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3D DATA ACQUISITION FOR SPATIO-TEMPORAL ANALYSIS OF ARCHITECTURAL AND URBAN ENVIRONMENT CHANGES OF WROCŁAW CATHEDRAL

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A b s t r a c t

This paper presents a method for preparing digital spatial data to study the spatio-temporal evolution of the urban and architectural environment. Methods for comparing spatial data from different periods allows a comprehensive spatial and temporal analysis of architectural changes and the urban environment surroundings of the Wroclaw Cathedral. The data can be obtained through digital surveying using various methods, digitization of architectural plans, old maps and iconographic sources, and downloading of current databases. The study of architectural change in historic buildings and changes in their surroundings is an important aspect of cultural heritage research. The use of digital spatial data makes it possible to analyse spatio-temporal data from different time periods and to trace their historical context. Capturing this data in digital form and storing it in a multi-resolution database allows comprehensive comparisons to be made and provides a broader general view of history.

Keywords: spatio-temporal analysis, digital spatial data, multi-resolution database, Wrocław cathedral

1. INTRODUCTION

The dynamic development of computer tools and their software has resulted in the collection, analysis and modelling of large complex data sets, both qualitative and quantitative. The modern tools of cartography 4.0 have made it possible to generate and make available to users, almost in real time, purposefully selected graphic and descriptive geographical information, enabling a multifaceted understanding of the world around us. The new forms of 2D, 3D, 4D and next-dimensional models have enriched the transmission of information, opening up other, hitherto untapped properties for perceiving not only present reality, but also for deepening the connection with the past, analysing the various stages of the creation and registration of spatial information, and predicting the effects of prospective changes

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in the parameters describing the future. The constant change of conditions shaping space and the multifaceted nature of the measurement processes, the influence of policy on the registration of property statuses, the temporal legal conditions and the way in which real estate is managed necessitate an interdisciplinary study of space. The requirements of the users make it necessary to adapt the GIS tools and, in the research described here, the HGIS (acronym for Historical Geographical Information System) to current needs. Reliable analysis of documents until recently often requires going back to the archives and starting from scratch again.

Through a comprehensive study of historical documents, architectural drawings, building records, maps, aerial photographs and other relevant sources [1], it is possible to trace the evolution of the form and function of historic buildings, as well as their impact on the infrastructure of its surroundings and the urban landscape.

Advanced digital technologies such as laser scanning, photogrammetry and geographic information systems (GIS) are used for spatio-temporal analyses. These technologies enable the creation of detailed 3D models, virtual reconstructions and interactive visualisations.

The documentation of architectural monuments is an important part of heritage conservation efforts. Accurate mapping of the current state of objects not only makes it possible to record them in detail, but also supports conservation processes, the planning of restoration and reconstruction work and the monitoring of any structural changes that may occur in the future. However, traditional inventory methods, based on manual measurements and the creation of technical documentation, can sometimes be time-consuming and do not always provide sufficient accuracy. In the face of today's needs for documenting historic buildings, modern digital technologies and photogrammetric methods are playing an increasingly important role, allowing rapid and detailed mapping of architecture in the form of multifunctional 3D models and accurate drawings. With its high resolution and ability to accurately represent details, this technique is very helpful for conservation work.

Various imaging techniques are now being used. Mapping, i.e. the creation of accurate maps and models, plays a key role in the documentation of historic buildings [2, 3]. It is used both to record architectural details and to analyse the technical condition of buildings. Advanced mapping techniques, such as laser scanning, photogrammetry or thermal imaging, enable the creation of detailed surface maps that can be analysed for cracks, deformation or other structural damage. In the context of heritage documentation, mapping also allows the integration of data from different sources, creating a comprehensive picture of an object that can be used for scientific, educational or conservation purposes. This makes it possible not only to preserve cultural heritage in digital form, but also to effectively plan restoration work and prevent further degradation of historic buildings.

Laser scanning, which is one of the most accurate methods, is mainly used for the inventory of large, complex structures. Terrestrial laser scanning (TLS) is a measurement technology that allows accurate representation of space in the form of a 3D point cloud [4].

The use of photogrammetric methods is dictated by their wide-ranging capabilities, such as high mapping accuracy, registration of detailed surface and material information and the versatility of the resulting models. details, which facilitates analysis and orientation in documentation.

UAVs have become a valuable tool in photographic documentation, allowing them to reach places inaccessible to traditional methods. They can record an object from above, which is particularly useful in the case of ruins, allowing their shape to be fully mapped.

A non-metric camera provides additional visual information, including colour, which enriches the model with a realistic representation.

Photographic documentation of sites, sometimes supported by a photogrammetric inventory, is important to create a complete visual record. It includes an inventory and description of the photographs and a layout plan of the photographic sites. The photographs should show the site from all sides.

