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Digital Tool Supporting the Documentation and Analysis of Cultural Heritage: The Case of the Analytical 3D Model of the Zamość Fortress

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This paper presents a city-scale digital documentation and analysis workflow for cultural heritage assets, demonstrated on the example of the UNESCO-listed historic centre and fortress area of Zamość (Poland). The study integrates terrestrial laser scanning (TLS) with unmanned aerial vehicle (UAV) and terrestrial photogrammetry to produce a geometrically consistent 3D dataset covering over 100 buildings and key public-space elements. The processing pipeline includes scan registration, image-based reconstruction, and cross-sensor alignment, followed by the creation of an analytical 3D model segmented by address and parcel identifiers to enable linkage with municipal datasets.

A semantic layer is implemented by assigning a structured set of building- and neighbourhood-level parameters and mapping them into building information modelling (BIM)/openBIM structures (Revit shared parameters and industry foundation classes (IFC) Property Sets), targeting a level of information adequate for conservation-oriented diagnostics and urban-scale assessments rather than detailed component-level historic building information modelling (HBIM). Geometric quality is verified using independent checkpoints and registration statistics (e.g., root mean square error (RMSE) where applicable), yielding a typical spatial agreement on the order of 4 cm to 5 cm for the integrated model in representative test areas.

The resulting environment supports multi-criteria querying and visualisation, including functional categorisation, technical condition screening (e.g., moisture-related indicators), and energy-related attributes for prioritisation at the district scale. The main contribution is a reproducible integration of multi-source survey data with an explicit semantic/BIM mapping and verifiable accuracy reporting for a heritage city context, clarifying which outputs stem from the proposed method (data integration, segmentation, semantic schema, and validation) versus the standard capabilities of the employed software.

Keywords: digital twin, cultural heritage documentation, 3D modelling, terrestrial laser scanning, UAV photogrammetry, BIM/IFC.

1. Introduction

In recent years, there has been a dynamic development of digital technologies applied to the protection of cultural heritage. Analyses indicate the growing importance of digital tools in the processes of documentation, monitoring, and conservation of historic objects [1, 2]. A prominent role is played by methods based on the integration of laser scanning, photogrammetry, and BIM modelling, which enable the precise representation and management of heritage assets [3–5].

The concept of heritage building information modelling (HBIM) has become one of the key tools in contemporary conservation practice. It allows for the creation of semantic models that combine geometric data with information on materials, damages, and previous conservation interventions [6–8, 11]. At the same time, the scan-to-BIM methodology has been evolving, serving as a bridge between spatial data acquisition and digital modelling [9]. The use of these processes contributes to the creation of complex databases that support design and conservation decision-making [1, 4, 10].

The integration of 3D scanning, photogrammetry, and BIM has been applied in numerous case studies, demonstrating its effectiveness in the documentation of heritage objects [5, 10–12]. This approach makes it possible not only to faithfully reproduce geometry but also to enrich models with semantic data and structural parameters, which significantly increases their research and practical value [1, 13]. Simultaneously, thanks to the development of visualization and augmented reality tools, such models can also be applied in education and the dissemination of heritage knowledge [9, 14].

In recent years, increasing attention has also been devoted to the concept of the digital twin, which has transitioned from industry into heritage conservation. A digital twin enables real-time monitoring, load simulations, and the analysis of structural behavior under different scenarios [15, 16]. Methodologies for implementing digital twins in the context of heritage are also being developed, taking into account the integration of geometric, material, and environmental data [17]. Complementing traditional documentation, this approach makes it possible to predict degradation processes and assess the impact of environmental factors on the longevity of heritage assets [1, 16, 18].

The study addresses digital documentation at the city scale, encompassing over 100 buildings within the historic centre of Zamość, including public spaces and selected fortification elements. The dataset integrates TLS, UAV-based photogrammetry, and terrestrial photogrammetry.

Another important aspect of heritage protection research is the focus on the intangible dimension of heritage, which allows for a more comprehensive approach to its safeguarding [19]. At the same time, knowledge management in the context of BIM and HBIM is emphasized, leading to the creation of environments that support conservation and documentation processes [20]. The application of BIM in the documentation of historic buildings, including modernist ones, has been highlighted in international research, which points to the possibility of preserving architectural integrity while simultaneously using innovative technologies [21]. In the case of historic buildings, particular attention is also paid to issues related to Eurocodes and the requirements concerning masonry structures [22].

An important trend in the literature also includes emphasizing the significance of life cycle modelling of buildings based on BIM, enabling a holistic assessment of objects in their functional and environmental aspects [23]. At the same time, documentation and data management methods developed by international institutions, such as International Council on Monuments and Sites (ICOMOS) and United Nations Educational, Scientific and Cultural Organization (UNESCO), underline the necessity of integrating digital standards into conservation processes [24].

Research examples demonstrate that the combination of HBIM and digital twin technology may serve as the foundation for modern cultural heritage management systems. Such an approach enables predictive degradation analyses, conservation optimisation, and the integration of energy-related aspects [2, 6, 9]. Such solutions are gaining importance, particularly in the context of integrated approaches to conservation and adaptive planning [5, 17]. It is also noted that the inclusion of artificial intelligence and structural simulations in digital models may enhance their functionality and practical applicability [25]. In this context, the growing role of life cycle analysis and sustainable development aspects is also emphasized [26, 27].

Importantly, the development of digital technologies is also reflected in European regulations and research projects, which set directions for the future of conservation and the modernization of historic objects [28–30]. An example of a research initiative of considerable importance is the EASEE project, which aimed to improve the energy efficiency of multi-family buildings using modern technological solutions [31].

In summary, contemporary approaches to cultural heritage protection are increasingly based on digital tools that enable accurate documentation, analysis, and simulation of the behaviour of historic buildings and urban spaces. The integration of HBIM, scan-to-BIM, and digital twin methods into management processes constitutes a development path that not only enhances the effectiveness of heritage protection but also supports its adaptation to modern functional and environmental needs [3, 4, 12, 16, 19–24, 26].

This article fits into this research trend by focusing on the analysis of cultural heritage in the context of the city of Zamość and by demonstrating how modern digital tools can support documentation, conservation, and adaptive processes in historic urban spaces.

