THE INTEGRATION OF ARTIFICIAL INTELLIGENCE IN ARCHITECTURAL SURVEYING AND CULTURAL HERITAGE: DEVELOPMENTS, METHODOLOGIES, AND PERSPECTIVES OF THE DIGITAL TWIN

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Abstract: *The digital evolution in construction engineering, architecture, and heritage conservation has accelerated at an unprecedented pace, thanks to the integration of Artificial Intelligence (AI), advanced acquisition systems, and the Digital Twin paradigm. This paper comprehensively analyzes the latest innovations in architectural surveying, semantic segmentation of point clouds, and Heritage Building Information Modeling (HBIM) [1,2]. The analysis unfolds through the classification of Machine Learning and Deep Learning algorithms for the automatic recognition of architectural elements, exploring the effectiveness of neural architectures such as PointNet++ and DGCNN, and their ability to generalize on heterogeneous datasets. The transition from descriptive to predictive and prescriptive models is also examined, with an in-depth focus on case studies of global relevance, including the In-Heritage platform applied to the Palazzi dei Rolli in Genoa for IoT microclimate monitoring, and the Aïoli platform used for the post-disaster reconstruction and virtual anastylosis of Notre-Dame de Paris. Through a critical evaluation of the ethical implications, the interpretability of algorithms (overcoming the "black-box" paradigm), and the integration of immersive reality (VR/AR) for spatial use, the research synthesizes the state of the art. It outlines prospects for a holistic, transparent, and technologically advanced approach to protecting built heritage [3].*

Keywords: *perspective, image analysis, building engineering, photographic survey, artificial intelligence, HBIM, digital twin, machine learning, semantic segmentation, virtual reality.*

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Introduction

The construction engineering, architecture, and monumental conservation sector has historically been resistant to the widespread adoption of automated digital technologies, favoring traditional analytical approaches and established investigative methodologies. However, over the past decade, unprecedented technological convergence has bridged this gap. The drastic reduction in the cost of sensing hardware, combined with the exponential increase in computational power, has allowed Artificial Intelligence (AI) to permeate the operational practices of structural diagnostics and architectural surveying. This transition has transformed spatial data from a mere inert geometric representation to a dynamic, semantically rich, and searchable information ecosystem in real time.

Recent scientific literature has systematized this revolution by identifying seven fundamental operational macro-categories in which AI-based image analysis [4] is redefining contemporary construction engineering: advanced photomodeling, intelligent thermographic mapping, automatic object recognition, infrastructure inspections assisted by Remotely Piloted Aircraft (UAV), synergistic implementation in BIM (Building Information Modeling)[1] [5] and FEM (Finite Element Method), the continuous monitoring of structural health (Structural Health Monitoring) and, finally, the early identification of cracks and material damage. Each of

[1] S. Menconero, Final report on research activity, Sapienza University of Rome, 2023.

these areas is no longer a silo, but an interconnected node within a holistic workflow that culminates in the creation of high-fidelity Digital Twins.

The deepest implication of this paradigm shift lies in the transition from the quantitative to the qualitative and predictive dimensions. The primary objective is no longer just the extraction of high-precision spatial coordinates, but the semantic interpretation of these coordinates. The current scientific challenge focuses on training neural networks to distinguish a load-bearing structural element from a decorative partition, correlate surface thermal variations with the shear strength of a wall facing, and predict structural collapse by analyzing imperceptible geometric deviations. This article aims to explore these developments in depth, analyzing the algorithmic architectures, data processing flows, and the ethical-epistemological implications of adopting AI in the delicate discipline of cultural heritage protection.

Data Acquisition Methodologies and Advanced Integrated Survey Techniques

The foundation of any advanced digital model, whether an HBIM database or a predictive digital twin, lies in the granularity, accuracy, and spectral richness of the data captured in the field. Architectural surveying technologies have evolved from direct, manual methods to hybrid reality-capture systems that blend digital photogrammetry, terrestrial laser scanning (TLS), and high-resolution infrared thermography.

LiDAR Sensors, UAVs, and Rapid Mapping in Complex Environments

The introduction of UAVs (Unmanned Aerial Vehicles) has significantly addressed the challenge of surveying roofs, inaccessible facades, and large-scale architectural complexes. Remote flight, coupled with ultra-high-definition optical sensors and miniaturized LiDAR systems, enables the automatic generation of precision orthophotos and dense point clouds, drastically reducing risks to human operators and acquisition times. Modern drones operate according to pre-programmed flight plans based on topological optimization algorithms, ensuring photographic overlays that are ideal for Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms.

However, surveying engineering faces unique challenges in confined, hypogeal, or underground spaces, where the Global Navigation Satellite System (GNSS) signal is absent, and UAV maneuverability is impaired. In these scenarios, research is moving towards the use of solid-state LiDAR sensors integrated into mobile devices (smartphones and tablets). Recent experiments on rock architecture and hermit complexes that are difficult to access, such as the Grotta dell'Angelo in Montesano sulla Marcellana, Italy, have shown that these low-cost sensors offer extremely promising, fast survey procedures. Although these devices have a higher noise floor than traditional massive TLS scanners, their portability enables them to extract valuable spatial information and document speleological features previously impossible to detect with conventional techniques, thereby accelerating preliminary investigations and democratizing access to 3D digitization.