Photogrammetry, like photography, creates images of objects and allows perspective distortions to be eliminated. This technique allows accurate measurements to be obtained without physical contact with the building, which is particularly valuable for objects that are difficult to access. Photogrammetric images, known as photograms, reproduce detailed information about the shapes and proportions of objects, making them valuable archival material, particularly useful for historic buildings [5].

Integrating the data allows a complete picture of the object to be created, which can be further analysed in terms of its structure and aesthetic qualities.

The subject of the presented research is the Wrocław Cathedral (fig. 1), which is one of the most important architectural and cultural monuments in Wrocław. The analysis of its architectural and urban changes, as well as the surrounding urban environment, is crucial to understanding its role in the city's history. This study uses digital spatial data (digitally acquired and digitised [6]) to accurately trace the spatio-temporal changes of the cathedral and its surroundings.

Fig. 1. Wrocław Cathedral 20/09/2024 (flooding)

A key objective of this research will be to document the architectural transformation that the cathedral has undergone, from its initial construction phase to its present form. Furthermore, by examining the construction techniques and materials used, it is possible to better understand the challenges faced by the builders and the development of construction techniques over the centuries.

In addition to the architectural evolution, the relationship of the cathedral to its urban context has also undergone significant changes over time. By examining the development of neighbouring buildings, the configuration of public spaces and the wider urban fabric, it is possible to analyse how the cathedral has influenced the spatial organisation of the city. Through comparative analysis of old maps and contemporary spatial data, we can identify changes in the intensity and height of development around the cathedral.

In the context of the historical analysis of the cathedral, the impact of significant historical events on the architecture is important. Wars, natural disasters and social change have left their mark on historic buildings, leading to both destruction and reconstruction. By examining post-war reconstruction efforts, we can explore the role of heritage conservation and restoration in shaping the cathedral's contemporary identity.

By analysing these digital representations, it is possible to visualise the appearance of the cathedral in different historical periods. Furthermore, by combining digital data with historical research, we can develop a more comprehensive representation of the evolution of the building.

This research aims to provide valuable information on the future conservation and management of Wrocław Cathedral. By understanding the historical development of the cathedral and the contemporary challenges, effective strategies can be developed to protect the cultural heritage and ensure its continuation for future generations.

2. THEORETICAL FRAMEWORK

In the strategy for acquiring digital heritage documentation, objective objectives and criteria must be defined, e.g. natural and anthropogenic threats, scarcity of digital documentation, scientific, historical and artistic values of monuments, buildings, cultural and heritage sites. In order to provide a comprehensive common digital data space for cultural heritage, the inventory work of old documents and documents created nowadays must be carried out in multidisciplinary teams. The key theoretical foundations come from architectural history, urban history and surveying and cartographic sciences. The digitisation of cultural heritage should follow the guidelines of the Commission Expert Group on the Common European Data Space for Cultural Heritage (CEDCHE). CEDCHE reviews and discusses policies on digital cultural heritage and the forthcoming Common European Data Space initiative. It also facilitates the exchange of information and good practice, working closely with cultural institutions.

The CEDCHE guidelines [7] for the digitisation of cultural heritage place great emphasis on strategic planning and proper management of digitisation processes. Cultural institutions should prioritise the digitisation of the most valuable or endangered resources. It is important to take into account a long-term vision, including the sustainability of digital resources and their preservation and accessibility.

In technical terms, the guidelines point to the need to use standards for image quality, file formats and metadata that ensure interoperability. It is recommended to use formats such as TIFF for archiving and the Europeana Data Model for metadata. Safeguarding digitised data and creating backups is an important element.

The guidelines also emphasise the importance of open access to resources, according to the FAIR (Findable, Accessible, Interoperable, Reusable) principles, while respecting copyright. The use of licences, such as Creative Commons, is recommended where possible to facilitate the reuse of materials. Collaborating with platforms such as Europeana allows for a wider reach and accessibility of digitised heritage, which is in line with the idea of interoperability and data sharing.

Another key element is the sustainability of digital assets. The guidelines impose the need to regularly migrate data to new media and formats to prevent data loss. All digitisation and preservation processes should be carefully documented.

The public involvement aspect also plays an important role. Institutions are encouraged to work with local communities and volunteers, which can include activities such as crowdsourcing when describing collections. The creation of educational tools and interactive applications allows for wider user involvement and promotion of digitised cultural heritage.