The study attempts to address the research gap concerning the application of integrated digital methods (HBIM, scan-to-BIM, and digital twin) not only to the analysis and documentation of individual objects but also of entire urban complexes.

In this paper, the term ‘city-scale analytical 3D model’ is used to describe a geometrically consistent and semantically enriched representation of the historic urban fabric, without implying the real-time synchronisation typically associated with a full digital twin. The study focuses on scan-to-BIM integration at the district scale, targeting a level of information adequate for conservation-oriented diagnostics and urban-scale assessment rather than detailed component-level HBIM.

The aim of this article is to propose methodological and practical frameworks for documenting and analysing the historic urban fabric of Zamość, enabling the scientific systematisation and advancement of existing research in this area.

2. Methodology

2.1. Justification for the choice of location

Zamość was selected as the subject of research due to its exceptional historical and architectural value, as well as the good availability of data and the presence of active conservation and urban planning initiatives [19, 24]. The city constitutes a coherent urban layout, enabling an analysis of the building structures and their transformations over time.

An additional advantage lies in the diversity of its building stock – ranging from monumental structures, through compact townhouse frontages, to post-industrial developments – which allows for a broad analysis of functions, technical condition, and energy potential. In the face of contemporary challenges related to the use, modernization, and energy efficiency of historic buildings, the development of a 3D model serves as a tool supporting the sustainable management of heritage resources.

The extent of the analysed area is presented in Fig. 1. The map delineates the adopted boundary of the case-study zone, covering the historic core of Zamość and the remains of the former fortress, which constituted the spatial frame for all subsequent acquisition and modelling tasks. This scope was selected to capture the complete set of key heritage structures together with their immediate urban context, while keeping the dataset size feasible for city-scale processing and semantic enrichment. The same spatial extent was also used as a consistent reference for organising datasets and linking building-level records to the 3D model.

FIG. 1. Presentation of the Old Town layout covered by our detailed study.

2.2. Spatial scope of the model

The digital model covered the central part of the Zamość Fortress – the Old Town within the boundaries of the original defensive walls, with particular emphasis on the Great Market Square and the adjoining quarters [18]. The analysis encompassed approximately 100 historic buildings of diverse functions (residential, commercial, and public), supplemented by selected elements of public spaces such as the market square surface, street network, greenery, and fragments of former fortifications. This defined scope enabled to obtain a comprehensive picture of the functioning of the historic centre in urban, technical, and conservation contexts.

2.3. Data acquisition process: photogrammetry and laser scanning

To develop a comprehensive 3D model of the historic centre of Zamość, an integrated spatial data acquisition methodology was applied, combining photogrammetry techniques with TLS [3, 13, 38]. Owing to their complementary properties, this approach made it possible to obtain detailed and precise geometries of heritage buildings while preserving the fidelity of architectural details [4]. The overall workflow of the applied methodology is presented in Fig. 2.

Photogrammetry was carried out both from the ground level (terrestrial photogrammetry) and from the air (aerial photogrammetry using UAVs). In total, more than 4500 digital photographs were taken, covering the entire study area – including roofs, front and rear façades, arcades, and inter-building spaces. The photographs were captured in high resolution (20 megapixels) and with approximate geolocation, facilitating the subsequent photogrammetric processing

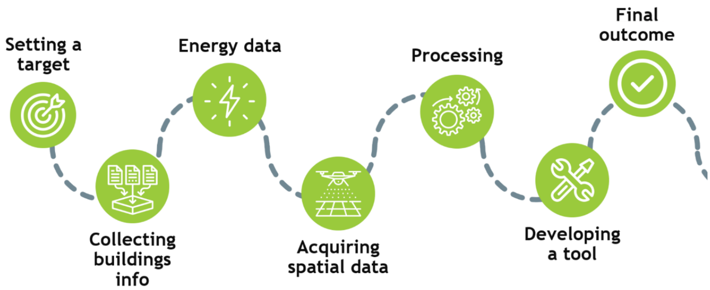


Fig. 2. Workflow of the study.

workflow. The resulting photogrammetry-based point cloud, together with the reconstructed camera positions, is shown in Fig. 3.

Fig. 3. Photogrammetry-derived point cloud and camera network (all image positions) generated in RealityCapture [33].

In parallel, more than 50 laser scans were performed from various static positions, enabling the generation of a dense point cloud representing the actual surfaces of buildings and public spaces. A geodetic-grade scanner was used, providing measurement accuracy at the level of a few millimeters and a range of up to 70 metres [24, 32]. Particular attention was devoted to the precise capture of problematic areas – such as arcade recesses, stonework details, and façade losses – which are often overlooked in standard inventory surveys. The resulting registered TLS point cloud is presented in Fig. 4.

The data acquired through both methods were processed using specialized software: FARO SCENE for the registration and merging of laser scans, and RealityCapture for generating photogrammetric models and textures. The total computation time exceeded 150 working hours, reflecting the high complexity and volume of the processed digital material [32–34].

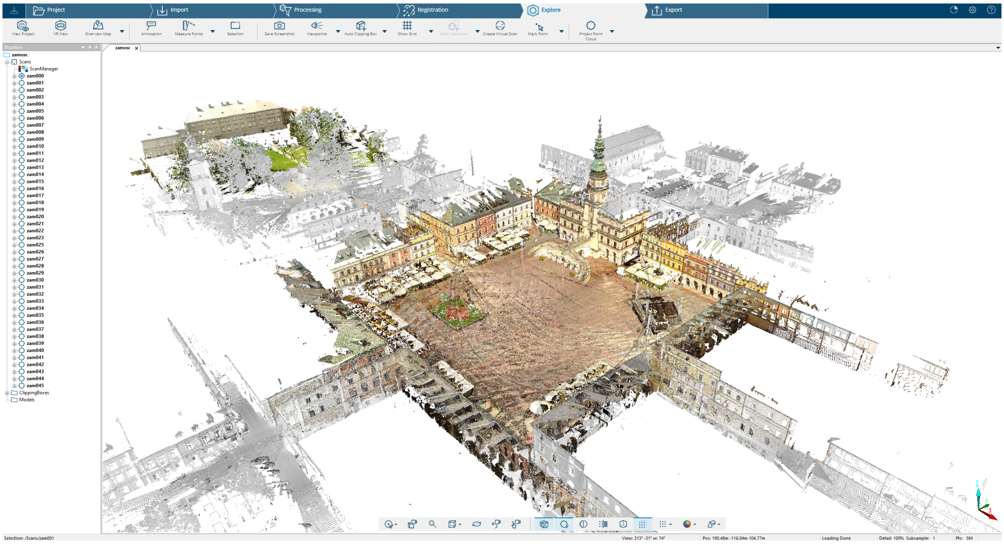


FIG. 4. TLS point cloud processed and registered in FARO SCENE [32].