Multisensory Integration and Intelligent Thermographic Analysis

Infrared thermography (IRT) has been a fundamental non-destructive, non-invasive technique in historical diagnostics for decades. However, the inherent low spatial resolution of traditional thermal sensors has historically limited their applicability for precision metric mapping. Recent methodological developments have overcome this limitation by allowing the algorithmic fusion (data fusion) of two-dimensional thermographic data with three-dimensional geometric data (point clouds and meshes).

This multisensory integration enables going beyond mere qualitative visualization of surface degradation. By applying advanced neural networks for instance segmentation (such as Mask R-CNN) directly on thermal imaging sets, it is now possible to automatically isolate specific façade elements, such as fixtures, wall portions, and structural thermal bridges. Even more relevant is the ability of these intelligent systems to directly calculate thermal transmittance (U) values from recorded temperature gradients, thereby transforming visual data into a quantitative thermo-physical estimate of the building's energy behavior. In addition, projecting the thermal mapping onto the photogrammetric models reveals invisible pathologies in the visible spectrum, such as subcortical rising-damp lenses, discontinuities in wall texture, and hidden plaster detachments, thereby directing subsequent endoscopic investigation campaigns and restoration sites with extreme precision.

Artificial Intelligence for Image Analysis and 3D Semantic Segmentation

The semantic enrichment of three-dimensional data is the most complex and promising frontier in geomatics and architectural surveying. The ultimate goal is no longer geometric recording ("where" a certain point in space is located), but rather its ontological interpretation ("what" that point represents: an arch, an entablature, a cross vault, or biological degradation).

Point Cloud Classification: The Evolution to Automation

Until the last five years, the procedures for annotating and classifying point clouds were predominantly manual. Experienced operators isolated and grouped the points using modeling software in an extremely subjective process that was prone to human error and computationally unsustainable for urban- or monument-scale datasets. The introduction of Machine Learning (ML) algorithms and Deep Learning (DL) architectures has automated the identification of architectural elements, the quantification of material conservation states, and the abstraction of structural elements preparatory to subsequent FEM simulations.

The intelligent classification of the raw data fulfills several key functions. Firstly, it allows us to distinguish and map different historical construction techniques, deepening the architectural and stratigraphic exegesis of the building. Secondly, it isolates evidence of previous restorations and quantifies the materials' state of conservation, an unavoidable step for scheduled maintenance strategies. Finally, it clearly separates the structural elements (pillars, wall partitions) from the purely decorative ones (stuccoes, moldings), facilitating the engineering of the BIM model and optimizing calculation performance.

Traditional Machine Learning vs. Deep Neural Networks

The algorithmic landscape is mainly divided between classic Machine Learning approaches, which rely on the preventive extraction of features (feature engineering), and Deep Learning models, which can learn directly from raw data [6].

In the Machine Learning domain, algorithms such as Random Forests (RF), Support Vector Machines (SVMs), and K-Nearest Neighbors (kNN) have demonstrated remarkable effectiveness and efficiency. The success of these approaches depends on the quality of the *features* calculated a priori for each point or cluster of points. A consolidated workflow involves extracting geometric covariance metrics from the local tensor (such as flatness, linearity, sphericity, anisotropy, and scattering) and integrating colorimetric attributes derived from photogrammetry (RGB, HSL, and HSV color spaces). Scientific evidence suggests a strong statistical correlation between the geometric features of covariance and the morphologies of classical architectural elements: flatness predominates in wall facings, whereas linearity or cylindricity is clearly evident in columns and ribs. This discretization enables precise identification of degradation patterns (such as biological patinas or saline blooms) and classification of stone materials.

On the other side of the spectrum, deep learning has introduced neural networks specifically designed to process the inherently sparse, unstructured, and grid-free nature of point clouds. Pioneering architectures such as PointNet and its evolution, PointNet++, address the lack of point ordering by using symmetric functions (typically *max pooling*) to aggregate information, achieving remarkable results in segmenting simple objects. More advanced models, such as the Dynamic Graph Convolutional Neural Network (DGCNN), seek to overcome PointNet's limitations in understanding the local spatial context. DGCNN employs "EdgeConv" modules to dynamically construct k-nearest-neighbor graphs around each point, thereby recalculating the gaps in the feature space layer by layer. This mechanism allows the network to capture geometric edges and sharp transitions between adjacent architectural surfaces with extreme sensitivity.

The scientific literature offers rigorous comparisons between these methodologies. Surprisingly, the application of DL models not specifically optimized for point clouds (such as 1D and 2D CNN networks or recurrent Bi-LSTM networks forcibly adapted to point sequences) has often shown severe limitations in the recognition of complex historical geometries, being surpassed in terms of Overall Accuracy by traditional ML algorithms such as Random Forest. To overcome this problem, researchers have developed hybrid architectures. One of them is DGCNN-Mod+3Dfeat, an innovative framework that combines the robustness of locally pre-computed geometric-radiometric features with the hierarchical abstraction capabilities of DGCNN dynamic graphs, thereby maximizing predictive performance on complex datasets, such as those in cultural heritage (Table 1).