Taking these guidelines into account, a data acquisition plan was developed to analyse the spatio-temporal evolution of the Wrocław Cathedral. St. John the Baptist Archcathedral in Wrocław is a monument of high historical and stylistic value, with relatively large dimensions and formal complexity. The Wrocław cathedral is one of the oldest cathedral churches in Poland and played an important role in the process of christianization of Silesia. The existing cathedral is the fourth standing in this location. The Wrocław cathedral is an object with special tangible and intangible values, having great significance for the Polish cultural heritage. It presents above average architectural values, retains the original spatial composition and original relations with the surrounding. The cathedral is located on Ostrów Tumski - a place of great aesthetic and historical value, which is famous, above all, for the numerous and well-preserved medieval and baroque historic buildings.

The Wrocław cathedral has been surveyed in the past by various traditional measuring methods, which will be a comparative material to the research carried out under the study. Currently, the monument does not have sufficiently accurate documentation of its state.

By examining historical documents, architectural drawings and building records, researchers can trace the development of the form and function of the historic cathedral in question over time. This includes an analysis of the different architectural styles and spatial and functional transformations of the building, such as Gothic and Baroque. The temporal scope of the study is the architectural substance created from the 13th century to the present day.

By analysing historical maps, aerial photographs and other spatial data, researchers can study changes in the urban fabric over time. This includes examining the development of neighbouring buildings, public spaces and the wider urban infrastructure, e.g. the course of important tracts. When analysing the historical development of the city, the role of the cathedral as an important point on the city map is evident, e.g. the location of the cathedral on an island in the Oder River made it an important landmark and catalyst for the development of this part of Wrocław.

3. RESEARCH METHODOLOGY

Digital heritage, a relatively new field of research, focuses on the use of digital technologies to preserve and interpret cultural heritage. Using digital spatial data and advanced analysis techniques, researchers can create detailed 3D models, virtual reconstructions and interactive visualisations of sites. These digital tools allow them to obtain metrics and visualise the appearance of an object in different historical periods. For example, with laser scanning and photogrammetry, we can accurately document the intricate details of the sculptural ornamentation and architectural elements of the cathedral, which can be difficult to assess with traditional methods.

This paper presents a method for preparing digital spatial data to study the spatio-temporal evolution of the urban and architectural setting of Wrocław Cathedral. Methods for comparing spatial data from different periods (using GIS tools), will enable a comprehensive spatial and temporal analysis of the architectural changes and urban environment of the Wrocław Cathedral. The data will be processed in spatial data processing, digital image and point cloud software, i.e. QGIS, Leica Cyclone, Autodesk ReCap 360, Agisoft Metashape, CloudCompare.

Data sources:

- surveying (classic and GNSS, laser scanning (fig. 2)),
- aerial or drone photogrammetry (fig. 3),
- ground photogrammetry (metric, non-metric),
- other non-invasive methods,
- public state registers,
- architectural designs,
- iconographic sources (plans, maps, engravings, paintings, photographs).

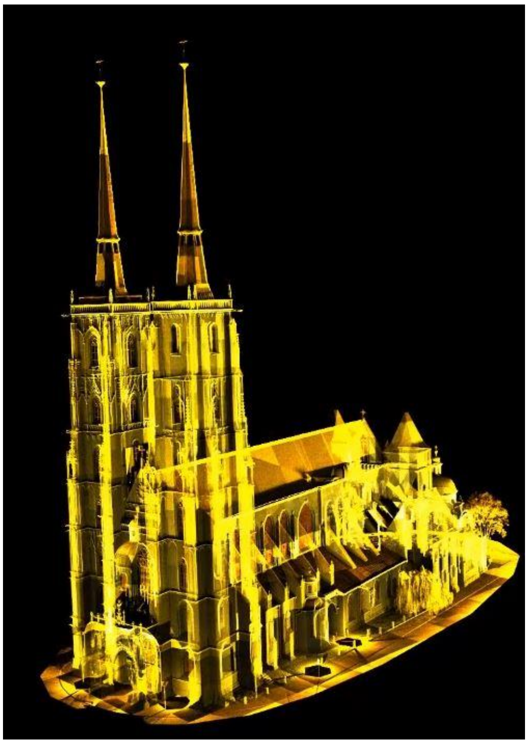

Fig. 2. Laser scan (Wrocław Cathedral) [8]

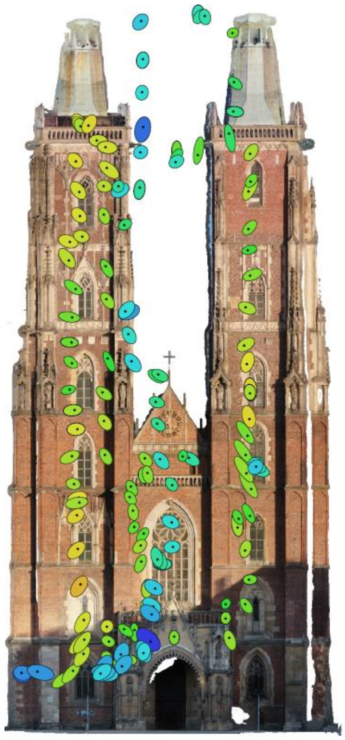

Fig. 3. Drone photogrammetry (Wrocław Cathedral)

3.1. Digital spatial data

This article shows the possibilities of developing material for comparisons of historical sources, available drawing and photographic documentation, current state records [6] with contemporary surveying results.

