sustainability

MDPI

Review

Advances in Geomatics Data Acquisition for Architectural Heritage: A Critical Review Toward Sustainable, Data-Driven Conservation

Agustí Costa-Jover [1,2], M. Amparo Núñez-Andrés [2,*] and Felipe Buill Pozuelo [2]

[1] Technical School of Architecture, Universitat Rovira i Virgili, Av. Universitat 1, Campus de Bellissens, 43204 Reus, Spain; agusti.costa@urv.cat
[2] Department of Civil and Environmental Engineering, Division of Geotechnical Engineering and Geosciences, Universitat Politècnica de Catalunya–Barcelona Tech, EPSEB, Av. Dr. Marañón 44-50, 08028 Barcelona, Spain; felipe.buill@upc.edu
* Correspondence: m.amparo.nunez@upc.edu

Abstract

This article presents a critical analysis of the evolution of geomatics data acquisition technologies in architectural heritage. The review traces this progression from 15th-century scientific drawings through discrete surveying methods and early analogue photogrammetry, culminating in modern massive capture systems such as digital photogrammetry and laser scanning. These advanced techniques have fundamentally transformed traditional approaches to 3D modelling. Based on the recent literature, we explore how this data is increasingly integrated into heritage building information modelling (HBIM), digital twins, and AI-based tools, driving a paradigm shift in the development of sustainable conservation strategies for historic buildings. Finally, while digital tools can actively reduce the environmental impact of buildings, we critically weigh these benefits against the direct energy and carbon costs of the digitisation process itself.

Keywords: geomatics techniques; HBIM; massive capture; bibliometric review

1. Introduction

The conservation of architectural heritage faces a dual challenge in the 21st century: the urgency of preserving historical constructions against increasing environmental stressors and the necessity of aligning this preservation with global sustainability goals. In this context, the documentation of heritage assets is no longer a passive act of archival recording but an active, critical component of conservation efforts. The sustainable preservation and management of historic buildings require accurate, comprehensive, and accessible data.

This article addresses the evolution of geomatics data acquisition technologies and their integration into digital workflows. While techniques such as photogrammetry and laser scanning have reached a level of maturity in terms of geometric precision, the challenge has shifted towards data interpretation and management. The transition from simple computer-aided design (CAD) to heritage building information modelling (HBIM) and, more recently, to digital twins (DTs) represents a paradigm shift, moving from static representations of the past to dynamic simulations capable of predicting future behaviour.

The primary aim of this critical review is to analyse how these advancements are reshaping the discipline. It explores the hypothesis that high-fidelity geomatics data, when properly structured and semantically enriched, is a prerequisite for any sustainable

Check for updates

Academic Editors: Monica Dinu and Lucian-Cristian Ratoiu

Received: 29 January 2026
Revised: 11 March 2026
Accepted: 12 March 2026
Published: 19 March 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

conservation strategy. The article begins with a historical overview, tracing the lineage of documentation from Renaissance drawings to modern digital surveying. Subsequently, the recent literature (2020–2025) is analysed in a critical review, organised into six thematic domains ranging from data acquisition to AI-driven analysis. Finally, an assessment of the ecological cost of using these technologies is incorporated into the discussion on the sustainability of architectural heritage digitisation.

2. Historical Background: The Evolution of Architectural Heritage Documentation

The necessity of recording and documenting heritage, whether architectural or archaeological, dates back to antiquity. Early classical examples can be found in the works on perspective and stereoscopy by Leonardo da Vinci (1452–1519) and Albrecht Dürer (1471–1528). A historical analysis of the transition from hand drawing to the digital era reveals several distinct stages in the evolution of documentation methodologies.

2.1. From the Renaissance to Scientific Drawing (1500–1800)

Initially, around 1500, drawing ceased to be merely a projective tool for new buildings and began to be used to document and understand the past. However, even within these early representations, a distinction emerged. On the one hand, the *veduta tradition*, born in the 18th century, focused on artistic engravings of ruins and landscapes. On the other hand, the Renaissance marked the beginning of complete building representation.

A fundamental milestone in heritage conservation is Raphael Sanzio's letter to Leo X (c. 1519), co-authored with Baldassare Castiglione. This document proposed, for the first time, a methodical approach to surveying the monuments of Rome using a compass and quadrant, establishing the orthogonal triad of plan, section, and elevation still in use today.

Millimetre-level pre-scientific rigour was later introduced by Antoine Desgodets [1]. Almost a century later, Stuart & Revett [2] produced the first precise documentation of Greek architecture, employing plumb lines and measuring tapes with strict accuracy. During the 18th century, the "Grand Tour" further institutionalised the practice of measuring ruins in situ across Italy and Greece.