A summary of the acquisition and processing parameters for photogrammetric and laser scanning data is presented in Table 1, including the number

TABLE 1. Summary of acquisition and processing parameters for photogrammetric and laser scanning data.

Parameter	Photogrammetry (UAV + terrestrial)	Terrestrial Laser Scanning (TLS)	Remarks / Quality assessment
Number of images / scans	Approx. 4500 photographs	Approx. 50 scanning stations	Full coverage of the Old Town area
Measured surface [m^2]	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/m^2]	Approx. 3800	Approx. 31 250	Combined dataset
Registration accuracy (RMSE) [cm/mm]	Approx. 10 cm	Avg. 10 mm	Verified against control points
Coverage scope	Roofs, façades, streets, courtyards	Arcades, portals, hard-to-reach zones	Complementary data
Software	RealityCapture	FARO SCENE	Integration in Revit/IFC
Total computation time [h]	Approx. 150	Approx. 40	Multi-core workstation

of photographs taken, scanning stations, registration accuracy, and the main characteristics of the point clouds.

The presented comparison confirms the complementarity of the two methods – photogrammetry provided full coverage of roofs and façades, while TLS enabled high accuracy in detailed areas and hard-to-reach spaces. Combined, they allowed for the creation of a dense and precise 3D model [36]. The values in Table 1 show that the TLS dataset delivers markedly higher geometric precision (RMSE in the millimetre range) and substantially higher local point density, which is crucial for capturing fine architectural details and documenting vulnerable elements. At the same time, the photogrammetric dataset ensures complete areal coverage of the historic complex – especially roofs and upper elevations – so the integrated workflow balances completeness at the city scale with high-accuracy detail where it is most needed.

2.4. Data integration into the 3D model

The next stage consisted of integrating photogrammetric and laser scanning data within a coherent 3D modelling environment [3, 9, 41]. The base geometric model was generated from the point cloud, which served as the foundation for further reconstruction of building volumes, roofs, façades, and architectural details [2, 5, 10].

The geometric quality of the integrated TLS–photogrammetry dataset was evaluated using registration statistics available from the TLS workflow and independent checkpoints/control points used for verification of alignment. The resulting spatial agreement for the integrated model was typically within 4 cm to 5 cm in representative parts of the study area, which is adequate for city-scale heritage documentation and analytical applications.

Integration of TLS and UAV/terrestrial photogrammetry data (workflow steps):

- TLS registration: individual terrestrial scans were registered into a single coherent point cloud within the TLS workflow (target-/feature-based registration), and its quality was verified using registration statistics and control points,
- photogrammetry processing (UAV + terrestrial): imagery was aligned and processed into a photogrammetry-based point cloud within the same project coordinate context, using the embedded image geolocation as an initial constraint,
- common reference frame: both datasets were brought into a unified spatial reference by applying consistent control points/checkpoints, ensuring direct comparability and minimising systematic offsets,
- dataset integration: the TLS and photogrammetric point clouds were merged into a single coherent dataset, using TLS to stabilise geometry in de-

tailed areas and photogrammetry to complement roofs and visually inaccessible zones,

– quality control: the final alignment was evaluated by independent checkpoints and by reviewing residuals and local deviations in representative areas before exporting the integrated point cloud for subsequent modelling steps.

The final point cloud contained approximately 680 million points, corresponding to an average of about 6200 points/m^2 across nearly 110 000 m^2 of the historic building complex [12]. The highest data density was obtained in the building quarters surrounding the Great Market Square, while in peripheral areas the density was lower due to a reduced number of TLS stations and limited photogrammetric coverage. As a result, the integration stage produced the raw and textured 3D models, together with the consolidated point cloud used in subsequent processing. The integrated TLS–photogrammetry result, processed in RealityCapture, is shown in Fig. 5.

Fig. 5. Integration of TLS point cloud and UAV photogrammetric model for Zamość Old Town (left: raw 3D model, centre: textured 3D model, right: point cloud) visualised in RealityCapture.

2.5. Segmentation of the model according to administrative divisions

The developed 3D model was divided into logical segments corresponding to building quarters and individual structures, in line with the existing administrative and functional divisions. Each building was assigned a unique identifier and linked to a specific spatial unit (street, address number, cadastral parcel) [18, 21, 35]. This allowed the model to be connected with data from municipal resources, including building registries, heritage registers, and energy consumption records [6, 14].

Such segmentation enables end users to easily filter, select, and compare objects in both spatial and technical contexts. For example, it becomes possible to identify all buildings connected to the district heating network, compare their energy demand and thermal insulation condition, and then visualize the results on a 3D map in real time [35]. An overview graphic of this stage is provided in Fig. 6.

