 NaVT 400W	HST (High Pressure Sodium)	400	476	4100	1951,6
693	50	STJEPANA RADIĆA	1	TPK-03 NaVT 400W	HST (High Pressure Sodium)	400	476	4100	1951,6
694	51	STJEPANA RADIĆA	1	TPK-03 NaVT 400W	HST (High Pressure Sodium)	400	476	4100	1951,6
695	52	STJEPANA RADIĆA	1	TPK-03 NaVT 400W	HST (High Pressure Sodium)	400	476	4100	1951,6
696	54	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
697	59	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
698	63	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
699	64	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
700	65	STJEPANA RADIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
702	66	STJEPANA RADIĆA	1	SITECO CX 200 HST 250 W WITH REG	HST (High Pressure Sodium)	250	297,5	4100	1219,75
703	67	STJEPANA RADIĆA	1	SITECO CX 200 HST 250 W WITH REG	HST (High Pressure Sodium)	250	297,5	4100	1219,75
704	68	STJEPANA RADIĆA	1	SITECO CX 200 HST 250 W WITH REG	HST (High Pressure Sodium)	250	297,5	4100	1219,75
705	69	STJEPANA RADIĆA	1	SITECO CX 200 HST 250 W WITH REG	HST (High Pressure Sodium)	250	297,5	4100	1219,75
706	70	STJEPANA RADIĆA	1	SITECO CX 200 HST 250 W WITH REG	HST (High Pressure Sodium)	250	297,5	4100	1219,75
715	79	FRANA KRSTE FRANKOPANA	1	SITECO DL500 MAXI-K 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
716	80	FRANA KRSTE FRANKOPANA	1	SITECO DL500 MAXI-K 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
717	81	FRANA KRSTE FRANKOPANA	1	SITECO DL500 MAXI-K 150W	HST (High Pressure Sodium)	150	178,5	4100	731,85
718	82	TRG BANA JOSIPA JELAČIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
719	83	TRG BANA JOSIPA JELAČIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
720	84	TRG BANA JOSIPA JELAČIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
721	85	TRG BANA JOSIPA JELAČIĆA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
722	86	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
723	87	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
724	88	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
725	89	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
726	90	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
727	91	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
728	92	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85
729	93	TRG J. J. STROSSMAYERA	1	LANTERN GRIČ MH 150W	Halogen	150	178,5	4100	731,85

Figure 16: Data Spreadsheet of Public Lightning Fixtures

A point shapefile representing the exact spatial location of each lighting point was generated within QGIS. Each point corresponds to a public lighting fixture within the pilot district. Using a common unique ID, the tabular data was then joined to the spatial layer to enrich the lighting point features with all relevant attributes.

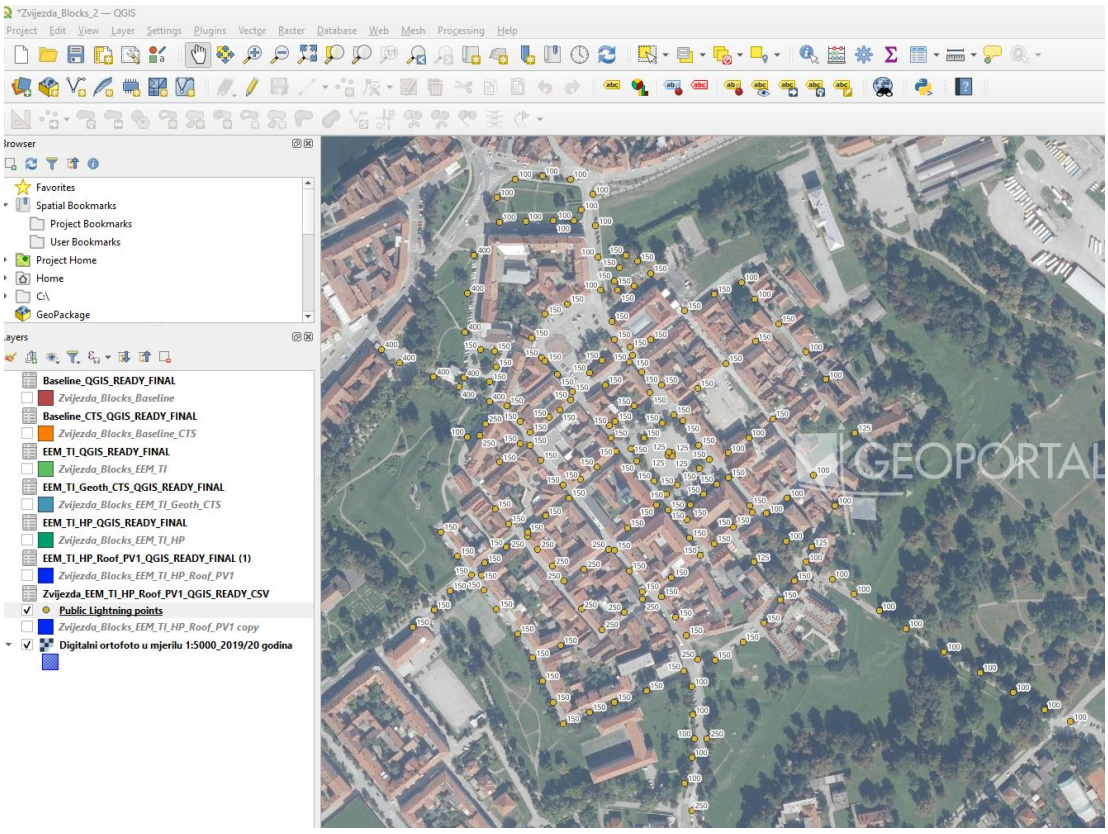


Figure 17: QGIS interface - spatial diplay and instaled power [W] of public lightning fixtures, baseline scenario (2022), Zvijezda

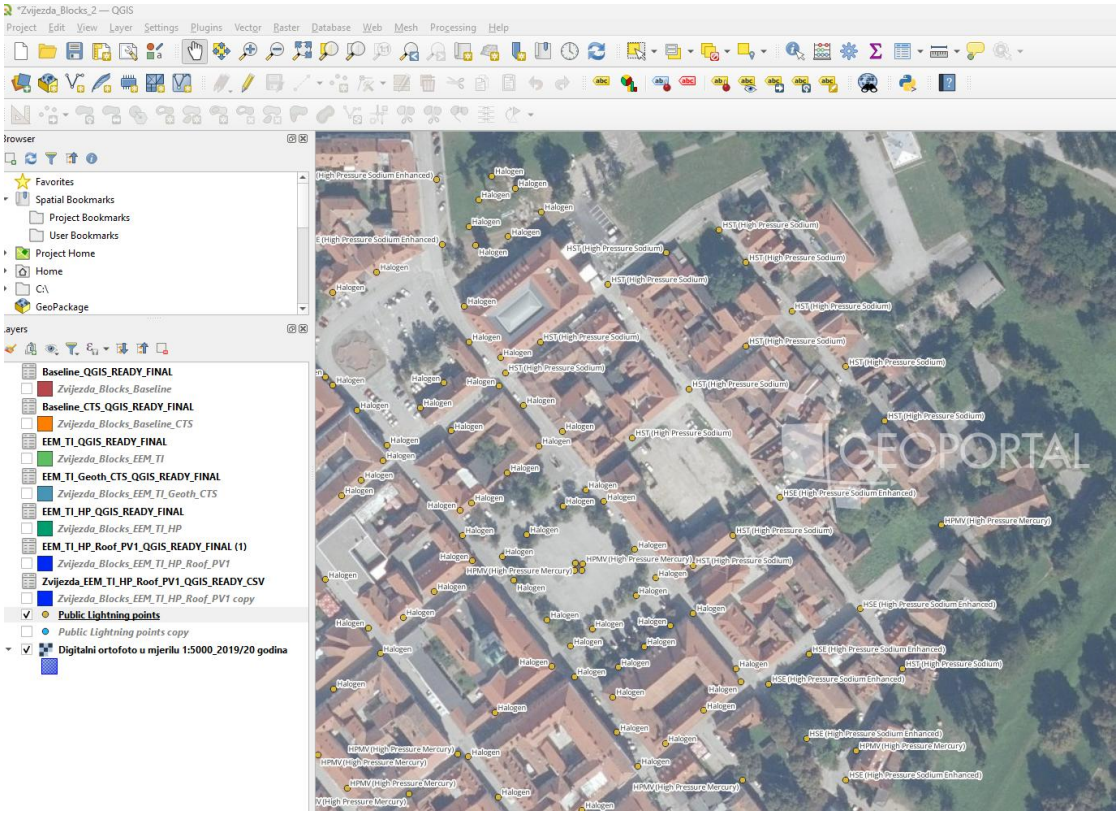


Figure 18: QGIS interface - spatial diplay of public lightning fixtures technologies/types, baseline scenario (2022), Zvijezda

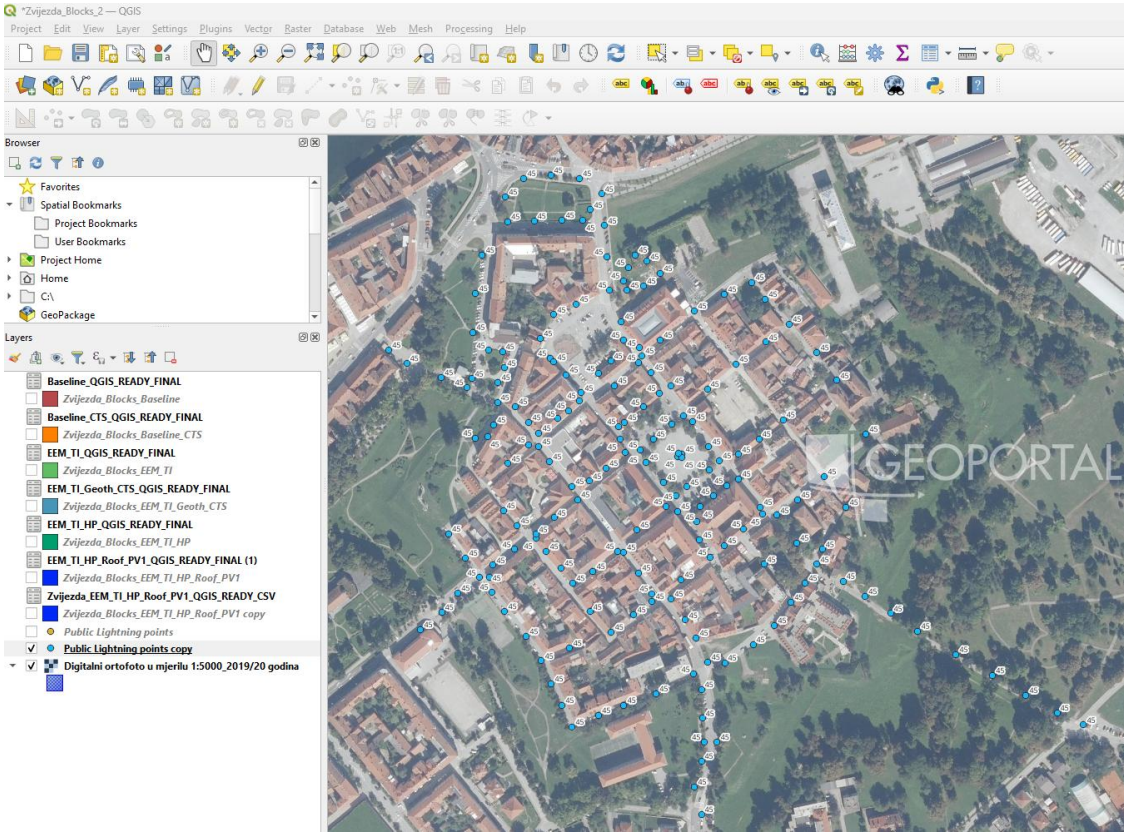


Figure 19: QGIS interface - spatial diplay and planned instaled power [W] of public lightning fixtures, reconstruction scenario (2025), Zvijezda