Table 1. Comparison of AI Architectures for Heritage Point Clouds

Methodology / Architecture	Operating Principle	Advantages of Cultural Heritage	Limitations
Random Forest (ML)	Construction of multiple decision trees based on pre-extracted features (geometric covariance, radiometry, and LiDAR return intensity)	Excellent variable interpretability, effective texture management, and low computational cost during training	Strong reliance on manual feature engineering; less capacity for complex hierarchical abstraction
PointNet / PointNet++ (DL)	Application of a multi-layer perceptron (MLP) on individual points and aggregation through symmetric functions (Max Pooling)	End-to-end learning directly from spatial coordinates; PointNet++ adds hierarchical analysis at multiple scales	Difficulty in capturing intricate topological structures at very high resolution without a prohibitive computational burden
DGCNN (DL)	EdgeConv modules for dynamically updating the local graph for each neural layer in feature space	Superior understanding of local spatial relationships and a clear definition of the edges of historical architectural elements	Demand for massive computing resources; need for huge and semantically perfect training datasets

The Generalization Problem and the ArCH Benchmark

One of the most difficult operational challenges in applying AI to historical heritage is the generalization problem [7]. Models frequently exhibit extremely limited transferability across different geographic regions, architectural styles, and acquisition conditions. A neural network meticulously trained to segment the moldings of a Greek Doric temple will inevitably fail to classify the pinnacles and buttresses of a Flemish Gothic cathedral, forcing operators to grueling, manual fine-tuning sessions.

Cutting-edge research has addressed this barrier by demonstrating that a Machine Learning model (specifically Random Forest), when trained on a transversal, essential set of architectural macro-classes (walls, roofs, openings, columns) and based on a selected core of invariant geometric features, possesses an unsuspected ability to generalize. This methodological approach enabled exporting a pre-trained model's weights to a 3D scenario that is entirely invisible to the network (an "unseen scenario"), yielding consistent classification regardless of the original acquisition technique (photogrammetry or LiDAR) or the geometric resolution of the data.

The historical absence of large-scale labeled datasets has hindered the training of high-performance DL networks for years. This gap has been partially addressed by the creation of public benchmarks, such as the *ArCH* (Architectural Cultural Heritage) dataset.

These datasets provide, for the first time, a standardized and rigorous validation ground comprising countless complex historical scenes, manually annotated by domain experts, enabling the scientific community to objectively measure and compare the performance of emerging algorithms.

Architectural Style Recognition and Visual Analysis via CNN

While three-dimensional segmentation analyzes volumetric spatiality, two-dimensional analysis of urban facades has benefited greatly from Convolutional Neural Networks (CNNs). The identification of the architectural style is not merely a purely historical-artistic exercise; it is a tool for objectively tracing the evolution of urban morphology, decoding the flows of cultural influence, and understanding the dynamics of social stratification within the building fabric.

Morphological Classification and Activation Maps (CAM)

The leap forward in large-scale visual classification is due to the exploitation of datasets extracted from massive digital archives. Foundational studies have used corpora comprising hundreds of thousands of panoramic images from Google Street View (for example, analyzing 150,000 elevations of the city of Paris over two centuries) to train CNN architectures that automatically discover and categorize visual patterns.

Advanced statistical models, such as Multinomial Latent Logistic Regression (MLLR) applied to features extracted from convolutional networks, and classifiers supported by Gabor filters, have been successfully employed to map the distinctive stylistic elements of specific construction periods. However, the greatest scientific value lies in interpreting the neural network's cognitive mechanisms. Using Explainable AI techniques such as Class Activation Mapping (CAM), researchers have generated heatmaps that "illuminate" the specific regions of the input image that the CNN focuses its mathematical attention on to formulate its probabilistic prediction.

The results of the CAM analyses offer surprising insights and are in perfect consonance with the theory of architectural composition. Neural networks, without any explicit programming (hard-coding), learn to systematically ignore spurious elements of the urban environment (pedestrians, cars, advertising signs) and almost entirely neglect the ground floors of buildings, which have historically been the most subject to invasive renovations and functional alterations for commercial purposes. On the contrary, algorithmic attention is heavily focused on the upper levels, the intersections between the base and the main floor, and predominantly on the shape, splay, and decoration of the fixtures and openings. This empirical discovery confirms the axiom that the window and its rhythm on the façade score constitute the primary genetic marker for tracing the evolution of the architectural style and the dating of the building (Table 2).