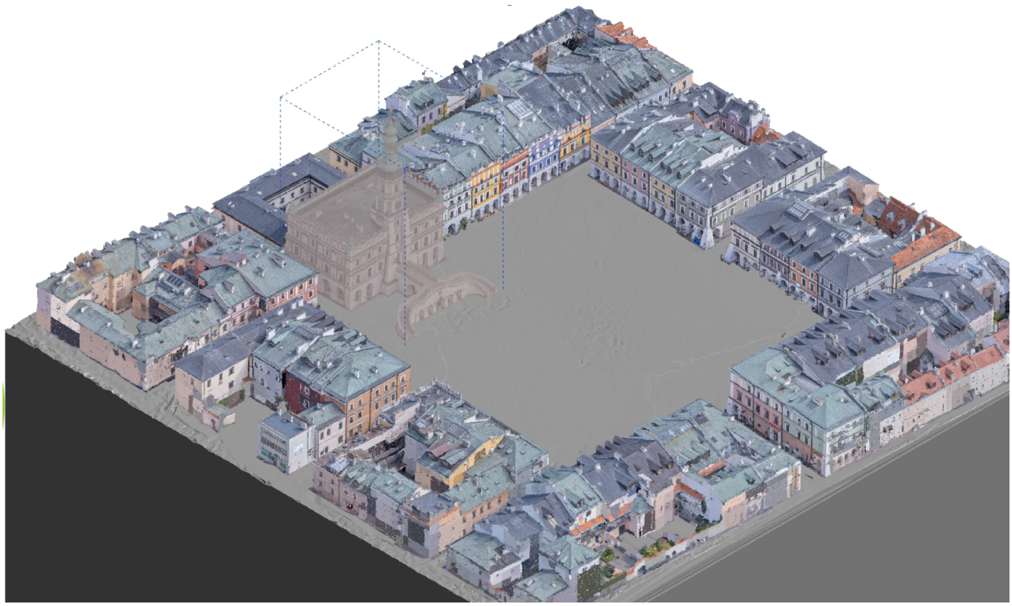


Fig. 6. Example of object selection in the segmented model – individual building elements can be selected independently, rather than selecting the entire model as a single object.

The introduction of the administrative layer also extends the model's applications to spatial planning, urban analyses, public consultations, and educational activities. Moreover, the segmentation establishes a one-to-one mapping between each geometric segment and its semantic record via a unique building identifier, enabling automated linking of spreadsheet/database attributes to BIM objects (Revit/IFC) in subsequent steps.

The spatial data segmented according to administrative divisions were imported into a BIM environment, using software such as Autodesk Revit and data interoperability tools (including CloudCompare and IFC Viewer). At this stage, semantic information was assigned to each model element – both geometric (e.g., façade area, number of floors) and functional-technical (e.g., heating type, roof condition, thermal insulation).

The entire dataset was saved in IFC format, ensuring compatibility with other IT systems and enabling further processing of the model in external analytical environments [14].

Each geometric segment created during segmentation was assigned a unique BuildingID/ObjectID, which served as the primary key linking geometry to the corresponding row in the attribute table. This established a one-to-one mapping between model objects and semantic records, enabling automated parameter assignment and reducing manual errors.

2.6. Preparation of descriptive data and preliminary analysis

In parallel with the development of the geometric model, a process was carried out to collect descriptive (semantic) data for all buildings included in the model [6, 7, 20]. This information was gathered from various sources, including:

- resources of the Department of Investment and Development of the City of Zamość,
- municipal building registries,
- geodetic and urban planning documentation,
- materials prepared by conservation and technical units.

The collected dataset covered more than 100 buildings, with each assigned a set of over 10 descriptive parameters, including:

- address and functional use,
- building footprint and number of storeys,
- technical condition of façades, roofs, and joinery,
- type of heating system and heat source,
- level of insulation of external partitions (walls, roof),
- presence and type of renewable energy sources,
- estimated annual energy demand.

The data were standardised and entered into spreadsheets, and then imported into the BIM modelling environment [21, 34]. By assigning unique identifiers to the buildings (consistent with the Revit/IFC system), it was possible to automatically link the data to the corresponding objects in the model. The entire process was carried out in a way that enables future data synchronisation – for example, in the event of updates [37]. An overview graphic of this stage is provided in Fig. 7.

In addition, a preliminary analysis of the collected data was carried out, which made it possible to determine the typology of buildings, identify structures in poor technical condition, and highlight special cases (e.g., buildings not connected to the district heating network, or those using heat pumps, etc.) [23].

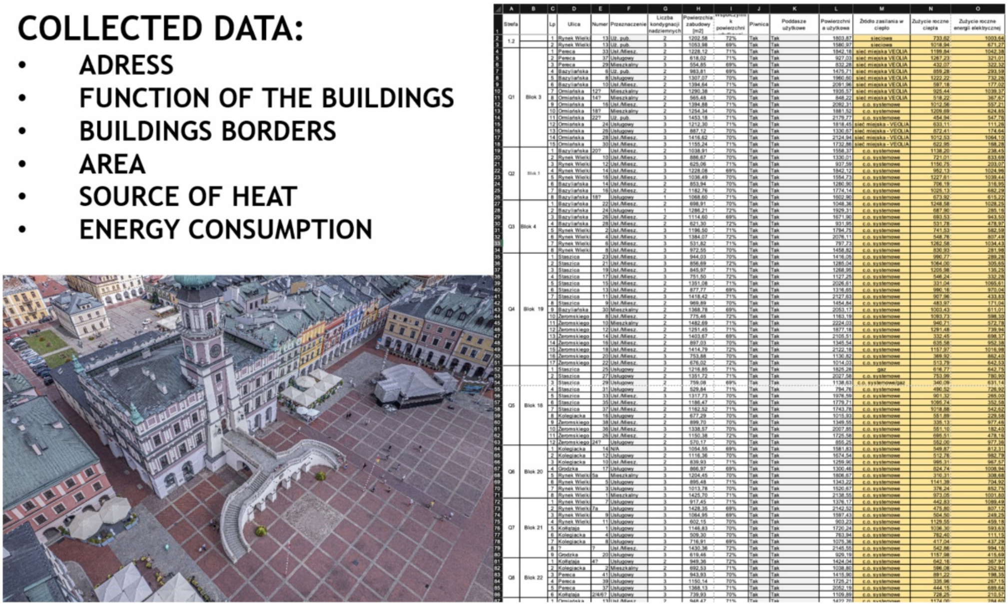


Fig. 7. Data standardisation process illustrated by a fragment of the semantic attribute table shown in Microsoft Excel (XLSX/CSV table).

This analysis served as the starting point for the further classification of objects into appropriate conservation and energy-related categories.

Semantic attributes were stored in structured spreadsheets (XLSX/CSV) following a 'one record–one building' rule. The dataset was standardised using controlled vocabularies, predefined units, and value ranges to reduce ambiguity and ensure consistent querying. Prior to BIM import, the tables were validated for completeness, data types, and uniqueness of identifiers (missing values, duplicates, and out-of-range entries were flagged and corrected).