Only general technical guidelines can be found in the building and surveying and mapping regulations as to how the documentation of a building should be prepared. Current guidelines for compiling an architectural and building inventory do not often take into account modern non-intrusive measurement methods (examples of which have been made and are shown here by the authors). Data was acquired by taking digital survey measurements using various methods, digitising architectural blueprints (fig. 5-6), old maps (fig. 7-8) and iconographic sources and downloading current databases (fig. 9). Significant improvements in the case of the need to collect geodetic and cartographic data were introduced by the Central Office of Geodesy and Cartography (GUGiK, Poland), which made it possible to download some of them free of charge from the State Geodetic and Cartographic Resource (PZGiK). Such activities are part of the global trend of developing publicly accessible databases and INSPIRE (Infrastructure for Spatial Information in Europe) [9].

3.2. Data Acquisition and Processing

In order to acquire the digital infrastructure, baseline reference data was first acquired for the surveys carried out on the current state of the cathedral and its surroundings. Surveying measurements were used, using both traditional and state-of-the-art techniques. Laser scanning technology, preceded by the classic measurement of alignment (georeferenced) points, was used to obtain point clouds of the cathedral. This measurement technique allowed complex architectural details such as mouldings, carvings and decorative elements to be recorded as accurately as possible. By generating dense point clouds, it is possible to create precise 3D models of the cathedral's façade. In doing so, precise measurements of the façade and spatial relationships to surrounding structures were taken. The dense point clouds, will then be used to create 3D models of the cathedral. As a first step, a model of the building will be created in the LOG200 geometric accuracy level. LOG200 [10] (appropriate geometry, 3D survey, data acquisition) refers to the geometric description coming from surveying, restitutions, and on-site data collection related to the LOD200 (digital documentation) in substitution of the schematic design phase of BIM LOD200. All these data can be useful to a schematic predesign phase that can be carried out within the LOD400 using low GOAs (Grades of Accuracy).

Aerial and ground-based photogrammetry were also used to create high-resolution digital images. Aerial photogrammetry (UAV) involved acquiring images of the cathedral and its surroundings from various angles and heights. Ground-based photogrammetry, on the other hand, captured images from ground level, often using non-metric cameras. By processing these images using specialised software, preliminary work was done to compare the detail and accuracy of the models.

A wide range of historical sources, including architectural drawings, maps, engravings, paintings and photographs, were digitised to provide a historical reference point. These sources offer valuable insights into the architectural evolution of the cathedral and its urban context. By digitising these sources, it is possible to analyse and compare with contemporary data to identify changes and continuity over time.

Publicly available geospatial data, such as maps available on open public records, were used to supplement historical and contemporary data. These data sources provided valuable information on land ownership, property boundaries and the evolution of the urban landscape surrounding the cathedral. By analysing these data, the researchers were able to identify changes in land use, urban development patterns and the relationship between the cathedral and the surrounding environment. For example, by examining historical cadastral maps, researchers can trace the development of the cathedral quarter and the surrounding neighbourhood over time. Additionally, by analysing topographical data, researchers can identify changes in elevation and landforms

By combining these various data sources and applying advanced analysis techniques, it is possible to depict individual sites over specific time periods of their existence. This research has important implications for the conservation and protection of this important heritage site.

3.3. Data Analysis and Visualization

For the analysis and visualisation of the collected spatial data, it is planned to use programmes such as QGIS, Autodesk ReCap 360, Agisoft Metashape, CloudCompare. These tools will enable the processing, interpretation and visualisation of complex data sets.

By combining historical and contemporary maps in a GIS environment, researchers will be able to identify changes in the urban landscape over time, such as the development of buildings and changing street patterns.

However, the accuracy of GIS analysis depends on the quality and accuracy of the input data. Errors in data collection, digitisation and georeferencing can affect the reliability of the results. Therefore, an accurate assessment of the quality and accuracy of the underlying data sources is crucial.

The study of architectural and urban changes relies on various spatial data acquisition and analysis methods. Below (Table 1) is a comparative assessment of the employed technologies, their advantages, limitations, and accuracy in relation to specific aspects of the studied objects.

