

Oleh Nester*

Master, Assistant
Uzhhorod National University
88000, 3 Narodna Sq., Uzhhorod, Ukraine
<https://orcid.org/0009-0003-9321-0532>

Integration of artificial intelligence into the restoration of architectural monuments: Methods and prospects

Abstract. The study aimed to identify the potential of intelligent digital technologies in assessing the condition of architectural heritage sites and justifying necessary interventions. Methods of systematisation, comparative and comparative-legal analysis, and case analysis were employed. The study established that artificial intelligence in the field of architectural heritage conservation improved professional expertise, digital documentation, condition analysis, forecasting and support for restoration decisions. The effectiveness was determined by data quality, expert validation, system compatibility and algorithm transparency. At the same time, key challenges remained, including incomplete automation, the complexity of integrating digital environments, and the need for human oversight. The global regulatory and ethical framework stipulated that the application of artificial intelligence in restoration must be based on the principles of authenticity, human oversight, accountability, and the use of reliable data. The study determined that Ukrainian legislation does not yet contain specific legal regulations on the use of artificial intelligence in restoration; therefore, its application was primarily linked to documentation, standardisation of damage assessment, data preparation and the professional training of specialists. The case studies of the Dunhuang Mogao Grottoes, Mezgit Castle, St Peter's Basilica, and Lausanne Cathedral demonstrated established approaches to the use of artificial intelligence in restoration practice, as well as in the monitoring and forecasting of the condition of heritage sites. Ukrainian practices in Lviv (Historic Centre Ensemble), Odesa (Odesa Historic Centre) and Chernihiv (T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre) represented a predominantly artificial intelligence-ready environment for the future implementation of such solutions. Therefore, the opportunities for the application of artificial intelligence were linked to the transition to comprehensive integrated systems for analysis, modelling and decision support, provided that the principles of authenticity, minimal intervention, scientific verification and mandatory human oversight were upheld. The practical significance of the possible use of results by restorers, architects, engineers and cultural heritage authorities in restoration practice, during the documentation and assessment of the condition of monuments, and in planning measures for their preservation

Keywords: heritage; digital recording; damage; digital replicas; condition monitoring

INTRODUCTION

Digitalisation of cultural heritage conservation had created a need for tools that can be used for documentation of the condition of architectural monuments and support

restoration decisions. In this context, methods such as artificial intelligence (AI), computer vision, digital modelling and spatial data analysis held promise for detecting

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*Corresponding author



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damage, classifying monument elements and processing data from digital surveys. Despite the high accuracy of digital technologies, their application in restoration practice was accompanied by difficulties in interpreting results, incorporating historical authenticity, material uniqueness and expert responsibility. This required a synthesis of the possibilities and limitations of integrating AI into the process of restoring architectural monuments. This topic had already been extensively explored in academic discourse. In a study by M. Mishra (2021), the various applications of machine learning for the structural monitoring of historic buildings were systematised, and it was demonstrated that algorithmic analysis improved the speed, at which technical anomalies were detected. Such approaches were most effective, when combined with data from actual surveys and remained grounded in the engineering context of the monument. V. Croce *et al.* (2023) demonstrated the potential of combining Historic/Heritage Building Information Modelling (HBIM) and AI for classifying architectural heritage in semi-automated scan-to-BIM reconstruction. This approach viewed AI not as an isolated recognition tool, but as a link in the transition from a point cloud to a structured information model suitable for further restoration decisions. M. Mishra & P.B. Lourenço (2024) summarised the state of research into AI-assisted visual inspection of cultural heritage sites as of 2024 and demonstrated that the automation of inspections enhanced the potential for early defect detection. At the same time, the study emphasised that the accuracy of such systems depended on the quality of training samples and the standardisation of damage features; consequently, the question of the reliability of interpretation remained open.

As S.W. Abusaleh (2024) established, machine learning helped to improve the effectiveness of architectural heritage conservation using predictive analysis and the optimisation of potential intervention scenarios. The author demonstrated that algorithmic analysis made it possible not only to assess the current condition of a site but also to justify the selection of the most appropriate measures, considering long-term consequences. This expanded the role of AI from the technical documentation of damage to supporting the strategic planning of restoration priorities. M. Buldo *et al.* (2024) demonstrated the effectiveness of using AI for the semantic enrichment of point clouds of architectural heritage, using the Palacio de Sástago in Zaragoza as an example. AI improved recognition and classification accuracy of the structural and decorative elements of a historic building, thereby increasing the informativeness of the digital model and reducing the risk of data loss during the preparation of restoration documentation. G. Sugiyama *et al.* (2025) proposed a comprehensive methodology for evaluating Heritage Digital Twins based on Portuguese case studies. The digital twin emerged not merely as a visual copy of a heritage site, but as an integrated environment for diagnostics, condition analysis and modelling the consequences of intervention. H. Hosamo & S. Mazzetto (2025) developed this line of research

by combining knowledge graphs and digital twins for the preservation of historic buildings. As a result, a path was outlined towards an intelligent system capable of linking geometry, historical data, material characteristics and expert judgement rules within a single information field. M. Zhang *et al.* (2025) proposed an automated method for surveying architectural heritage based on semantic point cloud segmentation. This development demonstrated that AI can accelerate the preparation of accurate geometric characteristics of a monument, which directly influenced the quality of the design of restoration measures.