2.7. Process structure and workflow organization

The overall methodology was structured as a coherent, iterative workflow consisting of seven consecutive stages, consistent with the scheme presented in Fig. 2. The stages were implemented with feedback loops between data acquisition, processing, and validation, to ensure both geometric reliability and semantic consistency of the analytical model [6, 9, 14]:

– setting a target (Subsec. 2.1) – defining the intended use of the model (heritage documentation, conservation-oriented diagnostics, and urban/energy-related analyses), establishing the spatial extent and level of detail, and formulating the key outputs expected from the digital twin [15, 17],

– collecting building information (Subsec. 2.6) – compiling the base inventory of buildings and public-space elements included in the study, assigning unique identifiers, and gathering core administrative and descriptive attributes required for subsequent integration and database structuring [6, 20],
– Energy data (Subsec. 2.6) – collecting and standardising energy-related attributes (e.g., heating type, estimated energy demand, insulation status, and related indicators) as a dedicated subset of the semantic dataset, using unified scales and controlled vocabularies to enable subsequent filtering and comparative analyses [27, 29],
– acquiring spatial data (Subsec. 2.3) – performing UAV and terrestrial photogrammetry operations and terrestrial laser scanning to capture complementary spatial datasets covering roofs, façades, streets, courtyards, and difficult-to-reach architectural details, while maintaining consistent referencing of the acquired material [11, 32, 38],
– processing (Subsec. 2.4) – registering and merging TLS scans, processing photogrammetric imagery, integrating both sources into a coherent spatial dataset, and generating the base geometric representation used for further reconstruction, segmentation, and preparation for information enrichment [3, 10, 36],
– developing a tool (Subsec. 3.3) – importing the segmented model into the BIM environment, assigning semantic information through dedicated parameters linked by unique identifiers, exporting structured outputs (e.g., IFC), and implementing an interactive digital twin interface enabling attribute-based visualisation, filtering, and reporting [1, 6, 14],
– final outcome (Subsec. 4.1) – obtaining an analytical, city-scale 3D model integrating geometry and standardised descriptive/energy data, prepared for multi-criteria assessments and future updates, with documented procedures supporting reproducibility and transferability to other historic urban contexts [17, 23, 25].

2.8. Methodological conclusions

The adopted approach proved both effective and scalable, allowing for the development of a highly detailed, segmented urban model that can be expanded and updated in subsequent stages [1, 9]. The key success factors included:
– the use of complementary technologies (laser scanning + photogrammetry) [5],
– the application of BIM and IFC standards as a common data integration language,

– precise coordination of geometric and descriptive data,
– the ability to perform multi-criteria analyses of diverse object attributes.

The developed methodology can serve as a model for other cities and research teams engaged in the documentation and analysis of cultural heritage in spatial terms. In the next stages, the model's application is planned to be extended with additional diagnostic and analytical functionalities, which will be discussed in later sections of the article [17].

3. Semantic data management

3.1. Categories of information assigned to model segments

One of the key elements in building the analytical model of the Zamość Fortress was the development of a semantic data structure, i.e., descriptive information linked to the geometric representations of buildings [1, 20]. These data serve as the basis for conducting technical, energy-related, functional, and conservation analyses [11].

For each building in the model, a standardised set of parameters – organised into logical thematic categories – was assigned, defined based on ISO 19650 principles and structured according to IFC4 Property Set logic.

Identification and location:
– address (street, number),
– cadastral parcel number,
– Revit/IFC identifier.

Functional and usage-related:
– main building function (residential, commercial, institutional),
– attic accessibility (usable/non-usable),
– number of above-ground and underground floors.

Geometric parameters:
– building footprint,
– usable floor area (if available),
– volume (for selected objects).

Technical condition:
– assessment of façade, roof, and window/door joinery condition,
– moisture level in basements,
– technical condition of sanitary installations.

Energy and environmental characteristics:
– type of heating (district heating, gas, biomass, heat pump, none),
– estimated annual energy demand [kWh/m^2/year],

– level of wall and roof insulation,
– presence of renewable energy sources (PV, collectors, heat pumps).

The parameters were defined with explicit units and data types, using consistent naming conventions and controlled vocabularies where applicable, to ensure validation, comparability, and seamless mapping to IFC4 Property Sets for interoperable analysis.

This set of attributes was standardised in the form of input data tables (spreadsheets in CSV/XLSX format) and subsequently linked to the 3D models through unique identifiers assigned to each object. The data were categorised in a way that enabled easy filtering and grouping of buildings according to any criterion (e.g., all residential buildings with non-modernised roofs and gas heating) [23].

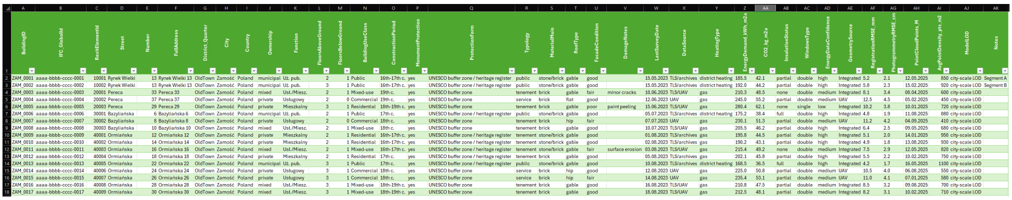
3.2. *Database structure*

For the purposes of the model, a flat relational database was developed, based on a 'one row – one building' scheme, with columns corresponding to descriptive parameters [21]. The database schema was adapted to the data import format for the BIM environment (Autodesk Revit) and for further analysis in external tools (e.g., CloudCompare, CellBIM).

Selected features of the data structure include:

– all fields were standardised (e.g., technical condition rating scales from 1 to 5, functional codes consistent with the national statistical classification – Główny Urząd Statystyczny (GUS)) [34],
– data types were clearly assigned (text, integer, floating-point number, Boolean value),
– consistency control was introduced (range validation, no duplicates, uniqueness of identifiers) [34].

An illustrative view of the implemented database schema and example records is shown in Fig. 8.