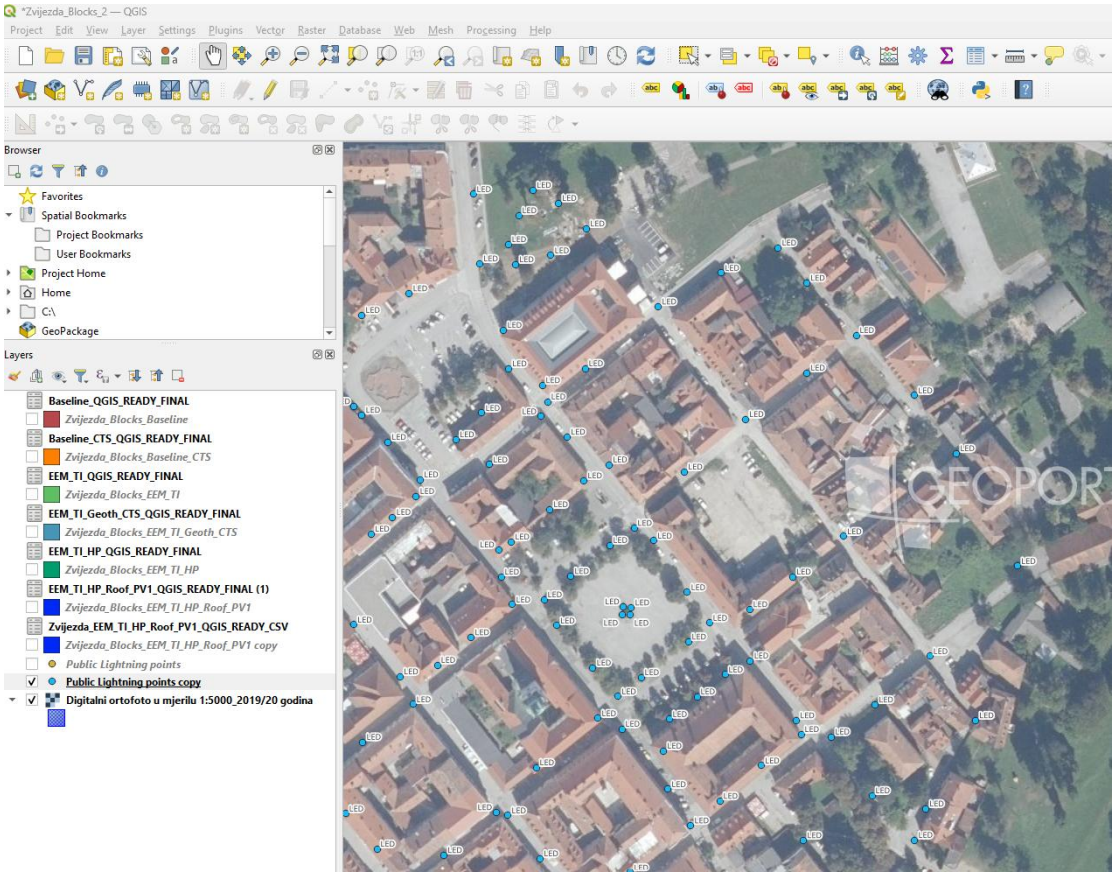


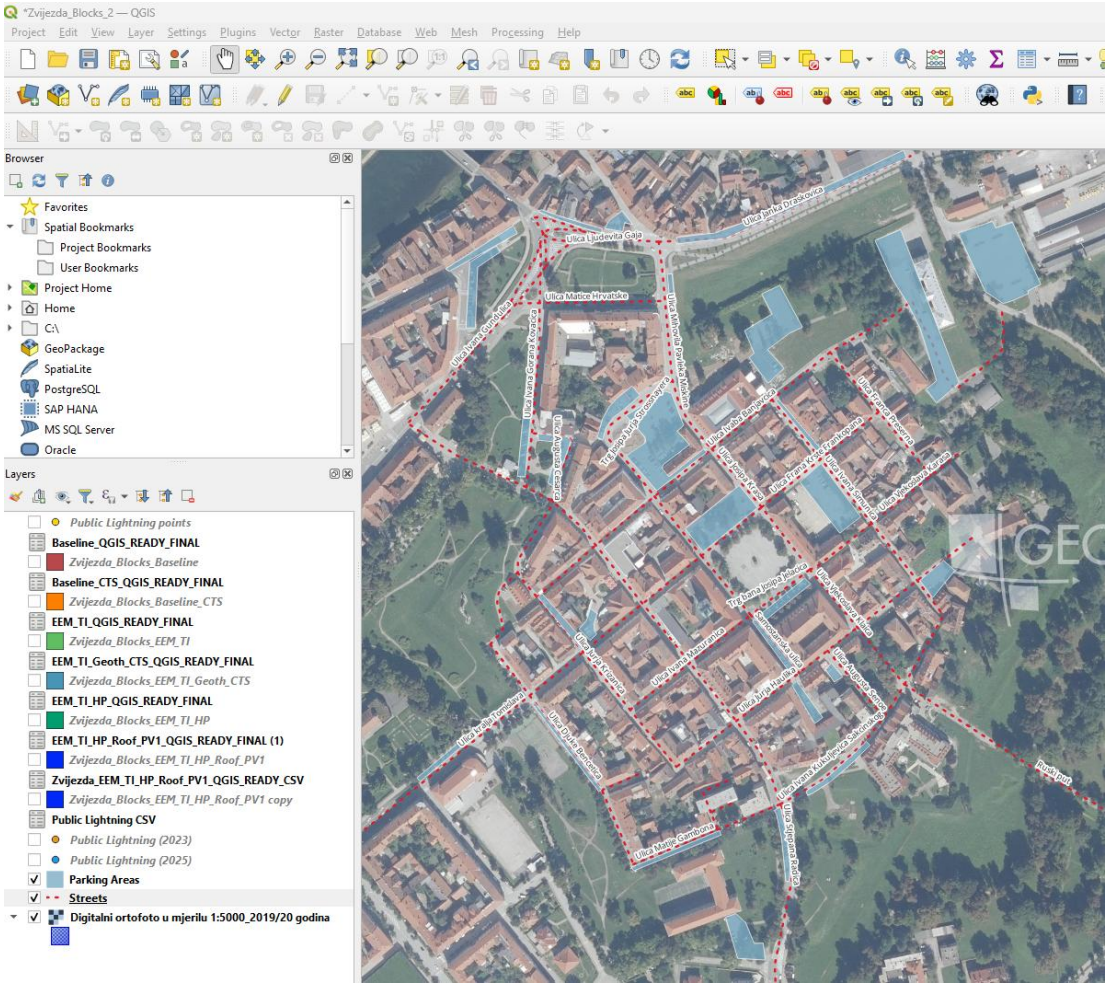
Figure 20: QGIS interface - spatial diplay of public lightning fixtures technologies/types, reconstruction scenario (2025), Zvijezda

This enabled the visualisation and spatial display of public lighting across the heritage area, facilitating the identification of energy-intensive zones, outdated technologies, or areas suitable for smart lighting upgrades. The GIS-enabled lighting layer supports planning for energy-efficient lighting interventions and integration into larger smart city strategies.

1.6. Digitalization of Streets and Public Parking Areas

As part of the comprehensive spatial data preparation for the Karlovac pilot Zvijezda, the local street network and public parking areas within the historic zone were also digitized. Using satellite ortho-photos and available city planning documents as references, vector layers were created in QGIS to represent both street axes and parking polygons.

The street layer includes names of all major and minor roads in the area and allows for spatial analysis such as accessibility, connectivity, and potential for public space redesign. Each street segment was labeled and stored as a polyline feature in the attribute table, with names assigned for legibility in the map layout. The public parking layer was structured as a polygon dataset, with each polygon representing an individual or grouped parking surface.


*Zvijezda_Blocks_2 — QGIS
Project Edit View Layer Settings Plugins Vector Raster Database Web Mesh Processing Help
Browser
Favorites
Spatial Bookmarks
Project Bookmarks
User Bookmarks
Project Home
Home
C:\
GeoPackage
SpatiaLite
PostgreSQL
SAP HANA
MS SQL Server
Oracle
Layers
Public Lightning points
Baseline_QGIS_READY_FINAL
Zvijezda_Blocks_Baseline
Baseline_CTS_QGIS_READY_FINAL
Zvijezda_Blocks_Baseline_CTS
EEM_TI_QGIS_READY_FINAL
Zvijezda_Blocks_EEM_TI
EEM_TI_Geoth_CTS_QGIS_READY_FINAL
Zvijezda_Blocks_EEM_TI_Geoth_CTS
EEM_TI_HP_QGIS_READY_FINAL
Zvijezda_Blocks_EEM_TI_HP
EEM_TI_HP_Roof_PV1_QGIS_READY_FINAL (1)
Zvijezda_Blocks_EEM_TI_HP_Roof_PV1
Zvijezda_EEM_TI_HP_Roof_PV1_QGIS_READY_CSV
Zvijezda_Blocks_EEM_TI_HP_Roof_PV1 copy
Public Lightning CSV
Public Lightning (2023)
Public Lightning (2025)
Parking Areas
Streets
Digitalni ortofoto u mjerilu 1:5000_2019/20 godina
Ulica Matice Hrvatske
Ulica Ljudevita Gaja
Ulica Ivana Gorana Kovačića
Ulica Ivana Meštrovića
Ulica Petra Zrinskog
Ulica Ivana Mažuranića
Ulica Ante Starčevića
Ulica Dr. Ante Bertoše
Ulica Matije Gupca
Ulica Vladimira Nazora
Ulica Ivana Kukuljevića Sakcinskog
Ulica Ivana Gundulića
Ulica Petra Preradovića
Ulica Vladimira Nazora
Ulica Dr. Franje Tuđmana
Ulica Matije Gupca
Ulica Ivana Meštrovića
Ulica Ante Starčevića
Ulica Dr. Ante Bertoše
Ulica Matije Gupca
Ulica Ivana Kukuljevića Sakcinskog
Ulica Petra Preradovića
Ulica Vladimira Nazora
Ulica Dr. Franje Tuđmana
Ulica Matije Gupca
Ulica Ivana Kukuljevića Sakcinskog
Ulica Ivana Gundulića

1.7. Outcome

This process resulted in:

- Structured and georeferenced digital twin baseline for buildings and blocks in the historical zone of Karlovac, Zvijezda
- Structured and georeferenced digital twin baseline for public lightning in the historical zone of Karlovac, Zvijezda
- Mapping of streets and public parking lots
- Readiness for further modeling steps in the project (e.g. simulation of EEMs, geothermal/RES integration)
- A flexible platform (QGIS + structured tables) for sharing insights with stakeholders, planners, and heritage experts

The Zvijezda pilot has demonstrated the effectiveness of integrating spatial, heritage, and energy datasets into a unified GIS environment. The structured approach allowed for scalable KPI aggregation and impact visualization, enabling Karlovac to simulate the effects of tailored EEMs across a heritage-sensitive urban context. This digital foundation will support both operational planning and cross-comparison with other pilot sites in the ZEB4ZEN project.

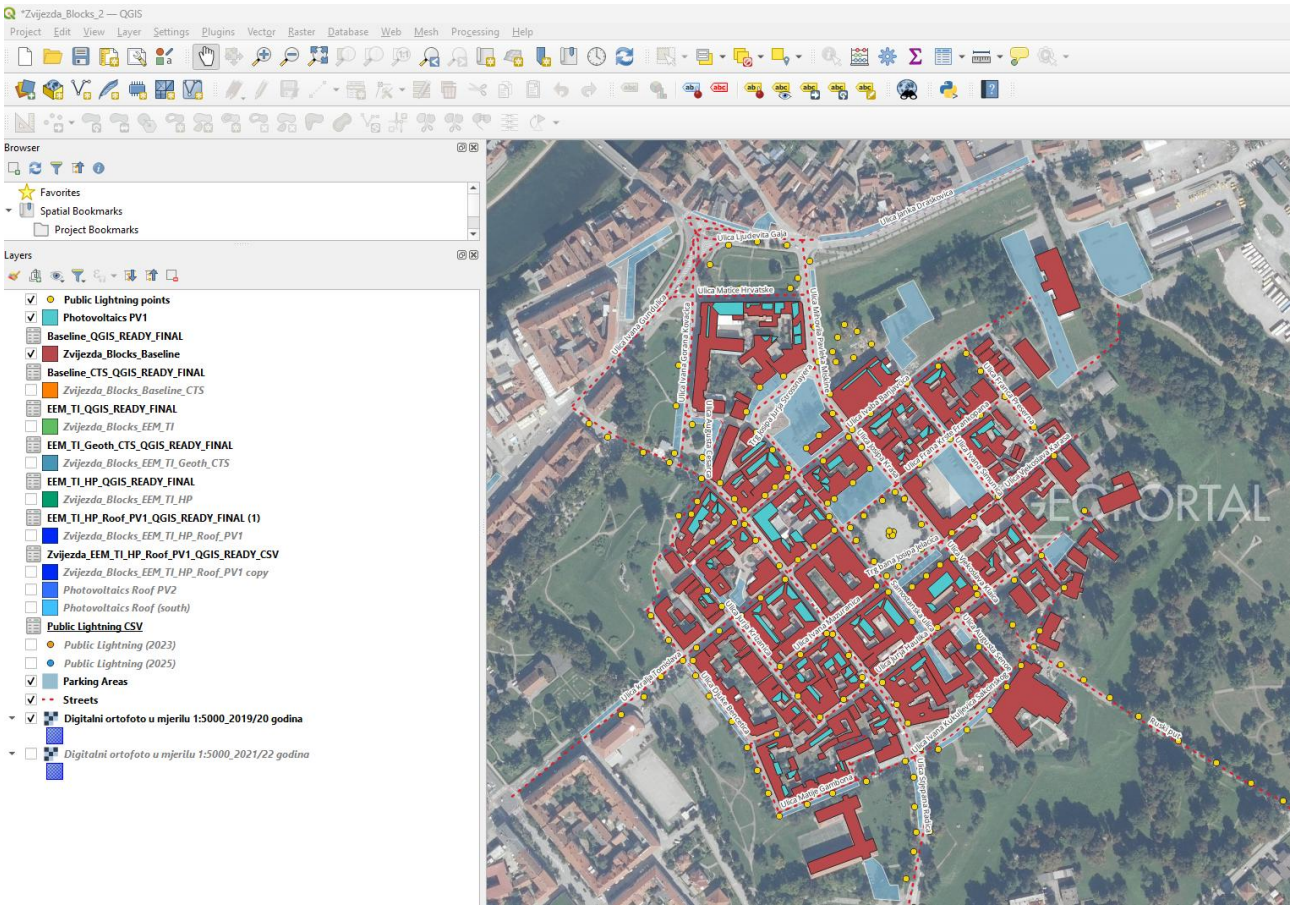


Figure 22: QGIS interface - comprehensive spatial digitalization of the Zvijezda pilot zone



Figure 23: Digital 3D scan of Karlovac pilot

2. ANNEX II: PALMANOVA PILOT DIGITALIZATION

2.1. SCOPE OF DIGITALIZATION

The following actions were carried out for each pilot:

1. Data Collection and Structuring

Tabular data was compiled in Excel spreadsheets containing:

- Administrative information (building ID, location, use)
- Cultural heritage attributes (construction date, typology, valorization)
- Energy data (heating needs, final/primary energy, CO_2 emissions)
- Public Lightning data

2. Spatial Referencing

Data was linked to spatial layers using:

- Parcel number as a key for building-level joins
- Block name for aggregations at district level
- Geo-location coordinates

3. QGIS Integration

Building and block polygon layers where prepared in QGIS, allowing for rich geovisualization and comparative analysis.