Table 1. Comparison of methods used and assessment of their accuracy

Method	Accuracy	Advantages	Limitations	Application
Terrestrial Laser Scanning	± a few mm	Very high accuracy, independent of lighting conditions	High cost, time-consuming, accessibility issues in difficult terrains	Facade inventory, structural measurements, 3D modeling
Photogrammetry (UAV - drones)	± a few cm	Low cost, fast data acquisition, visual data	Requires good lighting, dependency on GCPs, issues in shaded areas	Roof, facade, and site documentation
Ground Photogrammetry	± a few mm	High accuracy (comparable to laser scanning), visual data	More time-consuming than UAV photogrammetry, requires proper lighting	Architectural details, facades
Map Digitization	Depends on the source	Ability to analyse changes over time, integration with modern spatial data	Lower accuracy, substrate deformations, interpretation challenges	Urban transformation analysis, comparison of historical and contemporary plans

The combination of these methods allows for a comprehensive approach to documenting architectural transformations. UAV photogrammetry enables the efficient collection of large-scale spatial data, creating high-resolution 3D models. Meanwhile, terrestrial laser scanning ensures precision, making it indispensable for non-invasive documentation of historical architectural details.

To effectively process and analyse the data collected using these methods, specialised software solutions were employed. In particular, laser scanning data required robust processing workflows to enhance accuracy and remove potential artifacts. The following section details the tools and techniques used for refining and interpreting the collected datasets.

Leica Cyclon software was used to process and visualise the laser scan data. There, orientation of the scans, merging of the scans and cleaning of the scans from so-called noise was performed. The merged scans were then exported with a .bin extension and in FAIR-compliant open .las format).

The resolution of laser scanning can be affected by factors such as weather conditions, the reflectance of the object and the distance between the scanner and the target object. In addition, processing large point cloud datasets can be computationally intensive and time-consuming [11].

Agisoft Metashape was used for photogrammetry, a technique that involves creating 3D models from data extracted from photographs. The software enabled the generation of 3D models of the cathedral (in our case, for now, these are views of the façade). The accuracy of photogrammetric models depends, among other things, on the quality of the input data and the calibration of the camera. Factors such as lighting conditions, camera lens distortion and object texture can also affect the accuracy of the resulting models.

The processing of the images acquired using the UAV were done in Agisoft Metashape Professional: importing the images taken in the field, then loading the settings, regarding camera parameters, coordinate system, it was important that the local system was set. After checking all settings, the so-called merging of adjacent photos was performed using the "Align Photos" function. This function allows photos to be combined into blocks and generate a sparse point cloud. So-called markers were then added in Agisoft at those locations where distances were measured. It was therefore important to select the local coordinate system in advance, because once all markers were placed on the photos and the distances between them were entered, the programme automatically scaled the point cloud and aligned all the photos, which made the work at a later stage of data integration much easier. Once all markers were placed, optimisation was performed and errors were checked on both markers and distances. The dense point cloud was created in the highest possible quality and, once completed, was subjected to measurement noise cleaning.

Cloud Compare will be used to create a difference model. The software will identify differences between point clouds acquired at different times, indicating areas of change.

The accuracy of point cloud comparisons depends not only on their quality and registration, but also on the:

- Point cloud resolutions: the higher the point density, the more accurate the detail, enabling more accurate change detection.
- Characteristics of the comparison algorithm used: the type of algorithm and its ability to deal with noise and differences in point density affect the results of the analysis.
- Data filtering applications: removing noise and artefacts before comparison can significantly improve accuracy.
- Measurement conditions during acquisition: changes in lighting, atmospheric conditions or scanning angle can introduce differences between point clouds.
- Precision of measuring equipment: the accuracy of the laser scanner or other technology used to collect data affects the quality of the input data.
- Possible deformation of objects: changes in the structure of an object between acquisitions (e.g. due to temperature or damage) can affect the result of a comparison.
- Scale and scope of the comparison: the size of the study area and the scale of change are important for the level of detail of the comparison.

Taking these factors into account can significantly improve the reliability of the point cloud difference analysis.

4. SPATIO-TEMPORAL ARCHITECTURAL AND URBAN ENVIRONMENT CHANGES OF THE WROCŁAW CATHEDRAL

4.1. Architectural Evolution

In the 13th century, construction began on a Gothic cathedral to replace the earlier building. The process took more than two centuries. Distinctive features included slender towers, pointed windows filled with stained glass and richly decorated portals. In the 15th century, the monumental main altar was completed and distinctive gables were added. During the Renaissance, the cathedral underwent minor changes, mainly related to the interior furnishings. However, in the 17th century, during the Baroque era, the interior of the cathedral was enriched with new elements such as sculptures and altars. The cathedral suffered the greatest damage during the siege of Wrocław in 1945, when almost 70% of the building was ruined [12, 13]. The towers collapsed and the interiors were severely damaged. After the war, a comprehensive reconstruction was started, faithfully recreating the Gothic character of the building, but at the same time introducing some contemporary elements. In the 20th and 21st centuries, the cathedral underwent numerous restoration and modernisation works. In 1991, the cathedral's towers were fitted with new soaring helmets that restored the cathedral's former silhouette. Conservation work also included stained glass windows, the exterior façade and the interior, including Baroque and Gothic furnishings.