BuildingID	IFC_GlobalId	RevitElementId	Street	Number	FullAddress	District_Quarter	City	Country	Ownership	Function
ZAM_0001	aaaa-bbbb-cccc-0001	10001	Rynek Wielki	13	Rynek Wielki 13	OldTown	Zamość	Poland	municipal	Uż. pub.
ZAM_0002	aaaa-bbbb-cccc-0002	10002	Rynek Wielki	13	Rynek Wielki 13	OldTown	Zamość	Poland	municipal	Uż. pub.
ZAM_0003	aaaa-bbbb-cccc-0003	20001	Pereca	33	Pereca 33	OldTown	Zamość	Poland	mixed	Usł./Miesz.
ZAM_0004	aaaa-bbbb-cccc-0004	20002	Pereca	37	Pereca 37	OldTown	Zamość	Poland	private	Usługowy
ZAM_0005	aaaa-bbbb-cccc-0005	20003	Pereca	29	Pereca 29	OldTown	Zamość	Poland	private	Mieszkalny
ZAM_0006	aaaa-bbbb-cccc-0006	30001	Bazyliańska	6	Bazyliańska 6	OldTown	Zamość	Poland	municipal	Uż. pub.
ZAM_0007	aaaa-bbbb-cccc-0007	30002	Bazyliańska	8	Bazyliańska 8	OldTown	Zamość	Poland	private	Usługowy
ZAM_0008	aaaa-bbbb-cccc-0008	30003	Bazyliańska	10	Bazyliańska 10	OldTown	Zamość	Poland	mixed	Usł./Miesz.
ZAM_0009	aaaa-bbbb-cccc-0009	40001	Ormiańska	12	Ormiańska 12	OldTown	Zamość	Poland	private	Mieszkalny
ZAM_0010	aaaa-bbbb-cccc-0010	40002	Ormiańska	14	Ormiańska 14	OldTown	Zamość	Poland	private	Mieszkalny
ZAM_0011	aaaa-bbbb-cccc-0011	40003	Ormiańska	16	Ormiańska 16	OldTown	Zamość	Poland	mixed	Usł./Miesz.
ZAM_0012	aaaa-bbbb-cccc-0012	40004	Ormiańska	18	Ormiańska 18	OldTown	Zamość	Poland	private	Mieszkalny
ZAM_0013	aaaa-bbbb-cccc-0013	40005	Ormiańska	22	Ormiańska 22	OldTown	Zamość	Poland	municipal	Uż. pub.
ZAM_0014	aaaa-bbbb-cccc-0014	40006	Ormiańska	24	Ormiańska 24	OldTown	Zamość	Poland	private	Usługowy
ZAM_0015	aaaa-bbbb-cccc-0015	40007	Ormiańska	26	Ormiańska 26	OldTown	Zamość	Poland	private	Usługowy
ZAM_0016	aaaa-bbbb-cccc-0016	40008	Ormiańska	28	Ormiańska 28	OldTown	Zamość	Poland	mixed	Usł./Miesz.
ZAM_0017	aaaa-bbbb-cccc-0017	40009	Ormiańska	30	Ormiańska 30	OldTown	Zamość	Poland	mixed	Usł./Miesz.

BuildingID	FloorsAboveGround	FloorsBelowGround	BuildingUseClass	ConstructionPeriod	MonumentProtection	ProtectionForm	Typology	MaterialMain	RoofType	FacadeCondition	DamageNotes	LastSurveyDate
ZAM_0001	2	1	Public	16th-17th c.	yes	UNESCO buffer zone / heritage register	public	stone/brick	gable	good		15.05.2023
ZAM_0002	3	1	Public	16th-17th c.	yes	UNESCO buffer zone / heritage register	public	stone/brick	gable	good		15.05.2023
ZAM_0003	2	1	Mixed-use	19th c.	yes	UNESCO buffer zone	tenement	brick	gable	fair	minor cracks	10.06.2023
ZAM_0004	2	0	Commercial	19th c.	yes	UNESCO buffer zone	service	brick	flat	good		12.06.2023
ZAM_0005	3	1	Residential	18th-19th c.	yes	UNESCO buffer zone	tenement	brick	gable	poor	paint peeling	15.06.2023
ZAM_0006	2	1	Public	17th c.	yes	UNESCO buffer zone / heritage register	public	stone/brick	gable	good		05.07.2023
ZAM_0007	2	0	Commercial	18th c.	yes	UNESCO buffer zone	tenement	brick	hip	fair		07.07.2023
ZAM_0008	2	1	Mixed-use	18th c.	yes	UNESCO buffer zone	tenement	brick	gable	good		10.07.2023
ZAM_0009	2	1	Residential	16th-17th c.	yes	UNESCO buffer zone / heritage register	tenement	stone/brick	gable	good		01.08.2023
ZAM_0010	2	1	Residential	16th-17th c.	yes	UNESCO buffer zone / heritage register	tenement	stone/brick	gable	good		02.08.2023
ZAM_0011	2	1	Mixed-use	16th-17th c.	yes	UNESCO buffer zone / heritage register	tenement	stone/brick	gable	fair	surface erosion	03.08.2023
ZAM_0012	2	1	Residential	17th c.	yes	UNESCO buffer zone / heritage register	tenement	brick	gable	good		05.08.2023
ZAM_0013	3	1	Public	17th c.	yes	UNESCO buffer zone / heritage register	public	stone/brick	gable	good		10.08.2023
ZAM_0014	3	1	Commercial	18th c.	yes	UNESCO buffer zone	service	brick	hip	good		12.08.2023
ZAM_0015	3	1	Commercial	18th c.	yes	UNESCO buffer zone	service	brick	hip	fair		14.08.2023
ZAM_0016	3	1	Mixed-use	18th-19th c.	yes	UNESCO buffer zone	tenement	brick	gable	good		16.08.2023
ZAM_0017	3	1	Mixed-use	18th-19th c.	yes	UNESCO buffer zone	tenement	brick	gable	good		18.08.2023