Research conducted in Ukraine confirmed the value of using digital technologies to document, visualise and monitor the condition of historical and architectural heritage sites. I. Kovalchuk *et al.* (2025) demonstrated the significance of laser scanning and Building Information Modelling (BIM) for visualising historical and architectural heritage. This confirmed that digital modelling was not only a means of representation but also a basis for further analysis, compatible with AI tools. O. Chumak & J. Gorkovchuk (2023) refined approaches to the preliminary calculation of the accuracy of monitoring cultural heritage sites using unmanned aerial vehicles (UAVs) and laser scanning. This result was fundamental, as the effectiveness of any AI models in restoration directly depended on the reliability of the raw data. However, existing research had mainly focused on specific technological applications of AI, whilst its integration into the restoration process as a coherent sequence of documentation, diagnosis, forecasting and decision support had not yet been sufficiently systematised. The conditions for the scientifically sound use of such technologies also remained insufficiently defined, particularly regarding the quality of source data, expert verification, the compatibility of digital environments, the transparency of algorithmic processing, and adherence to the principles of authenticity preservation. Therefore, the study aimed to determine the role of digital tools in assessing the condition of architectural heritage sites and preparing well-founded intervention measures. To achieve this aim, the following tasks were set: to investigate the areas and methods of AI application in the process of digital documentation, condition analysis and change forecasting to justify restoration interventions on architectural heritage sites, to identify global and Ukrainian regulatory and ethical principles for the application of AI in the field of architectural heritage restoration, and to analyse global and Ukrainian experience of using AI in the field of architectural heritage conservation to outline the prospects for its further application.

MATERIALS AND METHODS

The study combined methods of systematisation, comparative and comparative legal analysis, and case analysis to classify the areas of application of AI in the field of architectural heritage restoration. Using the systematisation method, the areas of AI application in the field of architectural heritage restoration were summarised – Unmanned



Aerial Vehicle (UAV) photogrammetry and AI-enhanced Three-Dimensional (3D) reconstruction, computer vision for automated detection of cracks and defects, AI-based point cloud segmentation and the Scan-to-HBIM approach (Cotella, 2023; Ge *et al.*, 2024; Yiğit & Uysal, 2024). Moreover, digital twins, Structural Health Monitoring (SHM), predictive modelling, and AI as a system for supporting restoration decisions (Sharma, 2025; Tan *et al.*, 2025; Wang *et al.*, 2025). The selection of these approaches was based on their representativeness of the key stages of the restoration cycle – from digital documentation of the object and initial diagnosis to monitoring of technical condition, prediction of degradation processes, and support for decision-making. The synthesis was based on the following criteria: the method's function within the restoration cycle, key integration challenges, and the benefits of application. This approach had made it possible to organise the diverse areas of AI application and establish a comparative framework for further analysis of the possibilities and limitations of using AI in the restoration of architectural heritage. Using a comparative analysis, approaches relating to the digital documentation and 3D modelling of objects, the automated analysis of the technical condition of heritage sites, and the prediction of the consequences of restoration interventions were compared. The comparison was conducted in terms of the following aspects: the role of the technology in the restoration process, practical application possibilities, significance for assessing the condition of a monument, and the main limitations of implementation. This made it possible to systematise the areas of application of AI in the restoration of architectural heritage and to clarify the role in supporting professional restoration decisions.

Using a comparative legal analysis to identify the similarities and differences between the international and Ukrainian frameworks, this study compared the global and Ukrainian regulatory frameworks that defined the permissible limits and conditions for the use of AI in the field of architectural heritage restoration. The analysis was based on international documents – the International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter – 1964) (1964), a normative and principled document in the field of heritage conservation, and the United Nations Educational, Scientific and Cultural Organization (2021) policy document. The analytical report by M. Pasikowska-Schnass & Y.-S. Lim (2023) and the policy document by the Steering Committee for Culture, Heritage and Landscape (CDCPP) (2024) were analysed. Ukrainian legislation was represented by Law of Ukraine No. 1805-III (2000) and the United Nations Educational, Scientific and Cultural Organization (2024a). These documents were selected for their representativeness regarding key levels of regulation governing the application of AI in the field of architectural heritage restoration. It reflected the basic principles of heritage protection, ethical requirements for AI, specialised recommendations for the cultural sector, and the Ukrainian legal framework. This was done

to identify commonalities and differences between the international and Ukrainian frameworks, outline existing gaps in national regulation, and clarify the conditions for the responsible use of AI in restoration practice.

Using a case-study approach, the study systematised global and Ukrainian examples of AI implementation in cultural heritage conservation and restoration processes – the Dunhuang Mogao Grottoes (China) (Yu *et al.*, 2022), Mezgit Castle (Turkey) (Yiğit & Uysal, 2024). The study also covered St. Peter's Basilica (Vatican) (Smith, 2025; Microsoft, n.d.) and Lausanne Cathedral (Switzerland) (Vogel, 2025). The Ukrainian experience was represented by case studies – Lviv – Historic Centre Ensemble (UNESCO World Heritage Centre, n.d.a), Odesa – Historic Centre of Odesa (UNESCO World Heritage Centre, n.d.b) and associated cultural heritage sites), and the T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre, 2025 (Skamantzari *et al.*, 2025). The selection of international case studies was based on their representativeness of the main areas of AI application in restoration practice: automated restoration, damage detection, the creation of digital twins, and the prediction of the technical condition of monuments. The selection of Ukrainian case studies was determined by the nature of the publicly available source base. Since open sources provided the most comprehensive coverage of practices in digital documentation, 3D recording and damage assessment, these were selected for analysis. Due to the limited public representation of completed cases of comprehensive AI applications in Ukraine, these examples were considered AI-ready practices that formed the basis for the further integration of AI into the field of cultural heritage preservation. The case studies were compared using the following criteria: AI method or tool, functional purpose, and practical significance for restoration. This was done to analyse practical models of AI use in the restoration of architectural heritage and to identify the prerequisites for the further implementation of AI, particularly in Ukraine.