In the outline of the research special attention was given to the analysis of graphics, e.g. those by F. B. Werner, showing the former appearance of the Wrocław Cathedral and documentation from the period of its reconstruction after World War II, which are key sources for the reconstruction of the architectural and historical transformations of the building. Figures 4-6 show selected architectural changes.

Fig. 4. Drone and ground photogrammetry (2012)

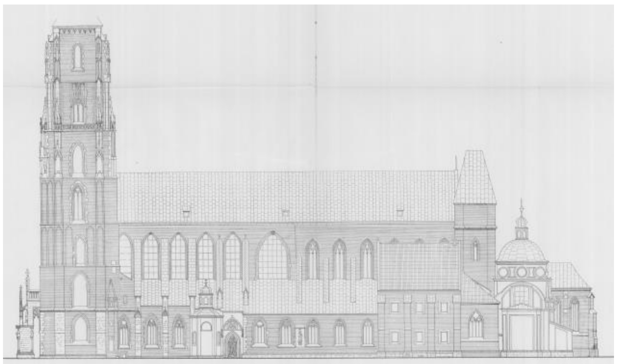

Fig. 5. Wrocław Cathedral before World War II [14]

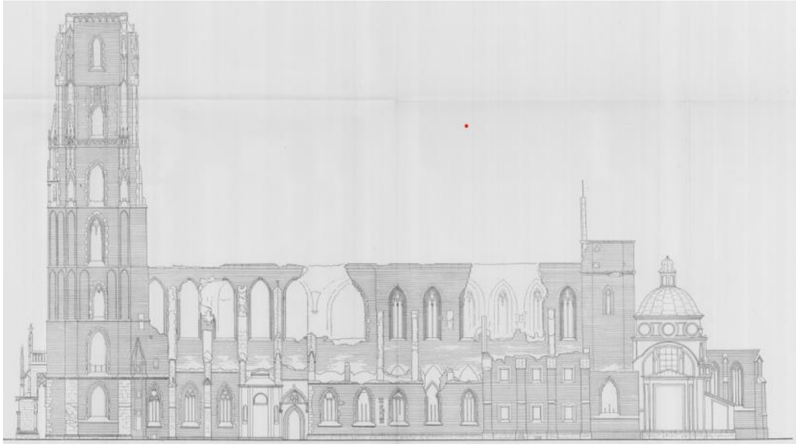

Fig. 6. Wrocław Cathedral in 1945 [14]

4.2. Spatial Evolution

The surroundings of St. John the Baptist Archcathedral on Ostrów Tumski in Wrocław have undergone significant urban transformations over the centuries. These changes reflect not only the architectural development of the cathedral itself, but also the wider historical, social and economic processes that have shaped the city.

In the Middle Ages, Ostrów Tumski, surrounded by the waters of the Oder River, was naturally defensive, and its buildings were characterised by a strict layout of narrow streets and stone buildings. In the immediate vicinity of the cathedral there were chapter buildings, canons' residences and other religious buildings, forming a coherent complex with religious functions. During the Renaissance and Baroque periods, the surroundings of the cathedral began to gain a more representative character. New bishop's palaces and clergy residences were built, giving the space a more monumental expression. Gardens and courtyards were also introduced, transforming the austere medieval landscape into a more orderly and ornamental urban layout. In the 19th century, Wrocław underwent intensive urbanisation, which also affected Ostrów Tumski. New transport links were introduced and the demolition of part of the defensive walls allowed better access to the area. However, despite the modernisation, Ostrów Tumski retained its sacred character, remaining separated from the hustle and bustle of the city. During the siege of Wrocław in 1945, the cathedral's surroundings were severely damaged. Many historic buildings were destroyed or damaged, requiring comprehensive reconstruction. Post-war work focused on reconstructing the medieval and baroque character of the surroundings.

The research outline on spatio-temporal urban changes includes an analysis of old maps, e.g. Weihner's plan, staff maps and BDOT data, which are key sources for analysing the transformation of the spatial layout of the surroundings of Wrocław Cathedral over the centuries. Selected changes in the urban layout are shown in Fig. 7-9.

Fig. 7. Ostrów Tumski, 1562, fragment of Weihner's plan [15]

Fig. 8. The surroundings of the Wrocław Cathedral, late 19th century [16].