BuildingID	DataSource	HeatingType	EnergyDemand_kWh_m2a	CO2_kg_m2a	InsulationStatus	WindowsType	EnergyDataConfidence	GeometrySource	RegistrationRMSE_mm	PhotogrammetryRMSE_cm	PointCloudPoints_M	AvgPointDensity_pts_m2	ModelLOD	Notes
ZAM_0001	TLS/archives	district heating	185.5	42.1	partial	double	high	Integrated	5.2	2.1	12.05.2025	850	city-scale LOD	Segment A
ZAM_0002	TLS/archives	district heating	192.0	44.2	partial	double	high	Integrated	5.8	2.3	15.02.2025	920	city-scale LOD	Segment B
ZAM_0003	TLS/UAV	gas	210.3	48.5	none	double	medium	Integrated	8.1	3.4	08.04.2025	600	city-scale LOD	
ZAM_0004	UAV	gas	245.0	55.2	partial	double	medium	UAV	12.5	4.5	05.02.2025	450	city-scale LOD	
ZAM_0005	TLS/UAV	gas	280.4	62.1	none	single	low	Integrated	10.2	3.8	10.01.2025	720	city-scale LOD	
ZAM_0006	TLS/archives	district heating	175.2	38.4	full	double	high	Integrated	4.8	1.9	11.08.2025	880	city-scale LOD	
ZAM_0007	UAV	gas	230.1	51.3	partial	double	medium	UAV	11.2	4.2	04.09.2025	410	city-scale LOD	
ZAM_0008	TLS/UAV	gas	205.5	46.2	partial	double	high	Integrated	6.4	2.5	09.05.2025	680	city-scale LOD	
ZAM_0009	TLS/archives	gas	195.8	44.5	partial	double	high	Integrated	5.1	2.0	14.01.2025	950	city-scale LOD	
ZAM_0010	TLS/archives	gas	190.2	43.1	partial	double	high	Integrated	4.9	1.8	13.08.2025	930	city-scale LOD	
ZAM_0011	TLS/UAV	gas	215.4	49.2	none	double	medium	Integrated	7.5	2.9	12.05.2025	820	city-scale LOD	
ZAM_0012	TLS/archives	gas	202.1	45.8	partial	double	high	Integrated	5.5	2.2	10.02.2025	750	city-scale LOD	
ZAM_0013	TLS/archives	district heating	168.5	36.5	full	double	high	Integrated	4.2	1.7	16.05.2025	1100	city-scale LOD	
ZAM_0014	UAV	gas	225.0	50.8	partial	double	medium	UAV	10.5	4.0	06.08.2025	550	city-scale LOD	
ZAM_0015	UAV	gas	235.4	53.1	partial	double	medium	UAV	11.0	4.1	07.01.2025	580	city-scale LOD	
ZAM_0016	TLS/UAV	gas	210.8	47.5	partial	double	medium	Integrated	8.5	3.2	09.08.2025	700	city-scale LOD	
ZAM_0017	TLS/UAV	gas	212.5	48.1	partial	double	medium	Integrated	8.2	3.1	10.02.2025	710	city-scale LOD	

Fig. 8. Example of the building-attribute database used in the workflow (Subsec. 3.2), implemented as a structured Microsoft Excel table following the 'one record–one building' rule, with unique BuildingID and BIM linkage keys (IFC_GlobalId, RevitElementId), and grouped fields covering administrative, heritage, energy, and geometry/quality parameters for subsequent mapping to BIM objects and IFC Property Sets.

The data are stored in a way that enables updating – changes in the database can be automatically synchronised with the 3D model via assigned IDs and corresponding family parameters (Revit Families) [20, 37].

3.3. Integration of data with the 3D model

In Autodesk Revit, semantic information was implemented as dedicated project/shared parameters, grouped into thematic sets (administrative, heritage, and energy-related). Parameter values were populated from the validated tables using the BuildingID/ObjectID key (semi-automated assignment), ensuring that each BIM object inherits the correct attributes. The enriched model was exported to IFC4, where the attributes were preserved as Property Sets linked to the corresponding geometric elements, enabling consistent use in external analytical environments.

The integration of semantic data with the 3D model was carried out in two stages:

1. Import into the BIM environment (Autodesk Revit)
   The spatial model was enriched with descriptive data through dedicated project parameters. Each object was assigned fields containing information from the input table. An overview illustration of this stage is presented in Fig. 9.
2. Synchronisation with analytical tools (e.g., CellBIM, CloudCompare)
   Data export was carried out in IFC4 format, compliant with the international standard for building information exchange [34]. This enabled the use of the model in external environments (including CellBIM for

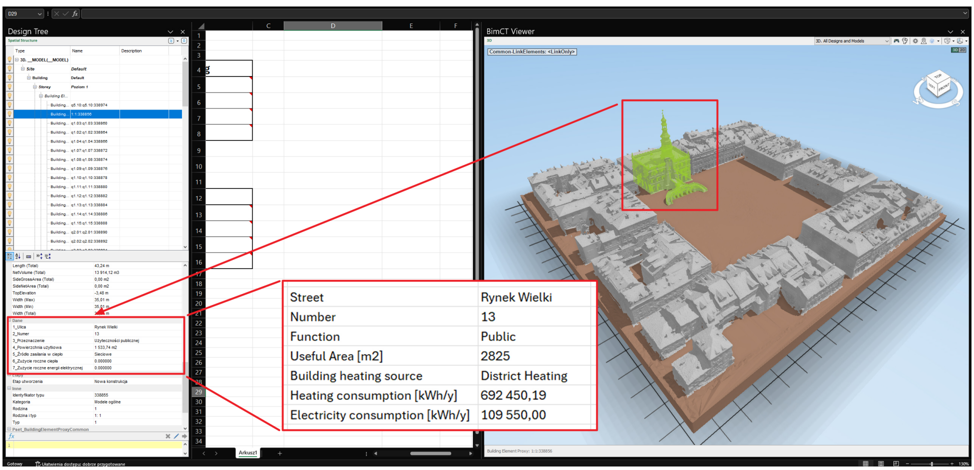


Fig. 9. Integration of data with the 3D Model. The IFC model is presented in Microsoft Excel with the CellBIM add-in, illustrating how object-level attributes are accessible as Property Sets for analysis and verification.

data analysis and CloudCompare for 3D data visualisation) [18]. In these environments, the data were read as Property Sets linked to geometric objects [34]. To demonstrate the effect of semantic enrichment, a sample building object is shown in Fig. 10 with its assigned parameter set. The same attributes are readable after IFC export as Property Sets, enabling attribute-based filtering and inspection in external tools.