RESULTS AND DISCUSSION

Areas of application for AI in the restoration of architectural heritage

AI was one of the key tools for the digital transformation of the architectural heritage conservation sector. In the field of architectural heritage restoration, AI should be viewed not as a replacement for a professional restorer, but as a tool for technologically enhancing professional expertise, expanding the possibilities for documentation, diagnosis, forecasting and decision-making in restoration projects (Kotsiubivska *et al.*, 2024; Shevchuk & Tarasiuk, 2025). Its significance lies not only in the automation of individual technical operations, but also in expanding the possibilities for recording, analysing, forecasting, and scientifically substantiating restoration decisions. In this context, AI should be viewed as a supportive analytical and predictive tool that works with large sets of visual, spatial and technical data and supported the professional expertise of architects, engineers and conservators (Sharma, 2025). Its application



encompassed the digital documentation and modelling of objects, automated damage detection, analysis of technical condition, prediction of degradation processes, as well as support for decision-making within the framework of conservation and restoration measures (Tan *et al.*, 2025). At the same time, in the field of architectural heritage, AI does not function as an autonomous agent in the restoration process, but merely accelerated data processing, identified patterns, compared intervention scenarios and

formed an analytical basis for further professional conclusions. Therefore, integration of AI should be viewed not as a replacement for professional restoration expertise, but as a form of technological enhancement (Pasikowska-Schnass & Lim, 2023). To systematise the main areas of AI application in the restoration of architectural monuments, it was useful to summarise the key methods, their functions within the restoration cycle, the main challenges of integration, and the practical impact (Table 1).

Table 1. Methods for integrating AI into the restoration process of architectural heritage sites

Method/approach	Role in restoration cycle	Key challenges of integration	The benefits of AI use
UAV photogrammetry and AI-enhanced 3D reconstruction	Digital documentation of the monument, creation of 3D models, and comparison of the monument's condition	Image quality requirements, large data volumes, and processing complexity	Shift towards faster and geometrically more accurate 3D reconstruction of historical objects, particularly for digital preservation, restoration and post-damage documentation
Computer vision for the automatic detection of cracks and defects	Automated inspection, fault localisation, initial diagnosis	Reliance on the quality of models and images, the need for expert validation, and a lack of specialised data	Integration of automated defect detection with routine monitoring systems and digital twins
AI-based point cloud segmentation and the Scan-to-HBIM approach	Transferring data to an HBIM model: integrating geometry, semantics and defects	Complexity of historical geometry, incomplete automation, and the limitations of existing solutions	Development of a semi-automated HBIM workflow as a basis for documenting interventions, analysing the condition and long-term management of the monument
Digital twin, SHM and predictive modelling	Monitoring of condition, recording of changes over time, and prediction of deterioration	Need for high-quality multi-source data, infrastructure, interoperability and metadata	Development of an integrated workflow: documentation → diagnosis → prognosis → post-intervention monitoring
AI as a decision support system in restoration	Risk assessment, prioritisation of interventions, and comparison of scenarios	The risk of a "black box", the need for transparency, human oversight and professional verification	Development of a data-driven but not autonomous restoration workflow, in which AI enhances expert judgement rather than replacing it

Source: based on V.A. Cotella (2023), Y. Ge *et al.* (2024), A.Y. Yiğit & M. Uysal (2024), H. Sharma (2025), X. Tan *et al.* (2025), H. Wang *et al.* (2025)

The effectiveness of integrating AI into restoration depended on several fundamental conditions: the quality of the source data, expert validation, the compatibility of digital systems, the availability of infrastructure, and the transparency of algorithmic processing. Therefore, AI in this field should be viewed as a tool to support restoration decisions, rather than as an autonomous mechanism for making them. The application of AI in the restoration of architectural heritage was complex in nature and encompassed several sequentially linked stages of work on a heritage site. At the initial stage, AI was used for the digital documentation and modelling of the object, which created the basis for the collection, structuring and visualisation of data regarding its geometry, materials and condition. The next level involves automated damage analysis, where computer vision algorithms can be used for rapid detection of defects, their classification, and the identification of the most vulnerable areas. Further sophistication of AI functions was evident in predictive modelling and the use of digital twins, which facilitate the transition from recording the current state to assessing potential changes over time. As a result, AI was increasingly becoming a valuable decision-support tool, enabling the comparison of

intervention scenarios, the prioritisation of work, and the enhancement of the soundness of the restoration process. At the same time, the effectiveness of AI integration depended directly on the quality of the input data, the technical infrastructure, the transparency of the algorithms, and the essential combination of automated analysis with professional expert assessment.

The digital documentation of architectural heritage was one of the most advanced areas of AI application, as it provided an accurate spatial and informational foundation for further analysis, monitoring and the planning of restoration work. It was most often based on a combination of photogrammetry, laser scanning and algorithms for the automated processing of spatial data. Photogrammetry provided a large volume of visual data on façades, structural elements and damaged areas, whilst laser scanning provided highly accurate information on the monument's geometry in the form of point clouds, enabling the recording of deformations, material loss and the slightest deviations in form. In this process, AI was used to accelerate data processing, its automated classification and preparation for further modelling (Sharma, 2025; Tan *et al.*, 2025). A significant step was the construction of 3D models of



historic buildings, which integrated the geometric, visual and technical characteristics of the site and form the basis for analysis, comparison of conditions over time and the preparation of scientific and design documentation. Equally relevant was the transition from point clouds to HBIM, where AI facilitated the automated recognition of elements and the structuring of data, which was essential for complex historic structures with heterogeneous composition (Cotella, 2023). A separate area of focus involved the use of digital twins, which combined a spatial model with monitoring data, damage assessment and predictions of the object's future condition, enabling continuous monitoring and analysis of the consequences of various intervention scenarios (Ge *et al.*, 2024). Thus, digital recording and modelling using AI was not only a means of documentation but also an analytical basis for assessing condition, planning restoration and monitoring effectiveness.