Table 2. Algorithmic Models for Architectural Style Recognition and Visual Analysis

Algorithmic Model	Type of Input	Objective and Main Output	Key Findings
Deep Convolutional Neural Network (DCNN)	Street View images (e.g., Paris)	Classification of the construction period and architectural style	Autonomous identification of diagnostic elements (windows, cornices); F1-score above 0.85 for historic buildings
Class Activation Mapping (CAM)	Final convolutional layers of DCNN networks	Visual localization (heatmap) of "areas of interest" for classification	Network validation: The algorithm ignores modern cars and shop windows, focusing on the decorative details of the noble floors
LR-CNN / Gabor Filters	Low-resolution or warped images	Object recognition under conditions of strong visual noise or degradation	Ability to distinguish complex styles (e.g., Baroque, Neoclassical) even in the absence of high-quality textures

Generative Design and Typological Flexibility

AI is not limited to the passive classification of the existing; it also extends to active architectural design. Generative and deep learning algorithms can process stylistic data to provide direct inspiration to designers during the concept phase, automating the exploration of layout alternatives (layout generation) and highlighting unexpected relationships between spatial constraints and programmatic instances.

A fascinating area of application concerns the design of dynamic and flexible facades, inspired by the principles of fractal geometry and algorithmic composition. Recent research shows that using specific fractal patterns (such as the golden triangle "1-2-√5") to generate textures and planar decompositions of cladding panels optimizes bioclimatic performance. These algorithmic-generative approaches support the creation of reactive architectural skins, capable of autonomously regulating the flow of solar radiation, preventing glare and limiting unwanted thermal loads, maintaining optimal visual comfort inside the building in response to changing external environmental conditions.

Heritage Building Information Modeling (HBIM) and Ontological Development

The semantically enriched metric data described so far constitute the necessary substrate for Heritage Building Information Modeling (HBIM). HBIM transforms the inert survey into a relational, parametric, and three-dimensional database, becoming the central pillar for the sustainable Life Cycle Management of the historic building and for the design of restoration interventions.

The Scan-to-BIM Paradigm and the Architectural Type

The conversion of raw survey data (point clouds) into a structured parametric model is referred to as *the Scan-to-BIM* methodology. In older workflows, point clouds were triangulated and converted into textured meshes; However, the inherent limitation of a mesh-only approach (mesh manipulation) lies in its ontological rigidity. A mesh lacks parametric intelligence: it does not know whether it is a wall, a window, or a floor, and it cannot be interrogated, quantified, or modified in accordance with the complex relational logic typical of BIM.

The epistemologically correct approach involves developing libraries of 3D objects (parametric families) from scratch, specifically designed to handle the anomalies, irregularities, and uniqueness of historical elements, rather than relying on standardized industrial libraries designed for orthogonal contemporary architecture. In this context, the HBIM is not merely a simple geometric container but rather a "process of knowledge" in continuous evolution and a means for developing and analyzing the *architectural type*.

Contemporary methodological guidelines impose strict parameters for the structural integration of geometric data with non-spatial information, such as historiographical data, archival sources, wall stratigraphy, petrographic analyses, and degradation reports. HBIM models thus serve as centralized virtual simulacra that support multidisciplinary teams. They enable precise quantification of estimative metric calculations for different design alternatives, advanced energy simulations, and the planning of maintenance interventions aimed at preserving material authenticity. New frontiers include the use of cloud-based artificial intelligence (such as Aurivus) that integrates directly as a plug-in into authoring BIM software, dramatically accelerating the recognition and translation of LiDAR scans into CAD/BIM models.

Levels of Detail (LoD) and Information Responsibility

A theoretical and extremely practical topic in HBIM modeling is the definition of the Level of Detail (LoD) or Level of Geometry (LoG). Conceptually derived from CityGML urban models, the concept of LoD organizes the description of the historical object according to a hierarchy of representation scales, governing the transition from the general volume to the meticulous detail (Table 3).

The classification developed by regulatory bodies such as Historic England outlines a path of increasing complexity: from LoD 1, which offers a basic conceptual representation of the volume, we progress towards LoD 3, a generic model that implements the classification of constituent materials, up to LoD 6, which represents the definitive "As-Built" model, incorporating all physical alterations, out-of-plumb and differential failures[2].

[2] BIM for Heritage. Historic England, 2017.

The selection of the optimal level of detail need not depend passively on the maximum resolution guaranteed by the available laser sensors. On the contrary, it is constrained by the client's desired output, legal liability considerations, and national public procurement guidelines. The unjustified increase in LoD involves immense computational burdens and slows down the fluidity of information management. In addition, interoperability among different authorial BIM platforms remains a heated topic of academic discussion, underscoring the urgency of adopting open formats (such as IFC) to ensure the longevity and long-term accessibility of heritage memories.

Table 3. Levels of Detail (LoD) for HBIM

Scala LoD (Historic England)	Definition and Degree of Accuracy	HBIM Purpose and Application
LoD 1 / LoD 2	Basic volumetric model; simplified conceptual representation without architectural details	Urban feasibility studies, mass analysis, and solar simulations on a neighborhood scale
LoD 3	Generic representation of the object with theoretical specification of structural components and materials	Preliminary thermal analysis, summary computation, preliminary design
LoD 4 / LoD 5	Detailed model with accurate physical dimensions, visible structural connections, and defined assemblies	Executive planning of the restoration, preliminary FEM calculation, and clash detection
LoD 6	"As-Built" model of very high metric rigor; It includes construction anomalies, chronic deformations, and high-resolution photorealistic textures	Real-time structural monitoring (Digital Twin), immersive virtual reality, and philological documentation of degradation

The Digital Twin Paradigm: IoT Ecosystems and Case Studies on a Global Scale

If the HBIM model represents the static database, or the faithful "As-Built" snapshot of a building at a given moment in time, the *Digital Twin* constitutes its dynamic, bidirectional, and interconnected evolution. A Digital Twin merges semantic three-dimensional geometry with a stream of continuous data from Internet of Things (IoT) sensor networks, transforming the building from a passive subject of investigation to an organism monitored in real time. This shift transforms models from purely descriptive to predictive, and ultimately to prescriptive.