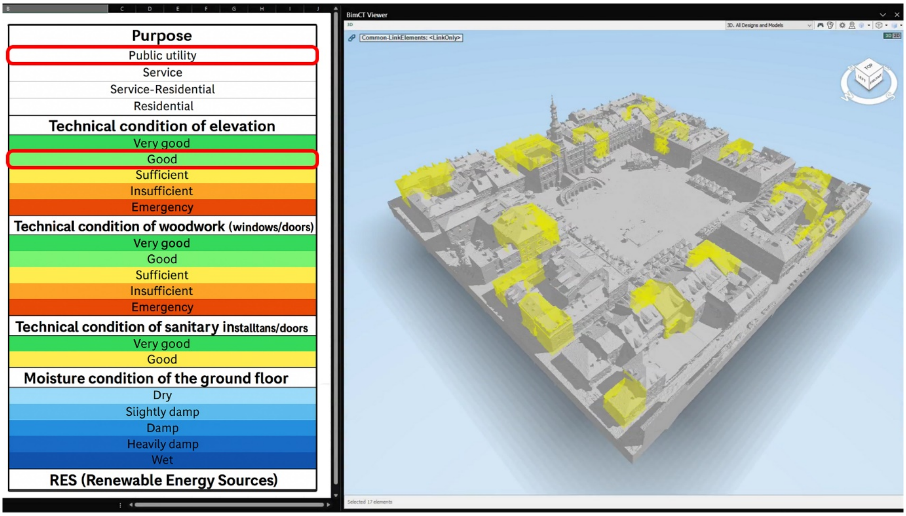


Fig. 10. Synchronisation of the enriched IFC4 model with external analytical tools for querying and visualisation. The figure presents an attribute-based inspection of Property Sets using tools such as CellBIM (data analysis), supporting filtering and verification of semantic information against the geometry.

The functionality of creating colour-coded attribute maps was also utilised – for example, to graphically represent energy consumption levels, insulation quality, or the condition of building elements [40]. This facilitates visual analysis and the identification of problematic objects within the historic urban fabric.

4. Results and conclusions

4.1. Assessment of the effectiveness of the approach

The effectiveness of the proposed workflow was evaluated using four criteria: geometric accuracy and alignment of the integrated spatial datasets, coverage and scalability at the level of the historic city centre, semantic completeness and consistency of the attribute database, and interoperability and usability of the enriched model in external analytical environments. The resulting analytical model covers more than 100 buildings within the historic centre and combines city-scale geometry with standardised descriptive information [34, 36, 41].

From a technical perspective, the following evidence was obtained:

– Geometric accuracy and alignment: the quality of the integrated TLS–photogrammetry dataset was verified using registration statistics from the TLS workflow and independent checkpoints/control points. In representative parts of the study area, the resultant spatial agreement after integration was typically within 4 cm to 5 cm, which is suitable for city-scale heritage documentation and comparative analyses [36];
– Coverage and scalability: the acquisition strategy ensured complementary coverage of roofs, façades, streets, courtyards, and hard-to-reach zones by combining UAV/terrestrial photogrammetry with terrestrial laser scanning, enabling a coherent representation of the historic urban fabric at the scale of the entire pilot area [41];
– Semantic completeness and consistency: a flat 'one row – one building' database was implemented with standardised fields, controlled vocabularies and range validation, and unique identifiers used as keys for automated linking between geometry and attributes. In the presented implementation, each building was described by a consistent core set of parameters (e.g., function, typology, condition and selected energy indicators), enabling repeatable querying and future updates without breaking the ID mapping [34];
– Interoperability and usability: the enriched model was exported in IFC4 and verified by reading the assigned Property Sets in external environments (e.g., CellBIM for attribute inspection and CloudCompare for 3D visualization). In addition, the interactive tool was tested on the 100-building dataset, supporting object-level selection and attribute-based exploration in a web-based context [34, 41].

Overall, the results demonstrate that the integration of heterogeneous sources (spatial surveys and administrative/heritage/energy attributes) can be implemented in a reproducible way, enabling practical heritage-management use cases such as condition screening, multi-criteria comparisons, and identification of modernisation potential at the scale of a historic town centre [34, 41].

4.2. Examples of applications in urban analysis

Based on the developed model, a series of thematic analyses were conducted, the results of which can be treated as direct indicators of the tool's usefulness. Selected examples include:

– Functional analysis revealed that a significant share of service-oriented buildings is concentrated around the Great Market Square, with a tendency to disperse toward the eastern quarters. This finding may serve as a basis for the revitalisation of residential buildings and their adaptation to commercial functions in line with conservation guidelines [39];

- Technical condition analysis enabled the identification of buildings requiring urgent conservation interventions (e.g., structures with leaky roofing or visible damage to joinery or façades). Such information can support the activities of municipal heritage protection services [11, 22];
- Energy analysis made it possible to identify buildings with the highest estimated energy demand (above 250 kWh/m^2/year), mainly in structures with unused attics, outdated heating systems, or a lack of partition insulation [26, 29, 31]. These results can serve as a foundation for planning thermal modernisation actions.

All of the above data were presented in real time within the interactive environment, with options for exporting reports and filtering results according to selected criteria.

4.3. Potential for tool development

The developed digital model and analytical tool represent only the first stage of a broader system supporting cultural heritage management in historic cities [8, 17]. In subsequent stages, the following development directions are possible:

- integration with temporal data – introducing change histories for each building, enabling the analysis of urban space transformations over time (e.g., renovations, functional changes, structural modifications) [37],
- real-time updating – implementing a synchronisation system with municipal cadastral databases (e.g., GESUT, EGiB, MPZP), allowing for the automatic refreshing of the model and descriptive data [35],
- extension to additional city areas – the scalability of the method makes it applicable not only within the boundaries of the Old Town but also in adjacent districts, including 19th- and 20th-century heritage sites [41],
- introduction of a participatory layer – enabling residents, investors, or researchers to add annotations and submit comments on individual objects, while maintaining expert oversight and content validation.

5. Final summary

The conducted research confirmed that modern digital documentation technologies can be effectively used not only for inventory purposes but, above all, as analytical tools supporting rational and sustainable cultural heritage management. The case of the Zamość Fortress demonstrated that it is possible to reconcile documentation precision with practical applications in planning, energy management, conservation, and education. The developed model may provide a reference model for other cities and institutions seeking to implement digital twins in heritage protection.

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