2.2. METHODOLOGY FOR DIGITAL TWIN DEVELOPMENT AND SPATIAL DATA INTEGRATION

2.3. Digitalization of Buildings in Palmanova

2.3.1. Step 1: Tabular Data Structuring and Conversion to QGIS-Ready Format

Two main Excel files were prepared to contain the building-level data:

- ***Palmanova_Buildings_RES.xlsx*** – *residential buildings*
- ***Palmanova_Buildings_NON_RES.xlsx*** – *non-residential buildings*

Each file includes:

- Name of Building and Address,
- Building type and usage (residential, non-residential, public, etc.)
- Heritage status and construction period
- Useful area (A_k)
- Condition classification (e.g., good, moderate, bad)
- Heating mode and energy mix for heating

	A	B	C	D	E	F	G	H	I	J	K	L
1	No.	Name of the Building	Legislative Building Typology	Adress	Dating	Total Gross Area (m^2)	Ak (m^2)	Qh,nd (kWh/m^2)	E (other Energy Needs) (kWh/m^2)	Heating Mode	Energy Mix	Energy class
2	1	Town Hall	Office and administrative building	Piazza Grande, 1	1598	1984,86	1574,33	141,04	84,69	Cental Heating	Gas	D
3	2	Former Mattei School	Other non-residential building	Piazza Grande	1599	2067,65	1640,00	141,04	84,69	Cental Heating	Gas	D
4	3	Loggia della gran Guardia	Other non-residential building	Via Savorgnan	1593	251,84	222,18	372,08	24,63	Cental Heating	Gas	G
5	4	Primary School	Schools	Via Dante Alighieri, 3	1922	2871,80	2396,81	206,15	41,24	Cental Heating	Gas	E
6												
7												
8												

Figure 24: List of non-residential buildings with attributes in Palmanova

	No.	Name of the Building	Legislative Building Typology	Adress	Dating	Total Gross Area (m^2)	Ak (m^2)	Qh,nd (kWh/m^2)	E (other Energy Needs) (kWh/m^2)	Heating Mode	Energy Mix	Energy class
12	1	Residential 1	Residential building	Borgo Aquileia, 3	First half of the 20th century	709,14	550,02	203,04	85,30	Cental Heating	Gas	E/F
13	2	Residential 2	Residential building	Via Dante Alighieri, 1	First half of the 20th century	2304,71	1787,57	203,04	85,30	Cental Heating	Gas	E/F
14												
15												
16												

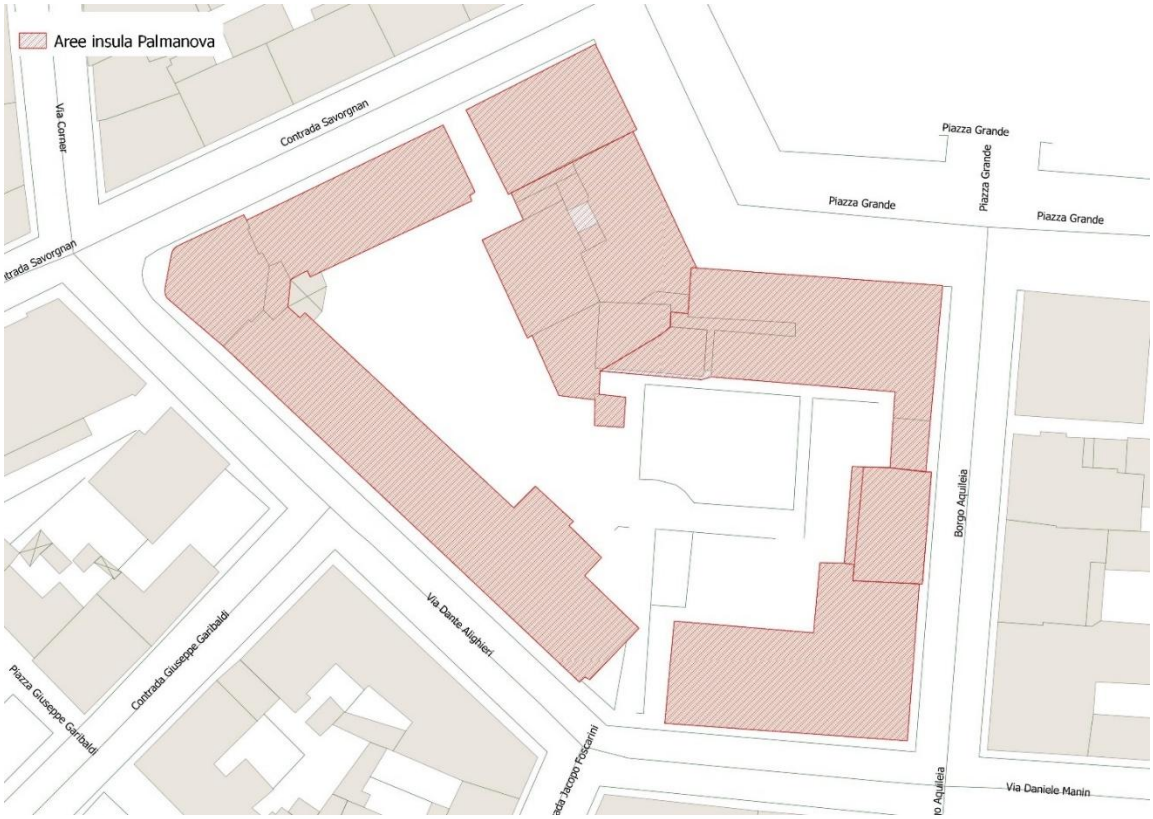
Figure 25: List of residential buildings with attributes in Palmanova

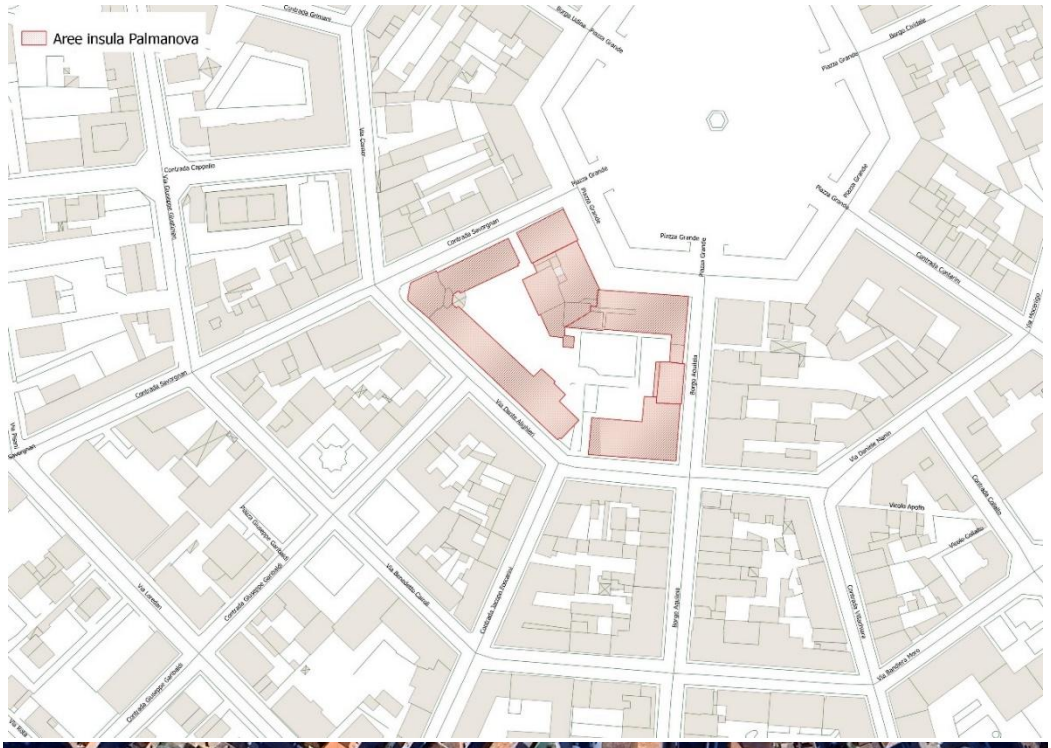
2.3.2. Step 2: Linking to Spatial Data in QGIS

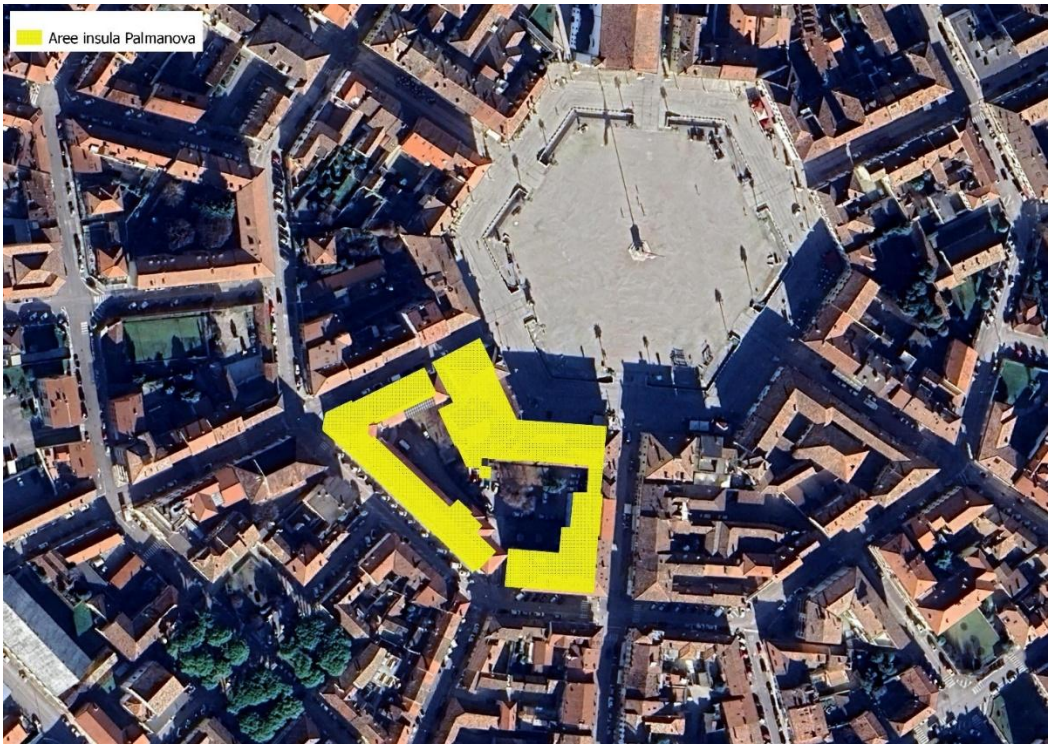
Starting from the regional technical map (https://irdat.regione.fvg.it/), additional layers were overlaid and the outlines of the buildings were traced using the geographical coordinates of the vertices.