Automated analysis of the condition of heritage sites expanded the capabilities of digital recording, moving beyond mere documentation to the diagnosis and interpretation of a site's technical condition. Practical value was determined by faster detection of defects, more accurate classification of damage, and systematic comparison of observation results over time. The most common task in this field was the detection of cracks and other localised defects using computer vision algorithms, which analysed images of façades, decorative elements or structural surfaces and can be used for recording of signs of deterioration in the technical condition of the object. The combination of UAV photogrammetry and digital twin technology created an effective basis for the automatic detection of cracks and structural surveys of historic buildings (Yiğit & Uysal, 2024). In addition to detecting individual defects, AI can classify damage by type, location, severity and potential hazard, which was essential for structures with complex damage patterns and limited resources for intervention (Wang *et al.*, 2025). Another function was the identification of high-risk areas based on a combination of digital survey data, information on existing defects and external impact parameters. Equally urgent was the automated comparison of a site's condition before and after intervention, which can help assess changes, record new damage and determine the effectiveness of stabilisation or restoration, particularly in the context of multi-stage monitoring or recurring threats. Thus, automated analysis of the condition of heritage sites facilitated a transition from piecemeal recording of defects to a systematic assessment of the site's technical condition.

In contrast to digital recording and automated condition analysis, which focused primarily on documentation and diagnosis, predictive modelling was geared towards assessing the potential consequences of restoration decisions in advance. In this context, AI performed not only an analytical but also a predictive function, enhancing the scientific rigour of design decisions and reducing risks to the heritage site. One of the main areas of such application was the modelling of possible restoration scenarios based

on data regarding the object's geometry, the nature of the damage, material properties, previous interventions and external influences. This made it possible to compare alternative courses of action and preliminarily assess their feasibility without replacing the restorer's professional judgement. Another significant aspect was predicting the consequences of different intervention methods, particularly the risk of further crack propagation, deformation, material loss, or disruption of structural equilibrium following the restoration. In practical terms, AI can also be used to prioritise restoration by ranking problem areas according to risk level, urgency of response and the potential consequences of inaction. This provided a basis for a more rational allocation of resources and systematic planning of interventions, particularly in cases of monuments that have suffered emergency damage or were partially destroyed. AI can reduce the risk of incorrect or excessive interventions, as preliminary digital modelling made it possible to identify potentially dangerous solutions even before practical work begins. In this sense, it supported the principle of minimal intervention, assisting in the selection of courses of action that were sufficient to stabilise or restore the site, but do not result in excessive alteration of its historical structure.

Therefore, the effectiveness of restoration in the context of AI application should be assessed according to criteria such as stabilising the condition of the site, reducing the risks of further deterioration, minimising interference with the historical structure of the monument, the accuracy and soundness of restoration decisions, as well as the ability to monitor results over time by comparing the condition of the object before and after the works. In this sense, predicting the effectiveness of restoration measures using AI should be viewed as a tool for enhancing the soundness of the restoration process, the effectiveness of which directly depended on the quality of the input data, the accuracy of the digital model, and the combination of algorithmic analysis with professional restoration expertise. Despite its high potential, the application of AI in the restoration of architectural heritage has several limitations. First and foremost, these included dependence on the quality of the input data, the need for expert validation, incomplete automation when dealing with complex historical geometry, and the requirement for compatibility between different digital environments. Transparency of algorithmic processing and the preservation of human control during the decision-making process for restoration also remained challenges. The findings of the study indicated that AI in the field of architectural heritage restoration should be viewed not as an autonomous decision-making mechanism, but as a tool for technologically enhancing professional expertise. This interpretation was consistent with the study by İ. Karadağ (2023), who demonstrated that machine learning can be beneficial in the conservation of architectural heritage, not only as a means of technical automation but also as a tool for the restoration and interpretation of lost or damaged parts





of historical sites. The author's study proposed a mixed methodological framework and confirmed that the effectiveness of such solutions depended to a large extent on the completeness and quality of the dataset and on the context, in which this data was generated. Accordingly, the use of AI in restoration practice should be viewed as a supporting analytical tool, the effectiveness of which depended on the quality of the input data and the professional interpretation of the results obtained.

O.E. Dragomir & F. Dragomir (2025) proposed a hybrid neuro-fuzzy approach for the proactive maintenance of cultural heritage sites, which combined feedforward neural networks for pattern recognition with Mamdani-type fuzzy logic inference systems (fuzzy inference system) for interpretable decision-making. The authors emphasised that in conservation practice, high predictive accuracy alone is insufficient, as transparency, explainability and the possibility of professional verification of the recommendations obtained are no less critical. This approach was consistent with the findings of the study, according to which the key conditions for the effective integration of AI into conservation were data quality, expert validation, transparency of algorithmic processing, and the preservation of human oversight. In this context, AI should be viewed not as an autonomous decision-making mechanism, but as a tool to support professional analysis and the justification of interventions. This logic was also supported by the study by L.E. Mansuri & D.A. Patel (2022), in which AI was used to build an automated visual inspection system for architectural heritage sites. The authors noted that such a system made it possible to reduce inspection time, cut costs, minimise the risk of human error and improve the consistency of defect recording. This was consistent with proposed research indicating that AI enhanced the capabilities of documentation and initial diagnosis but does not eliminate the need for a specialist to interpret the results. Consequently, automated visual inspection confirmed the value of using AI specifically as a tool to support the restoration process during the stage of identifying and initially analysing damage.