As evidenced during this period, the primary objective focused largely on analysing what was perceived as European "antiquity". At that stage, the significance and relevance of the structures left by civilisations across the Americas and Asia had not yet been fully recognised. Nevertheless, we observe the same underlying intellectual preoccupation that exists today: the drive to understand historical precedence—an investigative curiosity that would subsequently extend to these other geographic regions. At this point, there is a noticeable bias in the literature, as it is rare to find references to Asian countries or architectural drawings of the "New World", as the Americas were then known.

Historically, heritage surveying (architectural or archaeological) relied on discrete data capture. Measuring tapes, plumb bobs, theodolites, and compasses were used. The operator had to decide in situ which exact points were relevant (corners, mouldings, and plane changes) and measure them one by one. The result was an analogue model (paper plans).

2.2. The Institutionalisation of Documentation and the Birth of Photogrammetry (19th Century)

The 19th century saw the institutionalisation of graphic documentation and the advent of photogrammetry. This era gave rise to restoration theory and analytical drawing, with Eugène Viollet-le-Duc as the most prominent figure. His *Dictionnaire raisonné* [3] formalised the "analytical drawing", explaining the internal logic of the building alongside its restoration theory.

A quantum leap occurred with the invention of photography and, subsequently, photogrammetry. In 1851, the French government commissioned the *Mission Héliographique*, the first state-led mass photographic inventory of endangered monuments [4]. Later, in 1893, Albrecht Meydenbauer coined the term "photogrammetry" and founded the Royal Prussian Photogrammetric Institute (*Königlich Preussische Messbildanstalt*), creating the world's first archive of metric negatives and demonstrating that plans could be derived directly from photographs [5]. A detailed analysis of this evolution from the Renaissance can be found in [6].

During this period, the idea of preserving information about what human conflicts can destroy emerged. However, although photogrammetry was introduced, it should be noted that only features represented at the fixed scale were documented. Data selection still relied on the operator, who sought a balance between detail and the requirements of the objective.

2.3. International Charters and the Schools of Thought (20th Century)

The 20th century was defined by the establishment of international guidelines for heritage management:

- The Athens Charter (1931) [7]: The first international document to mention the importance of documentation prior to restoration.
- The Venice Charter (1964) [8]: The most influential document of the 20th century. It established that restoration must be preceded by precise archaeological and historical studies, recommending photogrammetry as a key surveying technique.
- The Lausanne Charter (1990) [9]: The document defined minimum standards for non-destructive recording in archaeological heritage management.

These mid-century recommendations promoted photogrammetry as a reference surveying technique. Two major European schools of thought emerged during this period. The French school, led by Maurice Carbonell (founder of CIPA), focused on an "objective" and metric approach, prioritising the creation of massive documentary archives to safeguard against loss. Conversely, the Italian school developed the concept of *Rilievo Critico* (critical survey). This philosophy posits that a drawing is not a neutral mirror but a selective interpretation where the author decides which lines explain the architecture. This approach, rooted in Gustavo Giovannoni's *Restauro Scientifico*, emphasises recording the building "as it is". He was the intellectual reference behind the Athens Charter and the primary drafter of the Italian Restauro Charter (1932) [10].

This evolved into the *Rilievo Integrato* (Integrated Survey) methodology, standardised by Mario Docci at the University of Rome "*La Sapienza*". Docci systematised surveying as a scientific discipline combining history and geometry [11]. In Spain, Antonio Almagro Gorbea pioneered computerised photogrammetry, becoming a reference in the Hispanic world through his work at the School of Arab Studies (CSIC-*Consejo Superior de Investigaciones Científicas* in Spanish).

Parallel to this, the French *Archéologie du Bâti* (building archaeology) emerged in the late 20th century, applying stratigraphic excavation principles to standing structures to analyse the chronological sequence of construction units (UEM).

Although these trends originated in Europe, they now have a global reach. We are witnessing a globalisation of heritage practice, where the aim is to employ universally applicable techniques. It must also be noted that a wide array of geomatics tools is currently available for obtaining 2D/3D information to carry out heritage surveys, ranging from direct spatial data collection systems to indirect capture systems and from simple to advanced technologies. It is increasingly common to deploy highly advanced data capture

tools even when simpler systems would suffice for the required precision. As we will see in subsequent sections, these simpler systems can also be more sustainable.