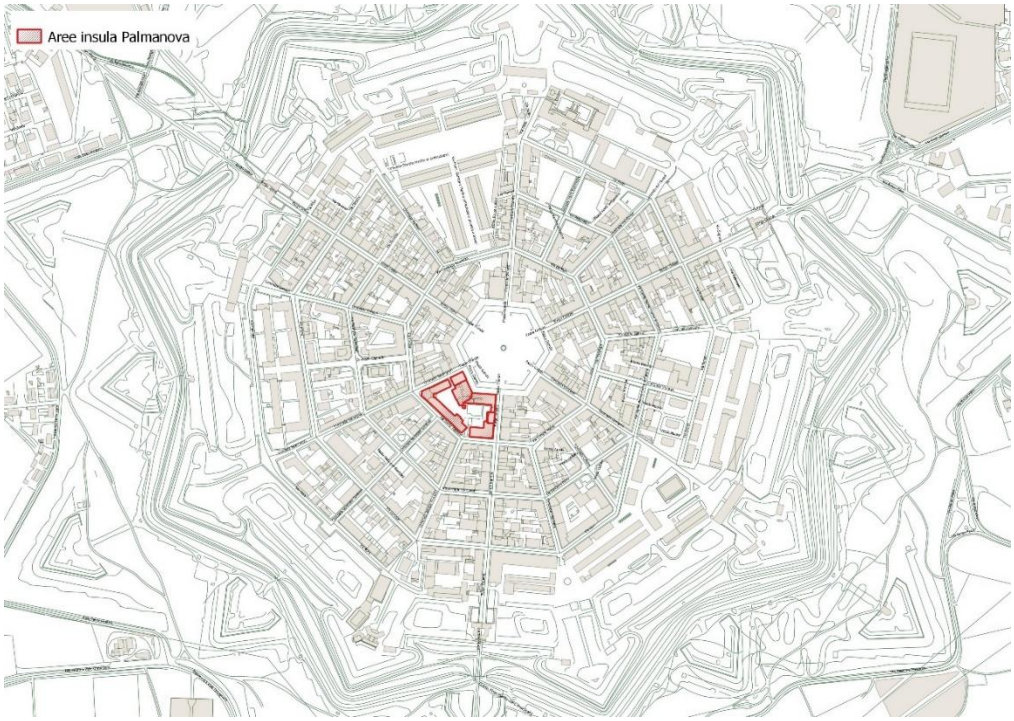
The building polygons for Palmanova were elaborated by APE FVG. These spatial datasets were subsequently adapted to ensure compatibility with the prepared attribute tables. The cadastral parcel number served as the primary linking field, allowing for accurate and consistent integration of building-level administrative, heritage, and energy-related information within the QGIS environment.

The following pictures represent the insula Q-GIS mapping with different zoom levels and different layers (city map and satellite).




Aree insula Palmanova


Aree insula Palmanova


Aree insula Palmanova


Aree insula Palmanova

Extract of the excel file with geographical coordinates of the buildings:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	ID	CODICE_SOT	NOME_SOT	NOME_CLAS	COD_SOT_GR	ELEMENTO	AREA	USO	Zona om.	Bldg block	Cadastral	nr floor	Anno costr	Nome	Anno ristr	vertex_ind	vertex_par	vertex_p_1	vertex_p_2	distance	angle	Lat	Lon
2	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	0	0	0	0	0	195,3916239	45,90488	13,30917	
3	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	1	0	0	1	8,85231E-06	249,4102233	45,90487	13,30916	
4	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	2	0	0	2	0,000265863	249,1868778	45,90478	13,30892	
5	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	3	0	0	3	0,000279644	295,7526645	45,90478	13,30892	
6	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	4	0	0	4	0,000397001	322,8337301	45,90488	13,30884	
7	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	5	0	0	5	0,000418114	16,15699845	45,9049	13,30883	
8	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	6	0	0	6	0,000691808	166,5858945	45,90489	13,30909	
9	1	4A1AMED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	330,85	Pubblico	A1	Block 1	770"1	"600	Loggia	1924	7	0	0	7	0,000838236	195,3916239	45,90488	13,30917	
10	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		0	0	0	0	0	0	180,1935802	45,90478	13,30885
11	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		1	0	0	1	1,14839E-05	197,2462977	45,90478	13,30884	
12	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		2	0	0	2	1,97497E-05	201,6396305	45,90477	13,30884	
13	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		3	0	0	3	0,000335547	250,8745256	45,90467	13,30855	
14	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		4	0	0	4	0,000359046	288,9532731	45,90466	13,30852	
15	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		5	0	0	5	0,000363244	289,833381	45,90467	13,30852	
16	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		6	0	0	6	0,000379681	249,7725843	45,90466	13,30851	
17	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		7	0	0	7	0,000405137	216,7614389	45,90465	13,30848	
18	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		8	0	0	8	0,000443248	153,741704	45,90462	13,30848	
19	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		9	0	0	9	0,000472265	87,0557434	45,9046	13,30851	
20	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		10	0	0	10	0,000494227	87,60739358	45,90461	13,30851	
21	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		11	0	0	11	0,000526301	121,9991094	45,9046	13,30853	
22	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		12	0	0	12	0,000987309	87,9586188	45,90434	13,30894	
23	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		13	0	0	13	0,001039741	87,80547465	45,90437	13,30898	
24	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		14	0	0	14	0,001012192	179,2106321	45,90433	13,30906	
25	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		15	0	0	15	0,001141803	178,3751595	45,90432	13,30905	
26	6	4A1A0ED	EDIFICIO CIVILI	EDIFICATO	4A000ED	"087082	1666,66	Pubblico	A1	Block 1	310"2	"822	Scuola		16	0	0	16	0,001221351	177,6107157	45,90428	13,30912	

2.4. Digitalization of Public Lightning in Palmanova

As part of the broader effort to create a comprehensive digital twin of the pilot area, the public lighting infrastructure in Palmanova was also thoroughly digitalised.

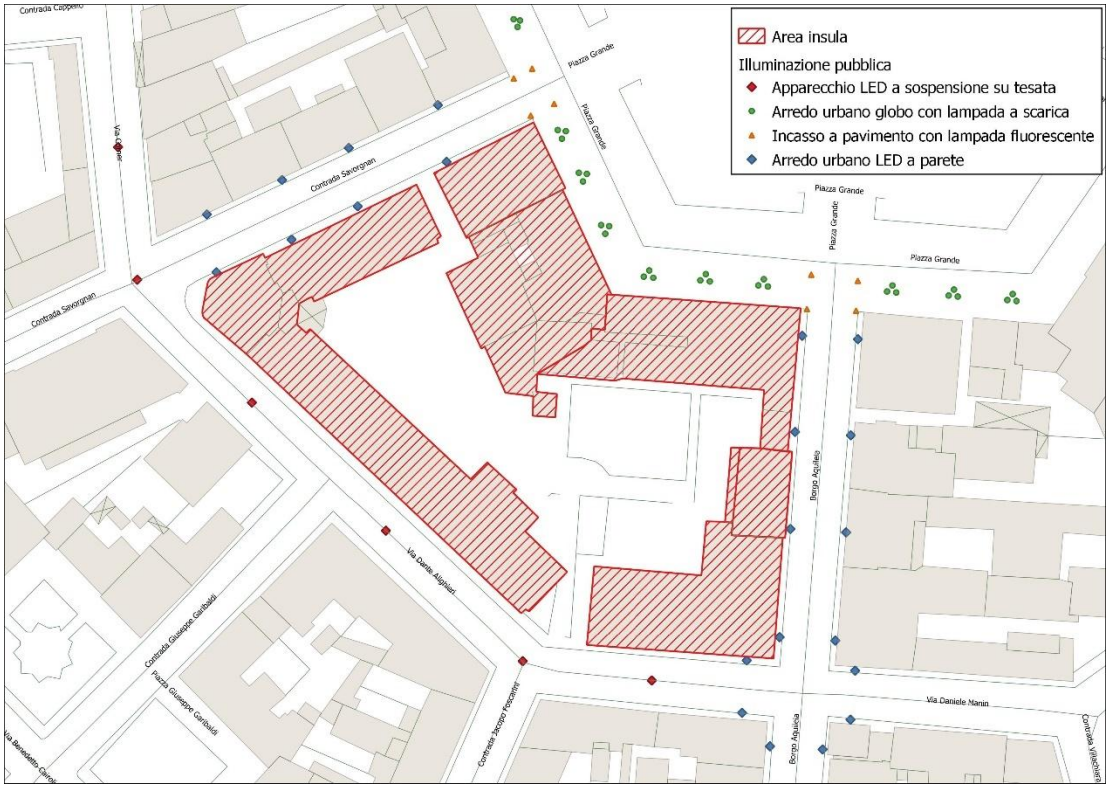


Figure Map of the insula with on individual lighting points
red squared - catenary street lighting
green dots - street poles
yellow triangles - floor lights
blue squares - wall lanterns on brackets

2.5. Outcome

This process resulted in:

- Structured and georeferenced digital twin baseline for buildings in the selected insula in the historical zone of Palmanova
- Structured and georeferenced digital twin baseline for public lightning in the selected insula in the historical zone of Palmanova
- Readiness for further modeling steps in the project (e.g. simulation of EEMs, geothermal/RES integration)
- A flexible platform (QGIS + structured tables) for sharing insights with stakeholders, planners, and heritage experts



Figure 26: Digital 3D scan of Palmanova pilot

3. ANNEX III: ZAMOSC PILOT DIGITALIZATION

3.1. Scope of digitalization

The annex presents the urban scale of the digital twin of Zamość's Old Town (UNESCO), integrating terrestrial laser scanning (TLS/LiDAR), UAV and terrestrial photogrammetry, and BIM/IFC. The goal is to combine precise 3D geometry with semantic data to support documentation, planning, conservation activities, and energy analyses of the historic urban fabric.

Zamość was selected for its exceptional historical and architectural value, coherent urban layout, data availability, and active conservation and planning initiatives. Its diverse resources—from monumental buildings, through compact tenement frontages, to post-industrial development—enable extensive analyses of function, technical condition, and energy potential.

The model encompasses the Old Town within the boundaries of the original defensive walls, with particular emphasis on the Great Market Square and adjacent quarters. The analysis covered approximately 100 historic buildings with diverse functions (residential, commercial, public) and selected elements of public spaces (market square surface, street network, greenery, fragments of former fortifications). The total area of the historic complex is approximately 110,000 m^2; the highest data density was obtained in the quarter surrounding the Great Market Square.



Figure 27 Presentation of the Old Town Layout Covered by the Detailed Study

The result is a basic, integrated 3D semantic model of the Old Town, enabling structured queries and thematic analyses in BIM/IFC environments (geometry with standardized attributes), ready for practical applications in conservation, planning, and energy.

3.2. Data acquisition and processing

An integrated acquisition methodology combining photogrammetry with terrestrial laser scanning (TLS) was used. The complementary properties of both techniques allowed for the acquisition of detailed and faithful geometry of heritage sites while preserving architectural details.

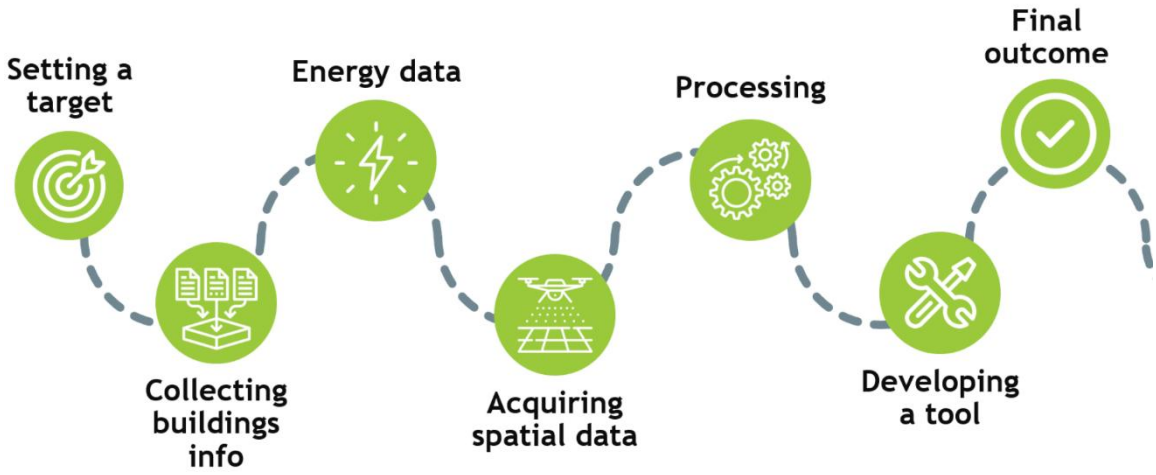


Figure 28 Workflow of the study

Photogrammetry was conducted from ground level and from the air (UAV). A total of over 4,500 20-megapixel images with approximate geolocation were acquired, covering roofs, front and rear facades, arcades, and spaces between buildings.



Figure 29 Presentation of the Photogrammetric Data Processing

Over 50 TLS scans were performed simultaneously from static locations, obtaining a dense point cloud of building surfaces and public spaces. A scanner with an accuracy of a few millimeters and a range of

up to 70 meters was used, with particular emphasis on difficult areas (e.g., arcades, stonework details, and facade defects).