In-Heritage and Microclimatic Monitoring: The Palazzi dei Rolli in Genoa

A paradigmatic case study of the application of the Digital Twin for environmental and urban protection is the "IN-HERITAGE" platform, operationally implemented in a pilot phase starting from December 2022 in the heart of the UNESCO site of the Palazzi dei Rolli in Genoa (directly involving the precious facades of Palazzo Tursi, Palazzo Reale, and Palazzo Spinola di Pellicceria) (Fig. 1).

The platform is engineered as an advanced decision support system to assess the resilience of architectural heritage to degradation factors exacerbated by climate change. The basic infrastructure consists of a rigorous geometric mapping obtained through TLS and photomodeling with drones, on which a photothermal diagnostic layer is superimposed. The real technological leap is the symbiotic integration with external IoT sensor networks and satellite big data. In-Heritage exploits the services provided by the global *Aura* sensors, which can monitor and transmit in real time the concentrations of severe pollutants that act as triggers for the chemical-physical erosion of the stone (such as NO2, PM10, PM2.5, SO2, H2S) and measure humidity, pressure, and environmental noise.

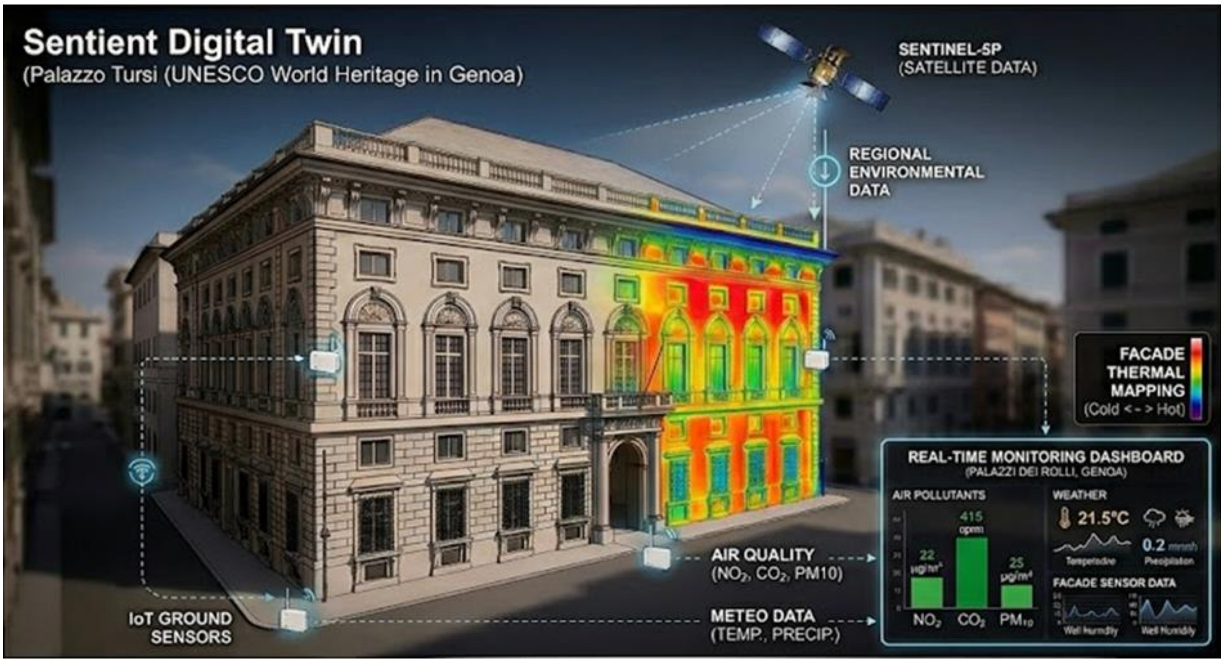

Fig. 1. *Conceptual representation of a "Sentient Digital Twin" applied to historical heritage (Palazzo Tursi, Genoa). The model integrates 3D geometry (HBIM), thermographic mapping of facades, and the flow of real-time environmental data acquired by ground-based IoT sensors and satellite surveys (Sentinel-5P)*

At the same time, the system collects data from the *Smart Rainfall System* (SRS). This disruptive, highly innovative technology estimates the intensity of atmospheric precipitation by analyzing, in real time, the attenuation of electromagnetic waves in satellite television signals received from a distributed network of pre-existing commercial dishes. The intersection of these variables transforms the perception of risk: the Digital Twin does not record damage a posteriori but calculates the probability of degradation by correlating acid rain or pollution peaks with the weakening of the stone binder.