The results of the study showed that the priority stage in integrating AI into the restoration cycle was the transition from the accumulation of spatial data to its structured semantic organisation. This approach was consistent with that of A. Gil & Y. Arayici (2025) proposed a hierarchical approach to the segmentation and classification of large datasets of point clouds of historic buildings using the Random Forest algorithm and the Uniclass system. In the context of this study, this supported the interpretation of AI as a tool that not only processes geometric information but also transferred it into a semantically organised environment, which was necessary for subsequent HBIM modelling, condition analysis and long-term management of the heritage site. The application of AI in working with point clouds had not only technical but also methodological significance, as it created a basis for integrating data into the digital restoration cycle. In their study, A. Felicetti & F. Niccolucci (2025) developed the concept of the Reactive Heritage Digital Twin

and demonstrated that combining AI with ontologies made it possible not only to structure complex data about a heritage object but also to expand the analytical and predictive capabilities of the digital twin. This approach involved integrating diverse information about the object's condition, its materials, damage and possible intervention scenarios into a single digital environment. This was consistent with the findings of the proposed study, according to which the effectiveness of AI in restoration was determined not only by the accuracy of individual algorithms but also by the ability to integrate different types of data within a cohesive digital environment. In this context, the digital twin emerged not as a means of autonomising decisions, but as a tool for enhancing professional analysis, forecasting and justifying restoration interventions. Artificial intelligence can therefore be effectively applied at various stages of the restoration cycle, from digital documentation and analysis of the technical condition to predictive modelling and support for restoration decisions. Its use improved the accuracy of documentation, expanded the scope for detecting damage, aids risk assessment and justified interventions; however, it does not eliminate the need for the restorer's professional expertise. At the same time, the effectiveness of AI implementation was determined by the quality of the input data, the level of expert validation, the compatibility of digital systems, the transparency of algorithmic processing, and the maintenance of human oversight. This provided grounds for viewing AI not as an autonomous decision-making mechanism, but as a tool for technologically enhancing professional restoration practice.

Regulation and prospects for the use of AI in restoration of architectural heritage: International and Ukrainian contexts

International regulations governing the use of AI in the restoration of architectural heritage should be viewed as a combination of traditional principles of heritage conservation and ethical requirements for digital technologies. The International Charter for the Conservation and Restoration of Monuments and Sites. (The Venice Charter – 1964) (1964) remained the foundational document in this field, as it defined the limits of permissible intervention in a monument through the principle of authenticity and respect for reliable sources. As applied to AI, this means that algorithmically generated reconstructions and digital interpolations may be used as analytical or research tools, but not as a self-sufficient basis for the physical reconstruction of lost parts of a site. A general ethical framework for the use of AI was provided by United Nations Educational, Scientific and Cultural Organization (2021), which shifted the emphasis from technical efficiency to human control, explainability, accountability, traceability and the auditability of AI systems. This was of fundamental importance for restoration practice, as decisions regarding a heritage site cannot be based solely on the formal accuracy of an algorithm. A more specialised framework for the field of culture and heritage was established by the Steering Committee for Culture,



Heritage and Landscape (CDCPP) (2024), which specified these requirements in terms of data quality, open standards, a trust infrastructure, and the impermissibility of replacing human participation with algorithmic procedures. An analytical supplement to this regulatory framework was a study by the European Parliament (Pasikowska-Schnass & Lim, 2023), which identified the key risks associated with the use of AI in the cultural sector, including algorithmic opacity, the “black box” effect, copyright issues and data governance. Thus, the international framework formed a comprehensive system of guidelines within, which AI can be regarded as a professionally and ethically acceptable tool for restoration practice.

In Ukraine, the context for the application of AI in the field of architectural heritage restoration differs from the global context. Whilst international documents primarily establish a value-based and ethical framework, the Ukrainian context was defined by a combination of legal regulations governing the protection of cultural heritage and practical challenges arising from the consequences of Russia’s full-scale war against Ukraine, the mass documentation of damage, and post-war reconstruction. The key document was Law of Ukraine No. 1805-III (2000), which established the priority of preserving the subject of heritage protection, the scientific nature of restoration measures, and the requirement for proper documentation. At the same time, it does not regulate AI as a separate technology; therefore, under current Ukrainian law, AI can only be regarded as a tool for research, design and analytical support for restoration, but not as an autonomous decision-making mechanism. The present state of the Ukrainian sector was reflected in United Nations Educational, Scientific and Cultural Organization (2024a), which stipulated the main priorities: the standardisation of data collection for damage assessment, the introduction of protocols for data collection, protection and dissemination, as well as the training of specialists in the field of documentation and damage assessment. This indicated that, in the Ukrainian context, the issue of AI was directly linked to data quality, the standardisation of methodologies, and the institutional capacity to work with

digital tools. Consequently, the Ukrainian practical context focused primarily on standardising damage assessment, field documentation, standardised procedures and professional training, rather than on delegating decisions to AI.

The international and Ukrainian frameworks do not contradict but serve different functions. International documents established a value-based and normative framework: authenticity, the prevention of speculative interference, human oversight, transparency, accountability and the use of reliable data. Ukrainian documents, on the other hand, stipulated procedural and practical level: conservation protocols, documentation, damage assessment, standardisation of methodologies, training of specialists and development of digital infrastructure. At the same time, it was precisely within the Ukrainian context that the main gaps were evident. Current sector-specific legislation does not contain specialised provisions regarding AI in restoration, so the legal admissibility of its use was currently derived indirectly – through general requirements for scientific rigour, proper documentation and the preservation of the object of conservation. For Ukraine, the issues of data standardisation, compatibility of methodologies and the dissemination of standardised damage assessment procedures remain critical. Therefore, the main task was determined not by accelerated implementation of autonomous AI solutions, but by the creation of the institutional, methodological and digital prerequisites for their responsible and scientifically verified use in the future. The outlined regulatory, ethical and institutional differences between the global and Ukrainian contexts provided grounds for moving from the level of principles to that of practical implementation. In this context, an analysis of specific case studies, in which AI was already being used for digital documentation, automated damage detection, technical condition forecasting and supporting restoration decisions was noteworthy. Such examples can trace how technological tools were integrated into cultural heritage conservation processes, what functions they performed and what practical significance they had for restoration; a summary was presented in Table 2.