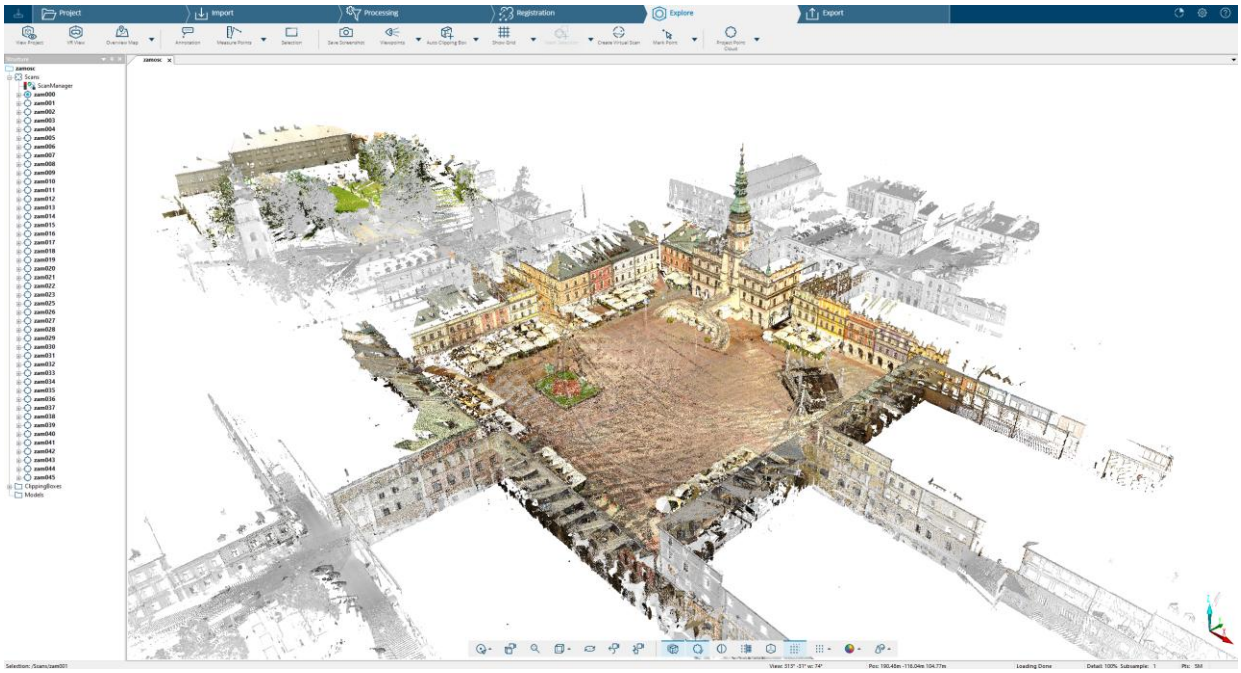


Figure 30 Model obtained from laser scanning

Data processing was performed using specialized software: FARO Scene for scan registration and stitching, and RealityCapture for generating photogrammetric models and textures. Total computational time exceeded 150 hours for photogrammetry and approximately 40 hours for TLS, reflecting the complexity and volume of the material.

Table 1: Key acquisition and processing parameters

Parameter	Photogrammetry (UAV + terrestrial)	Terrestrial Laser Scanning (TLS)	Remarks / Quality Assessment
Number of images / scans	approx. 4,500 photographs	approx. 50 scanning stations	Full coverage of the Old Town area
Measured surface [m²]	110,000	24,000	Aerial photography covered the entire study area, whereas scanning was limited to main communication routes
Number of points in cloud [million]	420	750	-
Average point density [points/m²]	approx. 3,800	approx. 31,250	Combined dataset
Registration accuracy (RMSE) [cm/mm]	approx. 10 cm	avg. 10 mm	Verified against control points
Coverage scope	Roofs, facades, streets, courtyards	Arcades, portals, hard-to-reach zones	Complementary data
Software	Reality Capture	FARO Scene	Integration in Revit / IFC
Total computation time [h]	approx. 150	approx. 40	Multi-core workstation

Table 1 summarizes key acquisition and processing parameters: 110,000 m² for photogrammetry and 24,000 m² for TLS, cloud density (~420 million photo points and ~750 million TLS points), average density (~3,800 points/m² for photogrammetry and ~31,250 points/m² for TLS), and registration accuracy (~10 cm for photogrammetry and ~10 mm for TLS). The coverage range (roofs/facades/pedestrian walkways vs. problem areas) and the software used were also indicated.

In the next step, the photogrammetry and TLS data were integrated into a coherent modeling environment. A 3D base model was generated from the point cloud; the total number of points after integration was approximately 680 million, corresponding to an average of ~6,200 points/m² for the nearly 110,000 m² historical complex. The highest data density was obtained in the development quarter around the Great Market Square; in the peripheral parts of the area the densities are lower (fewer TLS stations and limitations in photo shots).



Figure 31 Integration of TLS point cloud and UAV photogrammetric model for Zamość Old Town.

3.3. 3D model segmentation and identification

The model was divided into logical segments corresponding to development quarters and individual buildings, in accordance with existing administrative and functional divisions. Each building was assigned a unique identifier and linked to a spatial unit (street, serial number, cadastral plot number), enabling the model to be linked to municipal data resources (building registers, historical monument registers, energy consumption records).

This segmentation facilitates filtering, selection, and comparison of objects from a spatial and technical perspective—for example, identifying buildings connected to the district heating network, comparing their energy demand and insulation status, and then visualizing the results in an interactive environment. Segmentation also provides the basis for further assigning semantic data to model elements.

A parallel set of descriptive data was developed for all included buildings, obtained from the resources of the Zamość City Investment and Development Department, municipal building registers, surveying and urban planning documentation, and materials from conservation and technical units. The database included over 100 buildings, each with >10 parameters (including address and function, plan/outline and number of floors, façade/roof/windows condition, heating system and heat source, wall and roof insulation level, renewable

energy sources, estimated annual energy demand). The data was standardized in spreadsheets and prepared for linking to the model.

The database structure was designed as a "one row – one building" (flat table), with columns corresponding to descriptive parameters. Field standardization was implemented (e.g., 1–5 rating scales, function codes consistent with national classifications), unambiguous data types, and consistency checks (range validation, absence of duplicates, unique identifiers). This database structure facilitates grouping and filtering of buildings according to any criteria.

The integration of semantic data with the 3D model was accomplished in two stages. First, it was imported into the BIM environment (Autodesk Revit) and the model was extended with design parameters directly from the input tables. Next, the model was exported to IFC4 format, allowing it to be used in external tools (CellBIM, CloudCompare). Attributes are read as Property Sets associated with geometric objects, and attribute maps (thematic coloring by features) were used. The entire dataset was saved in IFC to ensure compatibility between systems and further processing.

3.4. Semantic data management

The model developed a semantic data structure associated with geometric representations of buildings, providing the basis for technical, energy, functional, and conservation analyses.

A standardized set of parameters was defined for each building, grouped into categories: identification and location (address, plot number, Revit/IFC ID), function and use (main function, attic accessibility, number of stories), geometric parameters (outline, optionally usable area, and for selected buildings, volume), technical condition (facades, roof, joinery, basement moisture, plumbing), and energy and environment (heating type, estimated annual energy demand [kWh/m²/year], wall and roof insulation level, presence of renewable energy sources).

The dataset covered over 100 buildings, each assigned over 10 parameters. Data was obtained from sources including the Zamość City Investment and Development Department, municipal building registers, geodetic and urban planning documentation, and materials from conservation and technical units. Information has been standardized in input sheets (CSV/XLSX) for further linkage to the model and updateability over time.

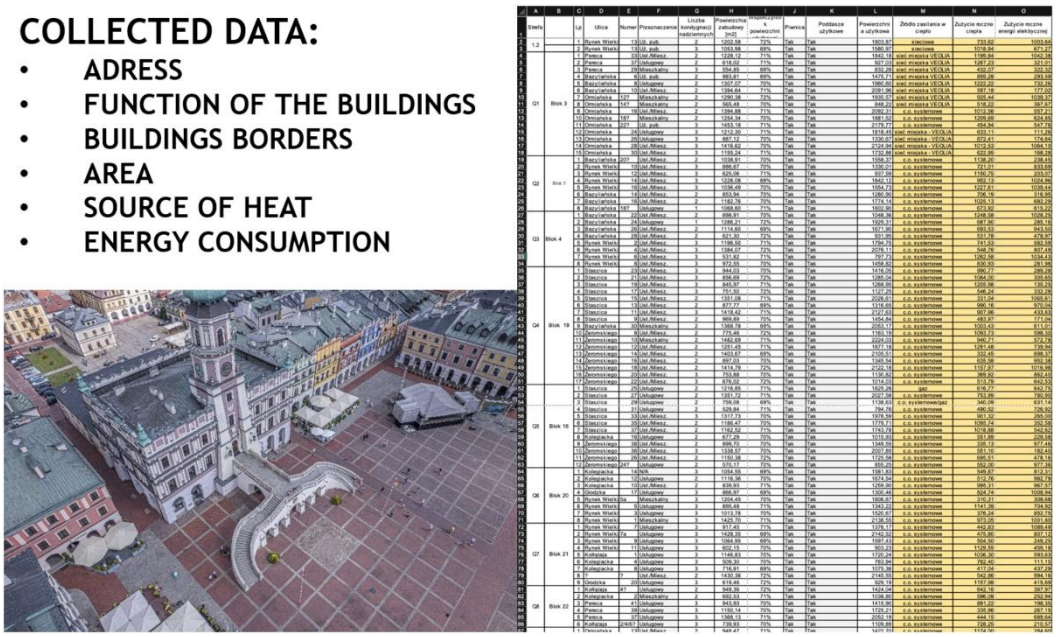


Figure 32 Data standardization process illustrated by a fragment of the semantic attribute table.

The database structure was adopted as a "one row – one building" (flat table) with columns corresponding to descriptive parameters. Fields were standardized (including rating scales from 1 to 5 for technical condition, function codes consistent with the Central Statistical Office classification), unambiguous data types were assigned, and consistency checks were implemented (range validation, absence of duplicates, unique identifiers). The schema was adapted for import into a BIM environment (Autodesk Revit) and further analysis in external tools (CloudCompare, CellBIM).

Linking to the 3D model is achieved through unique identifiers compatible with Revit/IFC, enabling automatic attribute linking and subsequent synchronization of changes (IDs and Revit Families parameters). Integration is performed in two stages: import to Revit with the assignment of design parameters, followed by export to IFC4, allowing attributes to be read in external environments as Property Sets. Thematic views are also used (coloring by properties, e.g., energy, insulation, condition).

3.5. Integration with BIM and analytical environments

Integration of the descriptive data with the 3D model was accomplished in two stages: first, the input tables were imported into the BIM environment (Autodesk Revit) and the model was extended with design parameters corresponding to the spreadsheet columns; second, the model was exported to IFC4, enabling its use in external environments. In these environments, attributes are read as Property Sets associated with geometric objects.

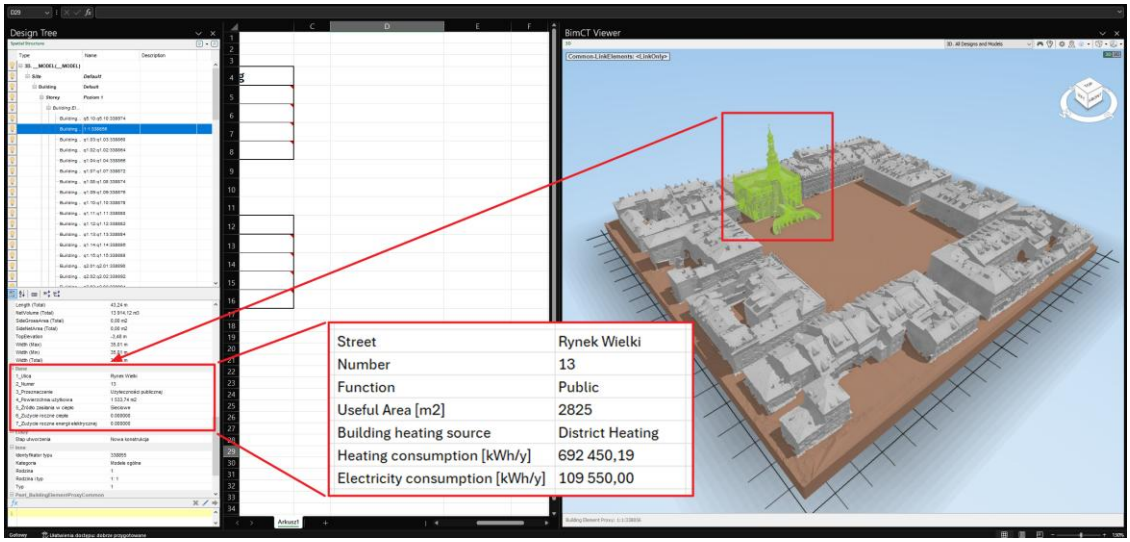


Figure 33 Integration of Data with the 3D Model

A linkage based on unique Revit/IFC-compliant identifiers was used, allowing data to be automatically linked to the appropriate model elements and synchronized upon updates (via IDs and corresponding Revit Families parameters).

In terms of interoperability, emphasis was placed on compliance with open standards (IFC4, openBIM) and compatibility with viewing and analysis platforms. In addition to processing in Revit, external tools, including CellBIM and CloudCompare, as well as IFC Viewer, were used for verification and analysis.