In addition, the DT adds value to strategic urban planning and the tourism economy. By analyzing the data, the city administration was able to correlate peaks in microclimatic stress within the buildings (increases in CO2 and vibrations) with overcrowding caused by the simultaneous disembarkation of thousands of tourists from cruise ships in the Port of Genoa. This prescriptive approach enables real-time modulation of entrances and reorganizes infrastructure maintenance in harmony with tourist dynamics, thereby extending the monument's overall useful life.

Post-Disaster Reconstruction and Virtual Anastylosis: The Cathedral of Notre-Dame de Paris [8]

In emergency contexts of post-disaster reconstruction, the Digital Twin abandons its mere maintenance function to assume the dual role of a custodian of stratified memory and an experimental computing environment for structural restoration. The catastrophic fire that devastated the Cathedral of Notre-Dame de Paris in 2019 triggered an international scientific convergence, leading to the development of an n-dimensional digital ecosystem managed by specific working groups for digital data (Fig. 2).

The technological fulcrum of this undertaking is the *Aïoli* platform, a cloud-based tool developed specifically to allow multidisciplinary teams (chemists, structural engineers, art historians) to apply collaborative semantic annotations in both 2D and 3D formats. For Notre-Dame, the Digital Twin is not intended as a simple and fascinating computer-graphics replica, but rather as the intersection of all human knowledge inherent in the structure [9]. The system aggregates medieval construction sketches, dendrochronological surveys of burnt trusses, historical preservation reports, and the massive LiDAR scanning campaigns serendipitously acquired before and logically after the collapse into a single logical space. The infrastructure models the semantics of topological and mereological spatial relationships (the relationships between parts and wholes), ensuring irrefutable tracking of the origin and reliability of each piece of information, in compliance with the CIDOC CRM ontological protocols.

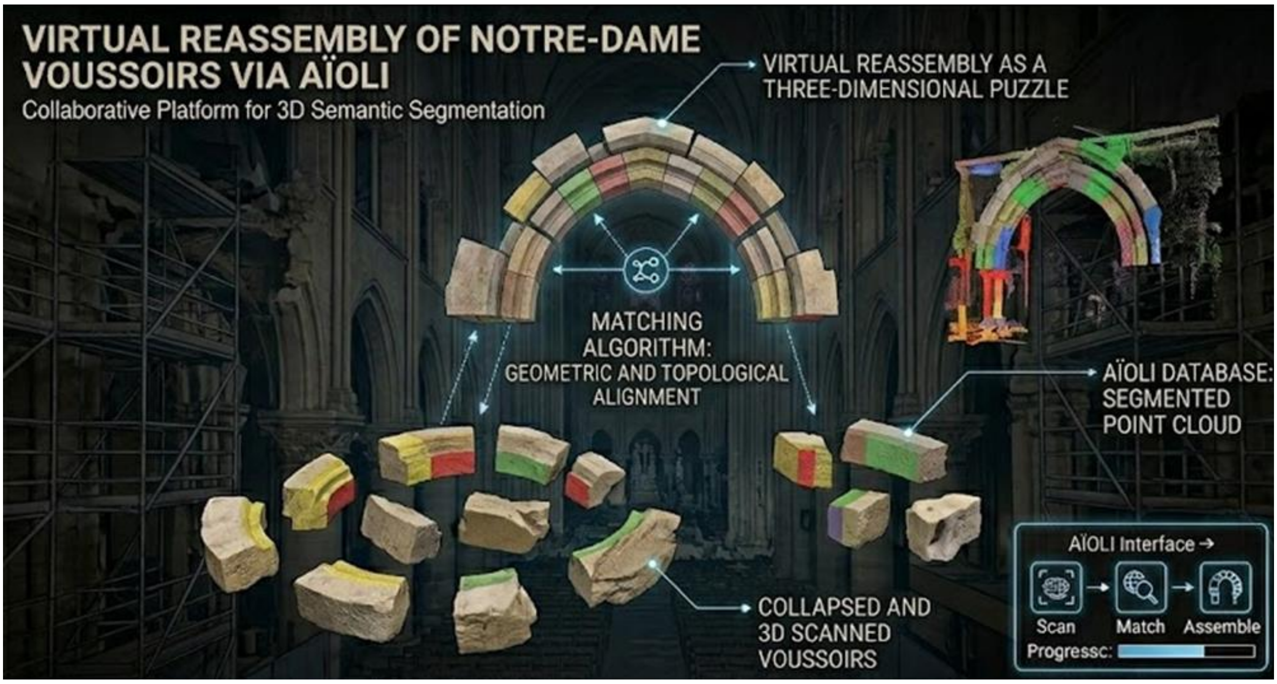

Fig. 2. *Virtual reassembly of the collapsed ashlars (voussoirs) of Notre-Dame de Paris using the collaborative platform Aïoli. The illustration shows the coupling algorithm based on the geometric and topological alignment of the 3D scans, managing the fragments as a complex three-dimensional puzzle*