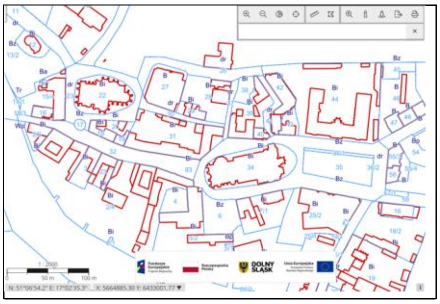

Fig. 9. The surroundings of the Wrocław Cathedral, 2024 [17].

4.3. Significance for historical-architectural research

This project is important for the historical-architectural research of Wrocław Cathedral, as it provides a comprehensive knowledge of the transformation of Wrocław Cathedral and its surroundings in the context of their spatio-temporal development. Thanks to the use of modern research tools, such as spatial data analysis, 3D models, photogrammetry and the integration of archival cartographic material, it is possible to analyse the original urban layout as well as the subsequent transformations.

In addition, the project fits into the broader context of heritage conservation by providing tools to support conservation processes and revitalisation planning. In this way, it contributes not only to the development of academic knowledge, but also to the practical use of research results in the protection and popularisation of historical heritage.

One of the key aspects of the project's implementation is to ensure the high accuracy of the measurements, which has a direct impact on the quality of the spatial analyses and the reliability of the results obtained. The project makes use of advanced technologies such as laser scanning (LIDAR), photogrammetry and BDOT data, which make it possible to achieve a precision of several millimetres when mapping architectural details.

The use of these methods makes it possible to accurately reproduce the geometric features of an object, both for large elements such as the body of a cathedral and for small details such as ornaments or decorations. The precision of the measurements is crucial for the creation of 3D models, which form the basis for further analysis and visualisation.

Comparing contemporary data with historical data, such as the Weihner plan or post-war documentation, also required taking into account differences in scales and measurement techniques. Through calibration and the use of advanced georeferencing algorithms, it has been possible to minimise errors due to these differences, allowing precise analysis of spatio-temporal changes.

High measurement accuracy is also important in the context of conservation work, as it provides the detailed data needed to identify damage, assess technical condition and plan repair and reconstruction measures. In this way, the project contributes not only to scientific knowledge, but also to the practical protection of cultural heritage.

5. SOCIAL AND EDUCATIONAL ASPECTS OF THE RESEARCH

The study of the spatio-temporal changes of Wrocław Cathedral and its surroundings goes beyond architectural analysis, bringing significant social and educational benefits. Documenting the cathedral’s transformation and ensuring open access to data strengthens cultural identity, supports educational initiatives, and engages society in heritage preservation.

A key element of the project is the open-access approach, which guarantees broad access to collected spatial and historical data. By publishing data in open repositories and integrating results with public GIS platforms, the research aligns with the FAIR principles (Findable, Accessible, Interoperable, Reusable). This enables institutions, researchers, and the local community to freely use the data, fostering further analyses, student projects, and educational programs.

The research also supports the development of cultural tourism. Interactive 3D models, virtual reconstructions, and GIS applications allow both tourists and residents to explore the history of the cathedral in a modern digital form.

Public engagement is an important aspect of the project. The study promotes participatory heritage documentation, involving residents, students, and historians in the co-creation of data resources. Initiatives such as archival photo-sharing platforms and crowdsourcing in archival research enhance the sense of responsibility for cultural heritage preservation.

The project also supports modern education by integrating open digital resources into the teaching of architecture, urban planning, and history. Schools and universities can use these materials for interactive learning, field studies, and digital reconstructions, making history more accessible and engaging.

6. FURTHER RESEARCH

6.1. 3D Modeling and Visualization

One of the key research goals is to create 3D models of the cathedral and its surroundings in different historical periods. By using advanced digital technologies such as laser scanning and photogrammetry, it will be possible to generate digital representations of the building's architecture and surroundings.

6.2. Spatio-Temporal Analysis

A spatio-temporal analysis of the changes in the form of the building and its surroundings will provide valuable insights into the evolution of the cathedral over time. It will also provide a basis for the preparation of documentation for historical-architectural research that will make it possible to determine the age and architectural condition of the building, as well as to learn about its history and carry out conservation or restoration work aimed at preserving and highlighting its artistic values, safeguarding and consolidating its historic substance, halting the process of destruction of historic elements, and planning the construction or repair of buildings in the vicinity.

6.3. Digital Heritage Platform

The development of a digital heritage platform is a key step in disseminating research findings and popularising knowledge about the historical and cultural significance of Wrocław Cathedral. The platform aims to provide researchers, students and the general public with easy and intuitive access to the rich resource of information about the heritage of this unique building. By integrating state-of-the-art digital tools such as 3D models, virtual reality, as well as interactive maps and geolocation applications and digital archives, the platform will create a multidimensional space for exploration and education. The project will make it possible to widely exploit the potential of digital technologies to promote cultural heritage.