Table 2. Case studies on the implementation of artificial intelligence in cultural heritage conservation and restoration processes

Case/object	AI method/tool	Function	Practical significance for restoration
Dunhuang Mogao Caves, China	Deep learning, automated restoration, object detection algorithms, search and analysis tools, style transfer, and AI for the Dunhuang specialised dataset	Automated restoration of wall paintings, accelerated analysis of large visual datasets, and support in building a thematic library of elements for research and conservation	More accurate reconstruction of lost or damaged sections of the mural, systematisation of visual elements, and greater justification for restoration decisions
Mezgit Castle, Turkey	UAV photogrammetry, digital twin technology and deep learning methods for automated crack detection	Automated crack detection on 3D models, support for the preparation of repair plans and subsequent monitoring of damage progression	Prompt identification of defects, assessment of the extent of damage and planning of restoration work based on a precise digital model of the building
St. Peter’s Basilica, Vatican	Photogrammetry, AI techniques and cloud computing for creating a high-precision digital twin of an object	Digital replica was created using around 400,000 high-resolution images; AI helped to improve the visualisation and identify signs of potential structural deterioration, including cracks and missing mosaic fragments	Provides a highly accurate digital framework for assessing the condition of a heritage site, planning conservation work and long-term monitoring of changes to the structure and decorative elements



Table 2. Continued

Case/object	AI method/tool	Function	Practical significance for restoration
Lausanne Cathedral, Sweden	AI-powered digital co-pilot, digital twin, augmented reality, 3D modelling based on laser scanning and photogrammetry	Assessment of the condition of historic stone structures, integration of structural and materials science data, and support for inspection and restoration decisions	Provides a digital framework for interdisciplinary analysis, early identification of problem areas and justification of conservation interventions

Source: based on T. Yu *et al.* (2022), A.Y. Yiğit & M. Uysal (2024), B. Smith (2025), B. Vogel (2025), Microsoft (n.d.)

The case studies analysed cover sites with a variety of conservation needs. In particular, the Dunhuang Mogao Grottoes complex in China presents the challenge of preserving wall paintings that were deteriorating; therefore, AI was used for digital restoration, analysis of large visual data sets, and to support conservation without direct intervention on the original. For Mezgit Castle, the key challenge was the detection and documentation of cracks, which necessitated the use of UAV photogrammetry, digital twins and automated diagnostic algorithms. In the case of St. Peter’s Basilica, AI was used as part of digital surveys and conservation monitoring to identify subtle structural vulnerabilities and support long-term monitoring of the monument’s condition. In contrast, Lausanne Cathedral in Switzerland demonstrated the need for continuous monitoring of the degradation of stone materials, early detection of problem areas and justification of conservation interventions. It was possible to argue that the application of AI in the field of cultural heritage reflected a gradual transition from the local use of digital tools to the comprehensive integration of intelligent technologies into the processes of documentation, diagnosis, monitoring and support for professional decision-making.

Thus, the practical potential of AI was implemented in several interrelated areas: the automated reconstruction of damaged sections, the detection of defects based on digital models, the creation of digital twins, and the prediction of spatio-temporal changes in the technical condition of heritage sites. In the examples given, AI does not function as a standalone replacement for a conservator but acts as an analytical support tool that enhanced the accuracy of documentation, the soundness of interventions and the possibility of long-term monitoring of the site. Taken together, this indicated a shift in the very logic of heritage conservation: from a reactive response to existing damage to proactive monitoring, risk prediction and scientifically grounded planning of restoration measures. While international case studies predominantly reflected mature forms of AI integration into cultural heritage conservation processes, Ukrainian practices primarily represented the stage of establishing the digital and methodological foundations for such implementation. In this sense, it was appropriate to regard them as AI-ready approaches that lay the groundwork for the subsequent use of AI in documenting, forecasting the condition of heritage sites and planning restoration interventions (Table 3).

Table 3. Ukrainian practices in digital documentation and AI-ready approaches to the preservation of cultural heritage

Case/object	Technologies/tools	Primary benefit	Value for further AI use
Lviv, 2024 (buffer zone of the UNESCO World Heritage Site “Lviv – Historic Centre”)	3D visualisation, damage and risk assessment, standardised UNESCO/ ICCROM form	An inspection of the damaged cultural heritage sites has been carried out, a detailed assessment of their condition has been conducted, and the groundwork has been laid for urgent conservation measures	Creates a structured database for subsequent AI-based risk analysis, damage classification and prioritisation of interventions
Odesa, 2025 (the UNESCO World Heritage Site “Historic Centre of Odesa” and associated cultural heritage sites)	Standardised methodology for assessing damage and risks, 3D architectural laser scanning, and professional training	The documentation of damage, analytical assessment and preparation of emergency stabilisation measures have been combined	Supports the transition to a digitally controlled restoration cycle, within which AI can be used to predict the condition of the tooth and plan interventions
The T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre, 2025	Ground-based laser scanning, photogrammetry, and geospatial analysis	Comprehensive digital documentation of the damaged site and a methodological framework for post-conflict condition assessment have been produced	Provides high-precision data for subsequent modelling, digital twins and algorithmic analysis of the monument’s technical condition

Note: table does not list completed AI-based restoration projects, but rather the most representative examples of Ukrainian AI-ready practices found in open sources; ICCROM – International Centre for the Study of the Preservation and Restoration of Cultural Property

Source: based on United Nations Educational, Scientific and Cultural Organization (2024b; 2025), M. Skamantzari *et al.* (2025)