The analytical environments utilized thematic views (coloring by attributes) to graphically present, among other things, energy consumption levels, insulation quality, and component condition, facilitating visual analysis and identifying problematic objects in the historic urban fabric.

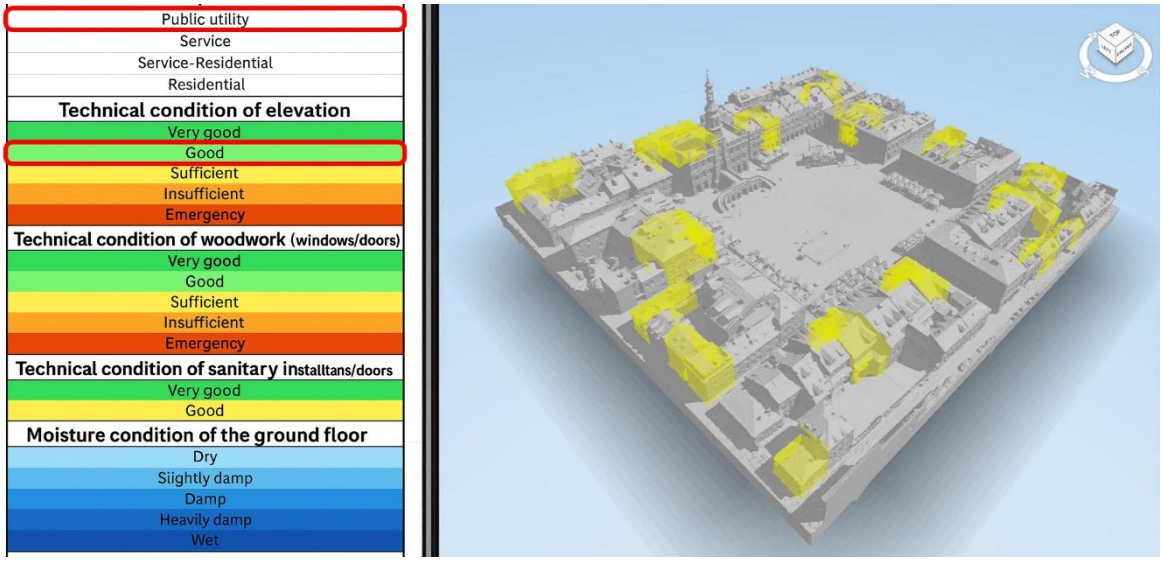


Figure 34. Main features of the interactive digital twin platform, in this case the highlighted objects are public utility buildings with a good technical condition of elevation

3.6. Baseline results and applications

The developed model confirmed the effectiveness of the approach combining laser scanning, photogrammetry, and BIM/IFC: high geometric accuracy of 4-5 cm, full compatibility with industry formats (IFC, Revit), efficient operation of the interactive tool in a web environment (tested on a set of 100 buildings), and a clear structure of the descriptive database (approximately 14 parameters per building, consistent identifiers).

The resource includes over 100 buildings in the Old Town, each assigned a standardized set of parameters (identification, function/use, geometric elements, selected aspects of technical condition, and energy and environmental characteristics). The data is integrated with the 3D model and presented in real time in an interactive environment, with the option of filtering results and exporting reports.

The thematic analyses indicate, among other things: (i) a concentration of service functions around the Great Market Square, with a tendency to disperse towards the eastern quarters; (ii) identifying buildings requiring urgent conservation interventions (leaky roofs, damaged joinery/facades); (iii) selecting buildings with the highest estimated energy demand (over 250 kWh/m^2/year)—often in buildings with unused attics, outdated heating systems, and lack of insulation.

The implemented solution effectively integrates the spatial model with real-world heritage management processes, providing insight into the city's structure, the technical condition of buildings, and the modernization potential of individual buildings. It can serve as a benchmark for other cities and institutions implementing digital twins in heritage protection.

Development directions were also identified: integration of temporal data (histories of changes to buildings), ongoing updating through synchronization with municipal cadastral databases (e.g., GESUT/EGiB/MPZP), expansion of the model to additional areas of the city (including 19th-20th century heritage), and the introduction of a participatory layer (annotations and comments from stakeholders with expert verification).

4. ANNEX IV: QUEDLINBURG PILOT DIGITALIZATION

4.1. Step 1: Tabular Data Structuring and Conversion to QGIS-Ready Format

In Quedlinburg a main Excel File comprised of several tabs were composed that contained building level data and included residential, as well as non-residential buildings.

The tabs included:

- Administrative data (building ID, address, cadastral parcel number, x- and y-coordinates, occupancy status) as shown in Figure 35: Administrative Data for QuedlinburgFigure 35
- Cultural heritage data (construction date, typology, architectural value, façade-, roof- and fenestration conditions, heritage valorization level, renovation restrictions) as shown in Figure 37
- Technical data (gross area, useful area, number of storeys) as shown in Figure 39
- Energy-baseline values (heating system type, installed heating capacity, main fuel type, baseline final energy, baseline primary energy, annual energy demand, baseline OPEX, baseline CO_2 emissions) as shown in Figure 40
- Socio economic data (ownership, condition ratings, energy poverty risk) as shown in Figure 38

Building_ID	Block_ID	Administrative_Cadastral_Parcel_Nr	Administrative_Building_Use_Type	Administrative_Street	Administrative_Street_Number	Administrative_Postal_Code	Administrative_City_Name	Administrative_Coordinates_X	Administrative_Coordinates_Y	Administrative_Occupancy_Status
1	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Residential and Commercial Building	Blasiistraße	1	06484	Quedlinburg	11.14097	51.78861	partially vacant
2	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Residential and Commercial Building	Blasiistraße	1	06484	Quedlinburg	11.14097	51.78861	in use
3	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Residential and Commercial Building	Blasiistraße	1	06484	Quedlinburg	11.14097	51.78861	in use
4	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Commercial / Trade Building	Blasiistraße	1	06484	Quedlinburg	11.14097	51.78861	in use
5	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Residential and Commercial Building	Blasiistraße	2	06484	Quedlinburg	11.14097	51.78861	in use
6	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Residential and Commercial Building	Blasiistraße	2	06484	Quedlinburg	11.14097	51.78861	partially vacant
7	16	Gemarkung Quedlinburg, Flur 37, FlSt. 4	Outbuilding / Garage	Blasiistraße	2	06484	Quedlinburg	11.14097	51.78861	in use
8	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	3	06484	Quedlinburg	11.14079	51.7886	in use
9	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	3	06484	Quedlinburg	11.14079	51.7886	in use
10	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	3	06484	Quedlinburg	11.14079	51.7886	in use
11	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	4	06484	Quedlinburg	11.14067	51.7886	in use
12	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	4	06484	Quedlinburg	11.14067	51.7886	in use
13	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	4	06484	Quedlinburg	11.14067	51.7886	in use
14	16	Gemarkung Quedlinburg, Flur 37, FlSt. 3	Residential and Commercial Building	Blasiistraße	5	06484	Quedlinburg	11.14054	51.78857	in use
15	16	Gemarkung Quedlinburg, Flur 37, FlSt. 3	Outbuilding / Garage	Blasiistraße	5	06484	Quedlinburg	11.14054	51.78857	in use
16	16	Gemarkung Quedlinburg, Flur 37, FlSt. 3	Residential and Commercial Building	Blasiistraße	5	06484	Quedlinburg	11.14054	51.78857	in use
17	16	Gemarkung Quedlinburg, Flur 37, FlSt. 3	Commercial / Trade Building	Blasiistraße	5	06484	Quedlinburg	11.14054	51.78857	in use
18	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	6	06484	Quedlinburg	11.14043	51.78856	in use
19	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	6	06484	Quedlinburg	11.14043	51.78856	in use
20	17	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Special Building	Blasiistraße	06_K	06484	Quedlinburg	11.14042	51.78869	in use
21	17	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Outbuilding / Garage	Blasiistraße	06_K	06484	Quedlinburg	11.14042	51.78869	in use
22	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	partially vacant
23	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	in use
24	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	partially vacant
25	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	in use
26	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	partially vacant
27	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	7	06484	Quedlinburg	11.1402	51.78856	in use
28	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	8	06484	Quedlinburg	11.13997	51.78853	partially vacant
29	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	9	06484	Quedlinburg	11.13986	51.78853	in use
30	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential Building	Blasiistraße	9	06484	Quedlinburg	11.13986	51.78853	in use
31	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	10	06484	Quedlinburg	11.13965	51.78845	in use
32	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	10	06484	Quedlinburg	11.13965	51.78845	in use
33	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	10	06484	Quedlinburg	11.13965	51.78845	in use
34	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	10	06484	Quedlinburg	11.13965	51.78845	in use
35	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	10	06484	Quedlinburg	11.13965	51.78845	vacant
36	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	11	06484	Quedlinburg	11.13935	51.78844	in use
37	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	11	06484	Quedlinburg	11.13935	51.78844	in use
38	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	11	06484	Quedlinburg	11.13935	51.78844	in use
39	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	11	06484	Quedlinburg	11.13935	51.78844	in use
40	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Commercial / Trade Building	Blasiistraße	11	06484	Quedlinburg	11.13935	51.78844	in use
41	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	12	06484	Quedlinburg	11.13923	51.78847	vacant
42	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Residential and Commercial Building	Blasiistraße	12	06484	Quedlinburg	11.13923	51.78847	vacant
43	16	Gemarkung Quedlinburg, Flur 37, FlSt. 8	Outbuilding / Garage	Blasiistraße	12	06484	Quedlinburg	11.13923	51.78847	in use
44	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	14	06484	Quedlinburg	11.13903	51.78844	in use
45	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Residential and Commercial Building	Blasiistraße	14	06484	Quedlinburg	11.13903	51.78844	in use
46	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Commercial / Trade Building	Blasiistraße	14	06484	Quedlinburg	11.13903	51.78844	in use
47	16	Gemarkung Quedlinburg, Flur 37, FlSt. 1	Commercial / Trade Building	Blasiistraße	14	06484	Quedlinburg	11.13903	51.78844	in use

Figure 35: Administrative Data for Quedlinburg

Building_ID	Block_ID	Heating_System_Type	Installed_Heating_Capacity_kW	Main_Fuel_Type	Baseline_Final_Energy_kW	Baseline_Primary_Energy_kW	Annual_energy_demand kWh (Estimation	Baseline_OPEX_EU	Baseline_CO2
1	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
2	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
3	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
4	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
5	16	Local heating	11.98	Gas	30,109	37,183	30,109	5,669	7.333
6	16	Local heating	11.98	Gas	30,109	37,183	30,109	5,669	7.333
7	16	Local heating	11.98	Gas	30,109	37,183	30,109	5,669	7.333
8	16	Local heating	7.65	Gas	19,227	23,744	19,227	3,620	4.667
9	16	Local heating	7.65	Gas	19,227	23,744	19,227	3,620	4.667
10	16	Local heating	7.65	Gas	19,227	23,744	19,227	3,620	4.667
11	16	Local heating	4.54	Gas	11,416	14,098	11,416	2,149	2.667
12	16	Local heating	4.54	Gas	11,416	14,098	11,416	2,149	2.667
13	16	Local heating	4.54	Gas	11,416	14,098	11,416	2,149	2.667
14	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
15	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
16	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
17	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
18	16	Local heating	6.12	Gas	15,382	18,996	15,382	2,896	4
19	16	Local heating	6.12	Gas	15,382	18,996	15,382	2,896	4
20	17	Local heating	31.43	Gas	78,985	113,005	78,985	19,311	24.5
21	17	Local heating	31.43	Gas	78,985	113,005	78,985	19,311	24.5
22	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
23	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
24	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
25	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
26	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
27	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
28	16	Local heating	32.43	Gas	81,503	99,952	81,503	15,019	20
29	16	Local heating	7.35	Gas	18,483	22,666	18,483	3,406	4.5
30	16	Local heating	7.35	Gas	18,483	22,666	18,483	3,406	4.5
31	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
32	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
33	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
34	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
35	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
36	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2
37	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2
38	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2
39	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2