7. DISCUSSION

Spatial databases solve one of the key problems that have hindered research into the history of architecture and urbanism so far: they allow for the permanent and orderly storage of source materials. Up to now, models and other studies mainly presented the results of research, while the collected sources remained in the resources of the authors and research teams, which often led to their destruction or dispersion The aim of further work is to organise the spatio-temporal stages of functioning and analyse the observed changes of the studied object and its surroundings. The accumulation of the collected graphic and descriptive information (in the form of digital copies) in a multi-resolution database requires the creation of an interoperable database with the flexible possibility of modelling and comparing the data it contains, in various geoinformatics tools. The changes observed in the shape of the cathedral as well as in its surroundings then have a definite temporal shelf life and thus a sequence of events. The relevant files in such an HGIS system. This approach also allows edited models and maps to be stored at different scales. An advantage of temporal-spatial databases is their ability to store geographic attributes, which are divided according to a basic topology into points, lines and polygons. This method of storage enables local geometric patterns to be captured by aggregating information from nearby points to learn about the shape features of the whole and parts of a building using clusters of points, and which allows elements to be extracted at multiple resolutions and the created models to be stored in large-scale model representations.

Spatio-Temporal Databases (STDBMS) offer temporal and spatial data storage based on specially designed field typologies. Extensive date fields are used here to store temporal information, which include not only the standard 'DATE' format, but also types such as 'TIMESTAMP', 'TIME', 'INTERVAL' and, in more advanced systems, 'PERIOD'.

As with time data, specialised operators are available here to perform queries on distance, area, length of objects and relationships such as intersection, neighbourhood or overlap. The functions available in these systems also support the modelling of spatial data, allowing the creation of models based on both geographical and descriptive data [18].

8. SUMMARY

The study of the architectural changes of historic buildings and the changes in their surroundings is an important aspect of cultural heritage research. The use of digital spatial data makes it possible to analyse spatio-temporal data from different periods, as well as to trace their historical context.

This makes it possible to determine changes in the shape of the buildings (here, for example, the evolution of the cathedral), but also their urban environment, including changes in the layout of streets, the distribution of buildings and their functions or public spaces. Collecting this data in digital form and placing it in a multi-resolution database enables comprehensive comparisons and results in the possibility of a broader view of history.

An important aspect is the way in which the data is stored and managed (a spatial database dedicated to a historic building) and the related, increasingly popular, way in which spatial data is presented in geographic information systems and the HBIM (Heritage Building Information Modeling) environment. If a 'digital twin' or BIM model is to be created, e.g. for site management, condition monitoring and planning of future renovations, it is necessary to acquire spatial data of a quality adequate to the required Level of Development (LOD) of the model. Therefore, a very important task in survey data collection is to determine the needed accuracy of the construction documentation.

Currently, as-built Building Information Modelling (HBIM) models show great potential in building history research. In recent decades, there has been increased interest from the construction sector in the use of Building Information Models (BIM) due to the many benefits and resource savings when assessing changes in the geometric shape of buildings [19]. One common data source used to create as-built BIM models is 3D point clouds, which can be obtained by laser scanning as it is able to quickly and accurately collect 3D measurements of the surrounding . The automatic creation of as-built BIM models from point clouds is important, but difficult due to the inefficiency of semantic segmentation [20].

By integrating GIS data into a BIM model, architects can not only view the building itself, but also understand its impact on its surroundings.

Georeferencing is a GIS term that originally refers to the process of associating a map or raster image with the spatial location of topographic data (2D or 3D). Georeferencing is necessary if building models are to be integrated into the surrounding geospatial environment in a GIS environment

Historical Building Information Modelling (HBIM) and Historical Geographical Information System (HGIS) can be integrated at application and data level [21]. Linking building information with the geospatial context is possible through cloud communication between building information modelling (HBIM) and geographic information systems (HGIS). Placing the HBIM model created for the next version of the building, in a given historical period, allows to analyse the surrounding context (environmental and social) at the time, which provides the addition of information and knowledge.

For example, HBIM information can be integrated into the HGIS environment [22, 23] and design and construction data can be transformed into HGIS resources. Users can use all the given information within their operational digital twin.

With data standards dedicated to HBIM/HGIS integration not currently available, it makes sense for some application projects to tactically adopt flexible methods of integrating HBIM and HGIS data. At a tactical level, a meaningful way to do this is to use a CAD technique and an ontology technique together, as the CAD technique can deal with the representation conversion problem and the ontology technique can theoretically provide full semantics transfer. Another technique that has the potential to provide full semantics transfer is the graph-based database, which should be explored in the future.

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