The analysed Ukrainian practices cover sites damaged as a result of russian attacks or those under immediate threat. In Lviv, these sites included monuments in the buffer

zone of the World Heritage site, damaged by the attack on 3 September 2024, for which an in-depth damage assessment was carried out, and priority stabilisation measures



were identified. In Odesa, the focus was on the historic centre, which had been inscribed on both the World Heritage List and the List of World Heritage in Danger since January 2023; repeated attacks have necessitated assessment missions, the provision of technical assistance, and the implementation of urgent repair and restoration measures. In Chernihiv, the case of the T. Shevchenko Music and Drama Theatre, which suffered significant damage in August 2023, was examined; consequently, 3D documentation, photogrammetry and geospatial analysis formed the basis for a post-conflict assessment of its condition. A summary of these practices suggested that Ukraine's experience in the field of cultural heritage preservation focused primarily on digital documentation, recording damage, standardising assessments and preparing data for further analytical use. The case studies demonstrated that the Ukrainian context represented not so much fully-fledged models of AI integration into the restoration process as the development of an AI-ready environment, within which structured datasets were created, survey methodologies were refined, and a digital foundation was built for future algorithmic analysis. A common feature of these practices was the combination of 3D documentation, damage assessment, geospatial analysis and professional training, which formed the basis for a transition from reactive documentation of the consequences of destruction to a more systematic, digitally driven approach to heritage conservation. Thus, the significance of the Ukrainian case studies presented was determined by the creation of the methodological, informational and infrastructural foundation necessary for the further implementation of AI in the practice of monitoring, condition forecasting and planning restoration interventions.

The prospects for applying AI in the field of architectural heritage conservation, therefore, lie primarily in the transition from the piecemeal use of digital tools to comprehensive, integrated systems for analysis, modelling and supporting restoration decisions. Whilst AI was used mainly for the digital documentation of sites, automated damage detection and the prediction of technical condition, its role may expand significantly in the future through the combination of 3D models, HBIM, digital twins, monitoring systems and predictive analytics algorithms. This created the possibility of continuous monitoring of the condition of heritage sites, comparing alternative intervention scenarios, and improving the soundness of restoration decisions. One of the most promising areas was the development of predictive models capable of assessing the likely consequences of various conservation and restoration measures even before their practical implementation. Such systems can be used to analyse the risk of crack propagation, deformation, material loss and other adverse changes, as well as to prioritise interventions under conditions of limited resources. Further refinement of automated analysis of the technical condition of heritage sites was required, in particular, the classification of damage, the identification of areas of increased vulnerability, and comparative analysis of the site's condition over time. At the same time, the

development of such technologies must take place in accordance with the fundamental principles of cultural heritage conservation. The promising approach was not the autonomous replacement of professional restoration judgement by an algorithm, but rather the enhancement of a specialist's analytical capabilities using intelligent digital tools. Therefore, further integration of AI into this field must combine technological efficiency with the principles of authenticity, minimal intervention, scientific verification and mandatory human oversight.

In the Ukrainian context, the prospects for applying AI in the field of architectural heritage conservation were linked primarily to the development of digital documentation, the systematisation of data on damage, and the establishment of an information infrastructure for the subsequent analytical use of AI. Several practical tasks were of paramount importance for Ukraine. First and foremost, it was advisable to establish unified standards for the digital recording of cultural heritage sites, which would ensure the compatibility of data obtained from different projects and regions. The creation of national and regional databases of damage, 3D models and technical survey results, which can be used for training and testing AI algorithms. Furthermore, interdisciplinary collaboration between conservators, architects, engineers, architectural historians and data analysts was essential, as the effective application of AI in this field was only possible through the combination of technical and humanities expertise. Implementation of pilot projects, in which AI could be used for the automated detection of damage, the ranking of problem areas by risk level, the comparative analysis of digital models before and after intervention, and the prediction of defect development was notable. It was also necessary to train staff, adapt digital tools to the existing cultural heritage protection system, and ensure that new technologies were compatible with existing procedures for scientific, design and restoration support. Under these conditions, AI in Ukraine could become not a replacement for a professional restorer, but an effective tool for supporting well-founded, timely and less risky decisions in the field of architectural heritage conservation.

The findings of the study revealed that the regulation of AI use in the restoration of architectural heritage should be based not only on technical efficiency, but also on ethical and regulatory principles, in particular transparency, accountability, control over data use, and the prevention of speculative interference with heritage sites. This was consistent with A. Wagner & M.-S. de Clippele (2023), viewing the digitisation of cultural heritage as a critical challenge, primarily linked to issues of intellectual property, access and law enforcement in the digital environment. In this context, the authors' conclusions support the interpretation of the present study, according to which digital technologies in the heritage sector require not only technical but also legal and ethical regulation. The effective use of AI in the restoration of architectural heritage was possible only if technological effectiveness was combined with





ethical principles and legal regulatory mechanisms. The study by U. Bachmann-Gigl & Z. Dabiri (2024) investigated the assessment of damage to cultural heritage sites in Ukraine using multi-temporal analysis of Sentinel-1 SAR (Sentinel-1 satellite radar data obtained using the SAR method) and demonstrated that a semi-automated approach was suitable for the rapid identification of areas of destruction in crises, although it has limitations regarding localised or isolated damage. This was consistent with the findings of this study, which characterised the Ukrainian context as an AI-ready environment focused on digital documentation, damage assessment, standardisation of procedures and data collection for subsequent analytical use. Therefore, for Ukraine, it was not autonomous AI solutions that were of primary importance, but reliable digital methods for recording and assessing damage, which can form the basis for the future integration of intelligent systems.

The study by L. Cecere *et al.* (2024) examined the combination of IoT and digital twins as a promising approach to predictive maintenance in the field of cultural heritage, emphasising the importance of continuous monitoring and an integrated digital environment for the long-term preservation of heritage sites. This interpretation was consistent with the findings of the present study, in which digital twins and predictive modelling were identified as one of the key areas of AI development in the restoration of architectural heritage. Both studies provided grounds for considering digital twins as the basis for predictive monitoring and restoration planning. The results of the study showed that the practical potential of AI in the field of architectural heritage conservation was realised across several inter-related areas – ranging from digital documentation and automated damage detection to the creation of digital twins and the support of restoration decisions. This conclusion was consistent with the approach of F. Gîrbacia (2024), who analysed research trends in the application of digitalisation in the field of cultural heritage and demonstrated that AI was increasingly being used for classification, computer vision, 3D reconstruction and other tasks involving the digital processing of heritage. The development of 21st-century AI in the heritage sector was systematic in nature and reflected a gradual transition from the piecemeal use of digital tools to their comprehensive integration. D. Ocón *et al.* (2026) proposed an ethical framework for the use of Generative AI in the restoration, reconstruction and reproduction of movable cultural heritage, emphasising the tension between the technological capabilities of GenAI and the requirement to preserve historical authenticity. Although the authors' study primarily addressed movable heritage, it was relevant to the present study as it aligns with the conclusion regarding the need to subject AI to the principles of authenticity, minimal intervention, scientific verification and mandatory human oversight. The authors' conclusions were therefore consistent with the findings of this study, which demonstrated that an international regulatory and ethical framework was a prerequisite for the acceptable use of AI in restoration practice. Thus, the