Figure 36: Energy Baseline Data for Quedlinburg

Building_ID	Block_ID	Year_of_Construction	Building_Typology	Architectural_Value	Facade_condition	Roof_condition	Fenestration_condition (windows/doors)	Heritage_Valorization_Level	Renovation_Restrictions
1	16	until 1829	Commercial, Residen	neglected maintenance	Half-timbered	Tiles: historic, roof	without plaster: appropriately renewed, windc	Individual monument	Determined by conservators
2	16	until 1918	Residential,Commerc	no noticeable damage	Brick masonry	Bricks: inappropria	without plaster: appropriately renewed, plaste	Individual monument	Determined by conservators
3	16	until 1719	Residential,Commerc	no noticeable damage	Half-timbered	Tiles: appropriately	without plaster: appropriately renewed, windc	Individual monument	Determined by conservators
4	16	after 1990	Commercial	no noticeable damage	Brick masonry	Bitumen or similar:	Plaster: historic, Windows: historic, Gates: hi	None	Determined by conservators
5	16	until 1720	Residential,Commerc	no noticeable damage	Half-timbered	Bricks: historic	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
6	16	until 1720	Commercial, Residen	no noticeable damage	Half-timbered	Bricks: appropriate	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
7	16	until 1918	Storage,Garage	no noticeable damage	Brick masonry	Bitumen or similar:	Windows: appropriately renewed, doors: inap	None	Determined by conservators
8	16	until 1720	Residential,Commerc	no noticeable damage	Half-timbered	Tiles: appropriately	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
9	16	until 1918	Residential,Commerc	no noticeable damage	Half-timbered	Roof structures: ap	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
10	16	until 1830	Residential,Storage,G	no noticeable damage	Half-timbered	Bitumen or similar:	Plaster: appropriately renewed, windows: app	Architectural monument	Determined by conservators
11	16	until 1535	Residential,Commerc	slight damage	Half-timbered	Tiles: historic (60s)	Plaster: historic, windows: inappropriately rer	Architectural monument	Determined by conservators
12	16	until 1990	Residential,Commerc	slight damage	Brick masonry	Bricks: historic	Plaster: historic, windows: historic	None	Determined by conservators
13	16	until 1720	Commercial	slight damage	Half-timbered	Bricks: appropriate	without plaster: appropriately renewed (paint	Architectural monument	Determined by conservators
14	16	until 1534	Residential,Commerc	no noticeable damage	Brick masonry, half-tii	Tiles: appropriately	without plaster: appropriately renewed, plaste	Architectural monument	Determined by conservators
15	16	until 1720	Residential	no noticeable damage	Half-timbered	Bricks: appropriate	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
16	16	until 1620	Residential,Commerc	no noticeable damage	Brick masonry	Tiles: appropriately	without plaster: appropriately renewed, cladd	Architectural monument	Determined by conservators
17	16	after 1990	Commercial	no noticeable damage	Half-timbered	Bricks: historic (+ p	without plaster: historic, windows: historic, dc	None	Determined by conservators
18	16	until 1534	Residential,Commerc	no noticeable damage	Brick masonry, half-tii	Tiles: appropriately	without plaster: appropriately renewed, plaste	Architectural monument	Determined by conservators
19	16	until 1830	Residential	no noticeable damage	Brick masonry, half-tii	Bricks: appropriate	without plaster: appropriately renewed, cladd	Architectural monument	Determined by conservators
20	17	until 1535	Community Use	slight damage	Solid natural stone	Slate: appropriatel	without plaster: historic, windows: historic, dc	Architectural monument	Determined by conservators
21	17	until 1918	Storage	slight damage	Natural Stone Solid, B	Tiles: historic, roof	without plaster: historic, windows: historic, dc	None	Determined by conservators
22	16	until 1918	Residential, Commerc	no noticeable damage	Brick masonry	Tiles: appropriately	Plaster: appropriately renewed, windows: app	Architectural monument	Determined by conservators
23	16	until 1830	Residential,Commerc	no noticeable damage	Half-timbered	Tiles: appropriately	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
24	16	until 1830	Residential, Commerc	no noticeable damage	Brick masonry, half-tii	Bricks: appropriate	without plaster: appropriately renewed, cladd	Architectural monument	Determined by conservators
25	16	until 1918	Residential,Commerc	no noticeable damage	Brick masonry, half-tii	Bricks: appropriate	without plaster: appropriately renewed, plaste	Architectural monument	Determined by conservators
26	16	until 1918	Residential,Commerc	no noticeable damage	Brick masonry, half-tii	Bricks: appropriate	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators
27	16	until 1945	Commercial	no noticeable damage	Brick masonry	Bitumen or similar:	Plaster: appropriately renewed, windows: app	None	Determined by conservators
28	16	until 1620	Residential, Commerc	no noticeable damage	Brick masonry, half-tii	Tiles: appropriately	without plaster: appropriately renewed, plaste	Architectural monument	Determined by conservators
29	16	until 1990	Residential,Commerc	no noticeable damage	Brick masonry, half-tii	Bricks: appropriate	without plaster: appropriately renewed, plaste	Architectural monument	Determined by conservators
30	16	until 1990	Residential	slight damage	Brick masonry	Bitumen or similar:	Plaster: historic, windows: historic (shop winc	None	Determined by conservators
31	16	until 1830	Community Use	no noticeable damage	Half-timbered	Bricks: inappropria	without plaster: appropriately renewed (from	Architectural monument	Determined by conservators
32	16	until 1720	Community Use	no noticeable damage	Half-timbered	Bricks: appropriate	without plaster: appropriately renovated, winc	Architectural monument	Determined by conservators
33	16	until 1720	Community Use	no noticeable damage	Brick masonry, half-tii	Bricks: appropriate	without plaster: appropriately renewed, windc	Architectural monument	Determined by conservators

Figure 37: Cultural Heritage Data for Quedlinburg

	A	B	C	D	E
1	Building_ID	Block_ID	Gross_Area_m²	Useful_Area_m²	Number_of_Storeys
2	1	16	557	445.5	5
3	2	16	557	445.5	5
4	3	16	557	445.5	5
5	4	16	557	445.5	1
6	5	16	251	200.3333333	5
7	6	16	251	200.3333333	5
8	7	16	251	200.3333333	1
9	8	16	160	128	5
10	9	16	160	128	3
11	10	16	160	128	2
12	11	16	95	76	4
13	12	16	95	76	2
14	13	16	95	76	3
15	14	16	88	70.5	4
16	15	16	88	70.5	2
17	16	16	88	70.5	2
18	17	16	88	70.5	2
19	18	16	128	102.5	4
20	19	16	128	102.5	4
21	20	17	959	767	4
22	21	17	959	767	3
23	22	16	151	120.8333333	4
24	23	16	151	120.8333333	3
25	24	16	151	120.8333333	5
26	25	16	151	120.8333333	4
27	26	16	151	120.8333333	4
28	27	16	151	120.8333333	1
29	28	16	635	508	5
30	29	16	144	115	5
31	30	16	144	115	3
32	31	16	198	158.4	6
33	32	16	198	158.4	3
34	33	16	198	158.4	3

Figure 39: Technical Data for Quedlinburg

	A	B	C	D	E
1	Building_ID	Block_ID	Ownership_Type	Physical_Condition_Ratings	Energy_Poverty_Risk
2	1	16	Public	neglected maintenance	Assessment needed
3	2	16	Public	no noticeable damage	Assessment needed
4	3	16	Public	no noticeable damage	Assessment needed
5	4	16	Public	no noticeable damage	Assessment needed
6	5	16	Private	no noticeable damage	Assessment needed
7	6	16	Private	no noticeable damage	Assessment needed
8	7	16	Private	no noticeable damage	Assessment needed
9	8	16	Private	no noticeable damage	Assessment needed
10	9	16	Private	no noticeable damage	Assessment needed
11	10	16	Private	no noticeable damage	Assessment needed
12	11	16	Private	slight damage	Assessment needed
13	12	16	Private	slight damage	Assessment needed
14	13	16	Private	slight damage	Assessment needed
15	14	16	Private	no noticeable damage	Assessment needed
16	15	16	Private	no noticeable damage	Assessment needed
17	16	16	Private	no noticeable damage	Assessment needed
18	17	16	Private	no noticeable damage	Assessment needed
19	18	16	Private	no noticeable damage	Assessment needed
20	19	16	Private	no noticeable damage	Assessment needed
21	20	17	Company	slight damage	Assessment needed
22	21	17	Company	slight damage	Assessment needed
23	22	16	Company	no noticeable damage	Assessment needed
24	23	16	Company	no noticeable damage	Assessment needed
25	24	16	Company	no noticeable damage	Assessment needed
26	25	16	Company	no noticeable damage	Assessment needed
27	26	16	Private	no noticeable damage	Assessment needed
28	27	16	Private	no noticeable damage	Assessment needed
29	28	16	Private	no noticeable damage	Assessment needed
30	29	16	unclear	no noticeable damage	Assessment needed
31	30	16	unclear	slight damage	Assessment needed
32	31	16	unclear	no noticeable damage	Assessment needed
33	32	16	unclear	no noticeable damage	Assessment needed

Figure 38: Socio-Economic Data for Quedlinburg

	A	B	C	D	E	F	G	H	I	J
1	Building_ID	Block_ID	Heating_System_Type	Installed_Heating_Capacity_kW	Main_Fuel_Type	Baseline_Final_Energy_kW	Baseline_Primary_Energy_kW	Annual_energy_demand kWh (Estimation	Baseline_OPEX_EU	Baseline_CO2
2	1	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
3	2	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
4	3	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
5	4	16	Local heating	28.3	Gas	71,117	93,400	71,117	14,384	19.25
6	5	16	Local heating	11.98	Gas	30,109	37,183	30,109	5,669	7.333
7	6	16	Local heating	11.98	Gas	30,109	37,183	30,109	5,669	7.333
8	7	16	Local heating	11.98	Gas	30,109	37,183	30,109	5,669	7.333
9	8	16	Local heating	7.65	Gas	19,227	23,744	19,227	3,620	4.667
10	9	16	Local heating	7.65	Gas	19,227	23,744	19,227	3,620	4.667
11	10	16	Local heating	7.65	Gas	19,227	23,744	19,227	3,620	4.667
12	11	16	Local heating	4.54	Gas	11,416	14,098	11,416	2,149	2.667
13	12	16	Local heating	4.54	Gas	11,416	14,098	11,416	2,149	2.667
14	13	16	Local heating	4.54	Gas	11,416	14,098	11,416	2,149	2.667
15	14	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
16	15	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
17	16	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
18	17	16	Local heating	4.21	Gas	10,590	13,078	10,590	1,994	2.5
19	18	16	Local heating	6.12	Gas	15,382	18,996	15,382	2,896	4
20	19	16	Local heating	6.12	Gas	15,382	18,996	15,382	2,896	4
21	20	17	Local heating	31.43	Gas	78,985	113,005	78,985	19,311	24.5
22	21	17	Local heating	31.43	Gas	78,985	113,005	78,985	19,311	24.5
23	22	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
24	23	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
25	24	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
26	25	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
27	26	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
28	27	16	Local heating	7.22	Gas	18,155	21,740	18,155	3,279	4.167
29	28	16	Local heating	32.43	Gas	81,503	99,952	81,503	15,019	20
30	29	16	Local heating	7.35	Gas	18,483	22,666	18,483	3,406	4.5
31	30	16	Local heating	7.35	Gas	18,483	22,666	18,483	3,406	4.5
32	31	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
33	32	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
34	33	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
35	34	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
36	35	16	Local heating	10.06	Gas	25,280	33,202	25,280	5,113	6.8
37	36	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2
38	37	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2
39	38	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2
40	39	16	Local heating	6.26	Gas	15,720	20,645	15,720	3,179	4.2

Figure 40: Energy Baseline Data for Quedlinburg

The Excel files were edited and converted into QGIS-compatible .csv format.

4.1.1. Step 2: Linking to Spatial Data in QGIS

For the spatial linking the geospatial data from the State Office for Surveying and Geoinformation Saxony-Anhalt (LVermGeo) was procured which provided general building outlines. Additionally address specific coordinates were acquired using the Saxony-Anahlt-Viewer which is also made available for use from the LVermGeo. Since the building coordinates could only be procured on an address level instead of a building level the coordinates are the same for every building of the same address. This process resulted in a point layer and a polygon layer as shown in Figure 41.

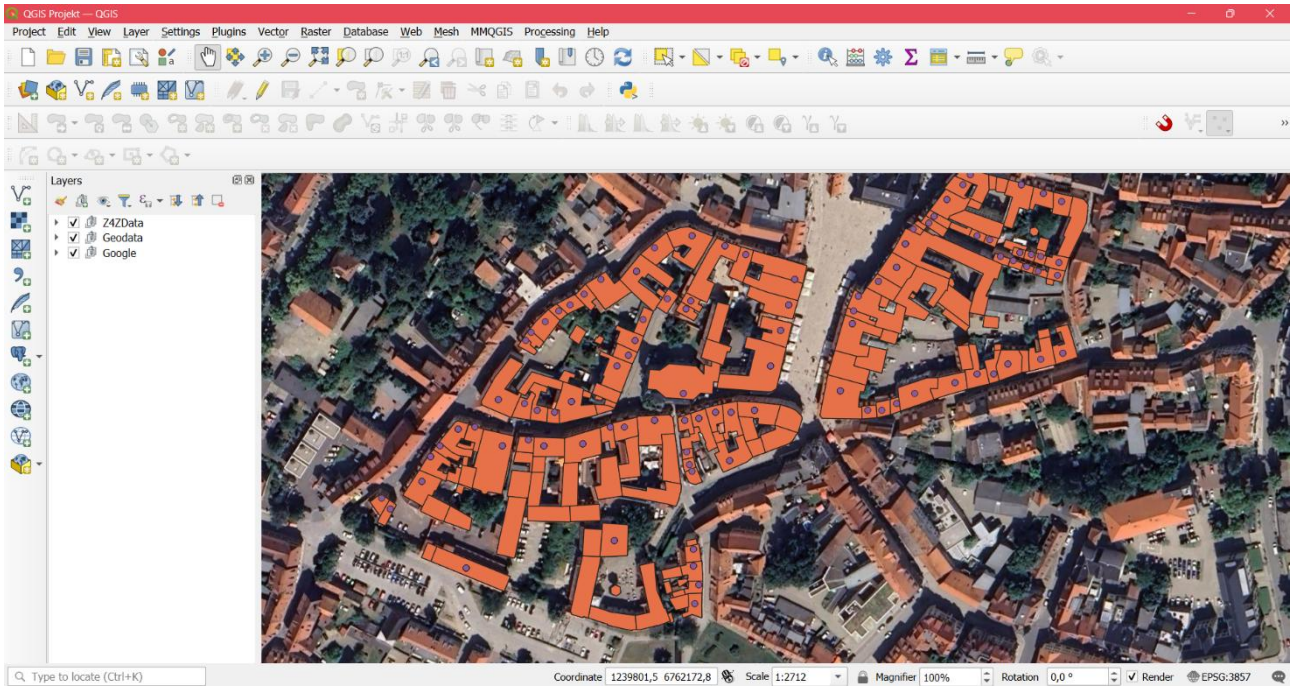


Figure 41: The polygon layer outlining the buildings and the point layer representing the administrative data in QGIS

The geospatial data was linked with the Administrative data through the coordinates by using the tool 'join attributes by location'. Due to the fact that several buildings had the same coordinates the joining was done on a 'one-to-many' basis which resulted in a joined layer as depicted in Figure 42.