One of the most daring engineering and theoretical applications within this Digital Twin is the virtual anastylosis of the nave's collapsed stone arches. Following the collapse, thousands of ashlars (voussoirs) were recovered from the rubble, cataloged, and individually scanned at very high resolution. The problem of their exact original repositioning has been addressed by artificial intelligence as a mathematical optimization problem and as an extremely complex three-dimensional puzzle. Combining operational research theories and reverse-engineering algorithms, the AI analyzed fracture planes, mortar residues, joint inclination, and shear impressions to couple the virtual segments, exploring an incalculable number of permutations that the human mind could not calculate. This simulation enabled the formulation and validation of physically and statistically accurate reconstruction hypotheses in the virtual environment before undertaking the physical handling and anastylosis of the heavy stone blocks, thereby acting as an essential bridge between the lost historical structure and the contemporary construction site.

Accessibility, Ethics (XAI), and Immersive Reality in the Context of Artificial Intelligence

The progressive delegation of diagnostic, analytical, and design responsibilities to high-complexity algorithms raises unavoidable epistemological and ethical questions, especially in humanistic and empirical disciplines such as architectural restoration.

Algorithmic Transparency and Overcoming the "Black-Box"

The pervasive inclusion of Artificial Intelligence in protection decision-making processes raises a potential conflict between the appeal of technological innovation and the imperative of philological reliability. Renowned researchers and experts engaged in heritage restoration frequently exhibit justified skepticism towards emerging software tools, driven by deontological fear of irreversibly altering the historical authenticity of the work due to fallacious machine-based predictions.

The central point of this academic and legal debate lies in the constitutive opacity of deep neural networks, a phenomenon known as the "black-box" problem. In complex Deep Learning models, the layers of hidden nodes and myriad nonlinear matrix operations prevent a human operator from retrospectively reconstructing the logical causal chain that prompted AI to provide a given result. If a neural network recommends the removal of a plaster based on a thermal pattern, but is unable to "explain" the physical principle behind its statistical deduction, the professional is faced with an unacceptable leap of faith in forensic engineering.

This limitation is compounded by the concept of "infrastructural embeddedness" explored in technological jurisprudence [10]: when AI systems become inextricable parts of the administrative and evaluation infrastructure, the lack of transparency creates significant liability gaps. Algorithmic decisions often rely on mere statistical correlations, depriving analysis of the fundamental causal explanation (intuitive causality) required in materials science. In the absence of transparency, there is a very high risk of training models that introject systemic biases, thereby perpetuating classification errors that disfavor vernacular architectural styles or minority typological anomalies that are poorly represented in the original training datasets.

To mitigate these risks, software engineering is transitioning to ethically responsible models based on Explainable AI (XAI) or "white-box" systems. The research aims to generalize explanatory visual frameworks that render the weighting variables driving neural network decision-making entirely intelligible. At the same time, it becomes imperative to structure sectoral ethical guidelines, specifically drawn up for the domain of cultural heritage, so that the choices made through AI are documented and slavishly comply with the Charter of London (transparency on the use of 3D models) and the Principles of the Seville Charter, ensuring that predictive reconstructions are always distinguishable from the surviving material original.

Virtual Reality, Space Anamorphosis, and Scientific Dissemination

The immense number of parametric digital assets and HBIM models produced in these investigations has a natural and highly effective application in museology, public communication, and interactive tourism through Immersive Virtual Reality (iVR) and Augmented Reality (AR) technologies. These tools possess the gift of democratizing the understanding of spatial hierarchies otherwise illegible to the lay public.

One of the most fascinating frontiers where survey, descriptive geometry, and iVR converge is the analytical simulation of ancient optical illusions, trompe-l'œil, and deceptive perspective machines, such as the paradoxical spaces engraved by Giovan Battista Piranesi in the *Prisons*. To fully decode imaginary architectures from non-rigorous perspectives, the researchers integrated the architectural survey with geometric analysis of perspective restitution and eye-tracking technologies, resulting in complex, navigable 3D models.

Specifically engineered virtual environments, such as the *AnGA* (Anamorphic Gallery) platform, immerse the user in modeled rooms, dynamically revealing the anamorphic illusion – a complex technique in which an image appears correct only from a specific, singular vantage point. In this context, iVR addresses and resolves a complex optical dichotomy: the physical use of anamorphosis in nature ideally requires monocular observation to eliminate depth perception, whereas immersive viewers rely on stereoscopic (binocular) vision. By parametrically managing the projection centers, these ecosystems blend the mathematical rigor of Renaissance optics with modern interactivity.

In addition, national initiatives of great magnitude, such as the *e-Archeo* project, have demonstrated the ability to translate vast diagnostic and stratigraphic databases into real, explorable ecosystems designed to enhance archaeological parks in Italy. Through AR and intelligent human-machine interfaces, the non-expert visitor can now physically visualize, in situ, the anastylotic hypotheses generated by scientific computing, observing the original volumes at full scale, superimposed in real time on the archaeological ruins, or cognitively interact with the stratifications of geophysical investigations applied to the ground.