application of AI in the field of architectural heritage conservation was developing within the framework of a combination of regulatory and ethical requirements, digital documentation, damage assessment, predictive modelling and support for restoration decisions. The effective and acceptable use of AI in restoration practice was only possible if technological effectiveness was combined with the principles of authenticity, scientific verification and mandatory human oversight.

CONCLUSIONS

The study's findings established that the application of AI in the field of architectural heritage conservation follows a consistent functional structure: from the digital documentation and modelling of a site to diagnostics, forecasting and support for the selection of restoration scenarios. Digital recording based on photogrammetry, laser scanning, 3D modelling and the transition from point clouds to HBIM forms not only a documentary but also an analytical basis for assessing the condition of a monument and monitoring the results of intervention. Automated damage analysis using computer vision expanded the possibilities for inspecting heritage sites, as it can be used for localisation of defects, their classification, the identification of high-risk areas, and the comparison of the site's condition over time. Predictive modelling using AI can be used for preliminary assessment of the consequences of various intervention methods, the ranking of problem areas by risk level, and the reduction of the probability of incorrect or excessive restoration decisions. International and Ukrainian frameworks for the application of AI were not contradictory but serve different functions: international documents stipulated ethical and value-based guidelines, whilst the Ukrainian context focused on documentation procedures, damage assessment and the development of digital infrastructure.

International case studies – including the Dunhuang Mogao Grottoes, Mezgit Castle, St Peter's Basilica and Lausanne Cathedral – have shown that AI was transforming the approach to heritage conservation, shifting it from reactive damage repair to proactive monitoring, diagnostics and risk-based planning of interventions. In Ukraine, however, practices tested on examples such as the Lviv Historic Centre Ensemble, the Odesa Historic Centre and the T. Shevchenko Chernihiv Regional Academic Music and Drama Theatre were, for the time being, primarily forming an AI-ready foundation rather than complete models of full-scale AI integration into the restoration process. Thus, whilst international experience demonstrated the expansion of AI's role from digital documentation to monitoring, forecasting and supporting professional decisions, the priority for Ukraine remained the creation of a digital and methodological foundation for the further implementation of such tools. A limitation of the study was its theoretical nature, as the conclusions do not include empirical testing of AI solutions in restoration practice. Future research should address empirical testing of AI tools in restoration practice, the standardisation of digital data, the creation of



specialised datasets, and the development of integrated systems based on HBIM, digital twins and predictive analytics. None.

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CONFLICT OF INTEREST

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**Олег Нестер**

Магістр, асистент

Ужгородський національний університет

88000, пл. Народна, 3, м. Ужгород, Україна

<https://orcid.org/0009-0003-9321-0532>**Інтеграція штучного інтелекту
в процес реставрації архітектурних пам'яток:
методи та перспективи**

Анотація. Метою дослідження було виявлення можливостей інтелектуальних цифрових технологій у оцінюванні стану об'єктів архітектурної спадщини та обґрунтуванні необхідних втручань. Були використані методи систематизації, порівняльного та порівняльно-правового аналізу, кейс-аналізу. Встановлено, що штучний інтелект у сфері збереження архітектурної спадщини підсилює фахову експертизу, забезпечує цифрову фіксацію, аналіз стану, прогнозування та підтримку реставраційних рішень. Його ефективність визначається якістю даних, експертною валідацією, сумісністю систем і прозорістю алгоритмів. Водночас ключовими викликами залишаються неповна автоматизація, складність інтеграції цифрових середовищ і потреба в людському контролі. Глобальна нормативно-етична рамка визначає, що застосування штучного інтелекту у реставрації має ґрунтуватися на принципах автентичності, людського контролю, підзвітності та використання надійних даних. Виявлено, що українське законодавство поки не містить спеціалізованого правового регулювання штучного інтелекту у реставрації, тому його застосування пов'язується передусім із документацією, стандартизацією оцінювання пошкоджень, підготовкою даних і професійною підготовкою фахівців. Кейси Dunhuang Mogao Grottoes, Mezgit Castle, St. Peter's Basilica та Lausanne Cathedral засвідчили вже сформовані підходи до застосування штучного інтелекту у реставраційній практиці, моніторингу й прогнозування стану пам'яток. Українські практики у Львові (Ансамбль історичного центру), Одесі (Історичний центр Одеси) та Чернігові (Чернігівський обласний академічний музично-драматичний театр ім. Т. Шевченка) репрезентували переважно готове до штучного інтелекту середовище для майбутнього впровадження таких рішень. Тому можливості застосування штучного інтелекту пов'язані з переходом до комплексних інтегрованих систем аналізу, моделювання й підтримки рішень, за умов дотримання принципів автентичності, мінімального втручання, наукової верифікації та обов'язкового людського контролю. Практична значимість полягає у можливості застосування результатів реставраторами, архітекторами, інженерами та органами охорони культурної спадщини у реставраційній практиці, під час документування, оцінювання стану пам'яток і планування заходів їх збереження

Ключові слова: спадщина; цифрова фіксація; пошкодження; цифрові двійники; моніторинг стану