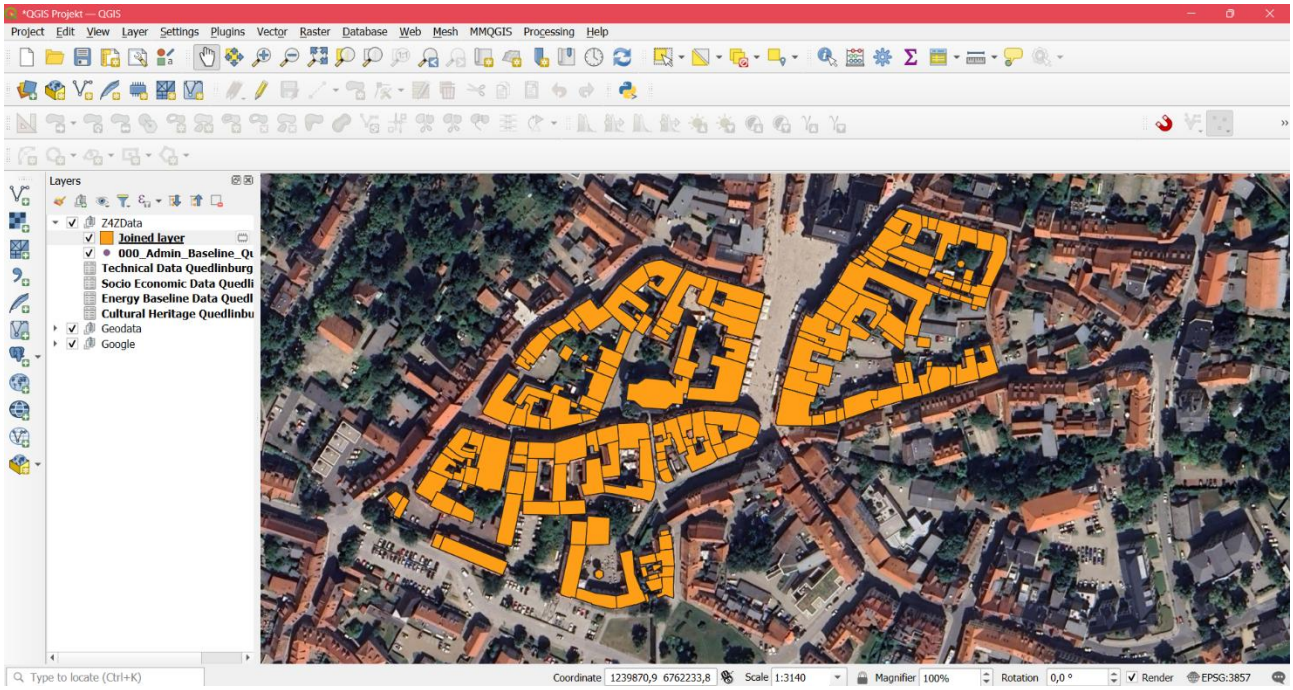


Figure 42: Joined building outline and administrative data layer in QGIS for Quedlinburg

4.1.2. Step 3 – Adding Additional Datasets

The other baseline data sets – heritage, technical, energy baseline, socio-economic – were joined with the joined Administrative layer by using the building ID's which were included in every dataset and allowed for smooth joining by using the vector join function in QGIS as shown in Figure 43.

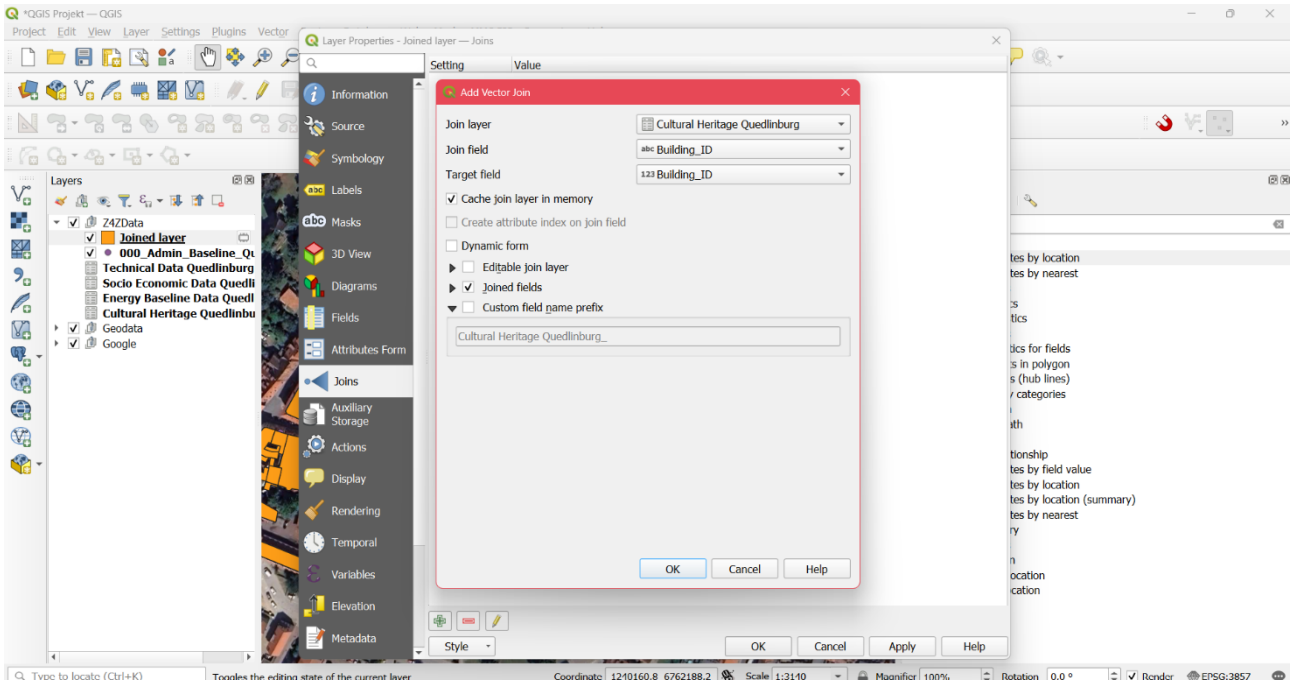


Figure 43: Vector join function for adding the cultural heritage data to the joined layer in Quedlinburg

This resulted in one final joined layer with all datapoints being spatially organized as one can see in Figure 44.

Joined layer — Features Total: 322, Filtered: 322, Selected: 0

	AGS	OI	GFK	Building_ID	Block_ID	ative_Cadastral_I	rative_Building_L	iministrative_Stre	strative_Street_N	istrative_Postal_	inistrative_City_N	istrative_Coordin	istrative_Coordin	rative_Occupanc	ritage_Year_of_
79	15085235	DEST0GGG00...	31001_1100	2	16	Gemarkung Q...	Residential an...	Blasiistraße	1	6484	Quedlinburg	11,14097	51,78861	in use	until 1918
80	15085235	DEST0GGG00...	31001_1100	3	16	Gemarkung Q...	Residential an...	Blasiistraße	1	6484	Quedlinburg	11,14097	51,78861	in use	until 1719
81	15085235	DEST0GGG00...	31001_1100	4	16	Gemarkung Q...	Commercial / ...	Blasiistraße	1	6484	Quedlinburg	11,14097	51,78861	in use	after 1990
82	15085235	DEST0GGG00...	31001_1100	5	16	Gemarkung Q...	Residential an...	Blasiistraße	2	6484	Quedlinburg	11,14097	51,78861	in use	until 1720
83	15085235	DEST0GGG00...	31001_1100	6	16	Gemarkung Q...	Residential an...	Blasiistraße	2	6484	Quedlinburg	11,14097	51,78861	partially vacant	until 1720
84	15085235	DEST0GGG00...	31001_1100	7	16	Gemarkung Q...	Outbuilding / ...	Blasiistraße	2	6484	Quedlinburg	11,14097	51,78861	in use	until 1918
85	15085235	DEST0GGG00...	31001_1100	8	16	Gemarkung Q...	Residential an...	Blasiistraße	3	6484	Quedlinburg	11,14079	51,7886	in use	until 1720
86	15085235	DEST0GGG00...	31001_1100	9	16	Gemarkung Q...	Residential an...	Blasiistraße	3	6484	Quedlinburg	11,14079	51,7886	in use	until 1918
87	15085235	DEST0GGG00...	31001_1100	10	16	Gemarkung Q...	Residential an...	Blasiistraße	3	6484	Quedlinburg	11,14079	51,7886	in use	until 1830
88	15085235	DEST0GGG00...	31001_1100	11	16	Gemarkung Q...	Residential an...	Blasiistraße	4	6484	Quedlinburg	11,14067	51,7886	in use	until 1535
89	15085235	DEST0GGG00...	31001_1100	12	16	Gemarkung Q...	Residential an...	Blasiistraße	4	6484	Quedlinburg	11,14067	51,7886	in use	until 1990
90	15085235	DEST0GGG00...	31001_1100	13	16	Gemarkung Q...	Residential an...	Blasiistraße	4	6484	Quedlinburg	11,14067	51,7886	in use	until 1720
91	15085235	DEST0GGG00...	31001_1100	14	16	Gemarkung Q...	Residential an...	Blasiistraße	5	6484	Quedlinburg	11,14054	51,78857	in use	until 1534
92	15085235	DEST0GGG00...	31001_1100	15	16	Gemarkung Q...	Outbuilding / ...	Blasiistraße	5	6484	Quedlinburg	11,14054	51,78857	in use	until 1720
93	15085235	DEST0GGG00...	31001_1100	16	16	Gemarkung Q...	Residential an...	Blasiistraße	5	6484	Quedlinburg	11,14054	51,78857	in use	until 1620
94	15085235	DEST0GGG00...	31001_1100	17	16	Gemarkung Q...	Commercial / ...	Blasiistraße	5	6484	Quedlinburg	11,14054	51,78857	in use	after 1990
95	15085235	DEST0GGG00...	31001_1100	18	16	Gemarkung Q...	Residential an...	Blasiistraße	6	6484	Quedlinburg	11,14043	51,78856	in use	until 1534
96	15085235	DEST0GGG00...	31001_1100	19	16	Gemarkung Q...	Residential an...	Blasiistraße	6	6484	Quedlinburg	11,14043	51,78856	in use	until 1830
97	15085235	DEST0GGG00...	31001_3041	20	17	Gemarkung Q...	Special Building	Blasiistraße	06_K	6484	Quedlinburg	11,14042	51,78869	in use	until 1535
98	15085235	DEST0GGG00...	31001_3041	21	17	Gemarkung Q...	Outbuilding / ...	Blasiistraße	06_K	6484	Quedlinburg	11,14042	51,78869	in use	until 1918
99	15085235	DEST0GGG00...	31001_2000	22	16	Gemarkung Q...	Residential an...	Blasiistraße	7	6484	Quedlinburg	11,1402	51,78856	partially vacant	until 1918
100	15085235	DEST0GGG00...	31001_2000	23	16	Gemarkung Q...	Commercial / ...	Blasiistraße	7	6484	Quedlinburg	11,1402	51,78856	in use	until 1830
101	15085235	DEST0GGG00...	31001_2000	24	16	Gemarkung Q...	Commercial / ...	Blasiistraße	7	6484	Quedlinburg	11,1402	51,78856	partially vacant	until 1830

Show All Features

Figure 44: FInal joined layer for Quedlinburg



Figure 45: Digital 3D scan of Quedlinburg pilot