Conclusion

The systematic and multidisciplinary investigation of the state of the art unequivocally confirms that Artificial Intelligence, advanced remote sensing techniques, and Digital Twins are no longer mere technological extensions for three-dimensional graphic representation, but have established themselves as a total cognitive paradigm, capable of refounding the methodologies of civil engineering, archaeology, and architectural restoration.

From solving mobility and scale challenges by coupling UAVs and compact LiDAR sensors for ultra-fast mapping, to integrating deep convolutional neural networks (such as DGCNN and PointNet variants) that automate the semantic segmentation of point clouds with previously unthinkable confidence rates, the industry has moved beyond the stage of manual abstraction. The demonstration that specific Machine Learning algorithms, such as random forests based on spatial geometric covariance, can address the critical problem of generalization, enabling the transversal interpretation of heterogeneous architectures and formal arrangements without costly retraining, represents a crucial juncture for the industrial scalability of historical relief [11] (Fig. 3).

The obligatory passage through the ontological structuring of objects in HBIM databases, whose detailed hierarchies (LoDs) encode both the deformational roughness of the historical monument and the legal responsibility of the professional, serves as a foundation for the dynamic interactions of Digital Twins. As crystallized in the formidable case studies of the Palazzi dei Rolli (interfaced with the atmospheric measurements of the SRS dishes) and the forensic reconstruction of the vaults of Notre-Dame, the Digital Twin elevates the building to a sensor of itself. By correlating microclimate, anthropogenic flows, and structural dynamics, the discipline transitions from an obsolete paradigm of reparative care to an era of predictive and prophylactic protection.

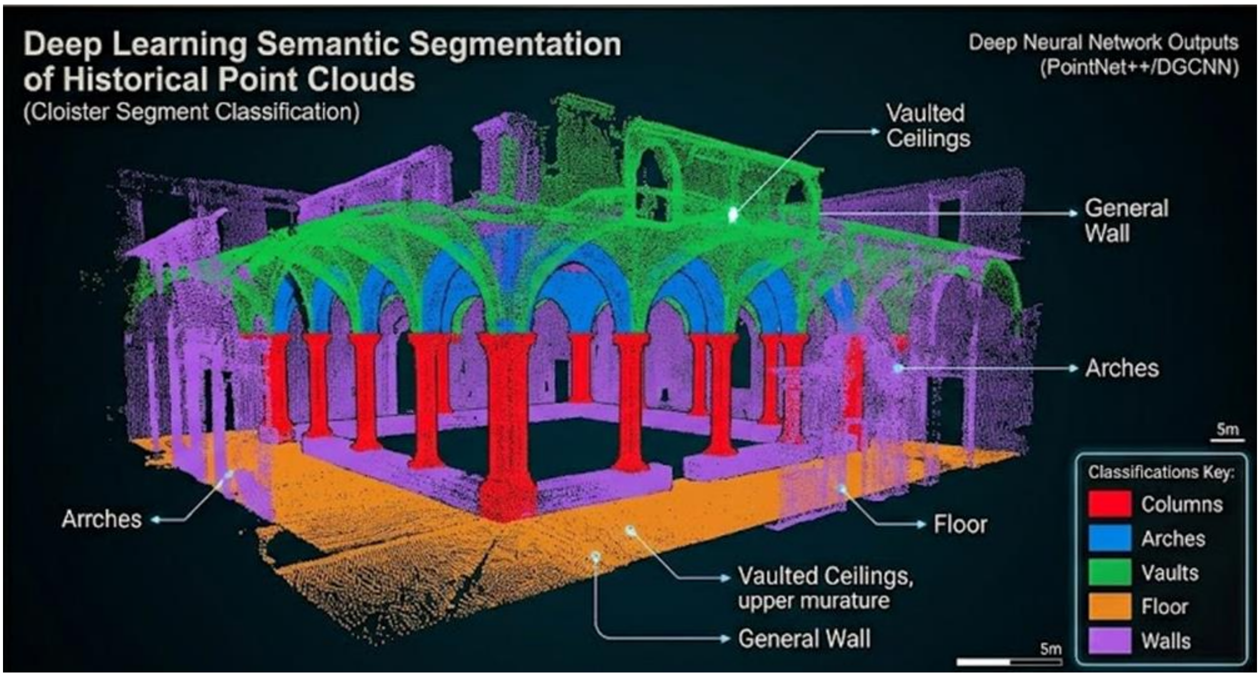

Fig. 3. *Semantic segmentation of a complex point cloud through Deep Learning architectures (e.g., PointNet++, DGCNN). The different architectural elements (columns, arches, vaults, masonry) are automatically classified and isolated to facilitate structural analysis and subsequent parametric modeling*

The research priorities of the next decade will focus on refining Explainable AI (XAI) logics to ensure the transparency and ethics of automated deliberations, and to avoid harmful interventions arising from black-box architectures. Equally decisive will be the bidirectional harmonization between the openBIM languages (IFC) and the complex FEM algebraic solvers to eliminate information degradation. With the widespread, mature adoption of these hybrid tools, heritage disciplines are intended to safeguard not only the material integrity but also the historical and expressive authenticity of the built civilization.

Conflict of Interest

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