2.4. From Analytical Photogrammetry to Massive Data Capture

Another major stage can be identified between 1970 and 2000, marked by the emergence of analytical photogrammetry and the introduction of the total station in the field of topography. Coupled with this was the advent of computer-aided design (CAD). The combination of these advances allowed for the establishment of a more systematised methodology, yet one that was still based—as in previous eras—on the selective collection of information and the drawing of the most representative elements.

The transition from paper to the digital era necessitated the establishment of new rules; consequently, the London Charter (2009) [12] set out the principles for the computerised visualisation of heritage. However, it was the advent of laser scanning sensors at the beginning of the 21st century, coupled with the rise of digital photogrammetry using Structure from Motion (SfM) algorithms [13,14], that truly transformed data capture into a mass process. Consequently, a new process of segmentation and identification of the architectural elements became necessary. These elements would subsequently form the basis for the creation of HBIM systems.

A leading authority in the transition of this philosophy to the digital world (laser scanning and BIM) is Roberto Mingucci from the University of Bologna [15]. Another prominent researcher in the field of photogrammetry and remote sensing applied to cultural heritage documentation is Fabio Remondino [16]. His work focuses on the combined use of 3D technologies, including laser scanners (LiDAR) and photogrammetric methods, to create precise digital models of archaeological sites and historic buildings [17].

Finally, all this digital information must be accompanied by a greater volume of data regarding the process itself. Documentation involves not only the building but also the process by which the digital model was created: metadata describes the content and context of the data (who, what, when), while paradata describes the collection process of that data (how, by whom, and under what conditions). A general timeline can be found in Figure 1, that summarizes the evolution of architectural heritage documentation.

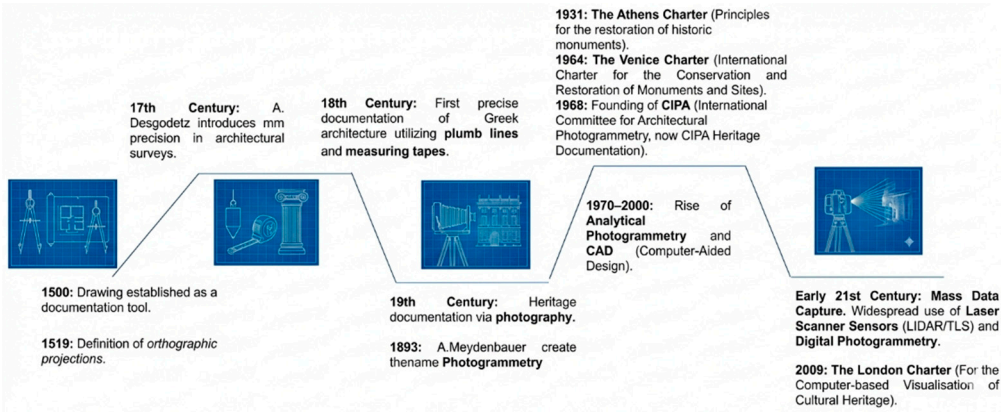


Figure 1. General techniques evolution timeline.

3. Literature Review: Digital Tools for Sustainable Preservation of Architectural Heritage

A qualitative literature review, rather than a strictly bibliometric analysis, was used to assess the integration of geomatics techniques in the architectural heritage field. The objective was not to provide an exhaustive statistical analysis of scientific production but to identify and discuss relevant trends, challenges, and technological shifts that have defined the field in recent years. Thus, a preliminary quantitative analysis based on article

keywords was first conducted. Subsequently, an in-depth study was carried out, expanding on the thematic groupings derived from these keywords.

3.1. Search Strategy and Selection Criteria

Architectural heritage, alongside the challenges and strategies for its conservation, is a virtually inexhaustible topic. Therefore, in order to focus the analysis on the objective of this article, the review was based on a targeted search of the scientific literature using explicit and reproducible criteria. The primary databases queried were Web of Science (WoS) and Scopus, chosen for their comprehensive coverage of engineering, geomatics, and heritage conservation journals.

The search was conducted using the following Boolean query structure applied to titles and keywords: ("architectural heritage" OR "built heritage" OR "historic building*") AND ("HBIM" OR "digital twin*" OR "artificial intelligence" OR "3D surveying" OR "geomatics" OR "photogrammetry" OR "laser scanning"). Beyond direct keyword queries, a "snowballing" method was adopted, where references within the initial search results were reviewed to identify further relevant contributions. To ensure transparency, the following inclusion and exclusion thresholds were applied:

- Document type: Only peer-reviewed journal articles.
- Language: Only articles published in English, to ensure a common baseline for semantic analysis.
- Temporal scope: The search primarily targeted the last six years (2020–2025) to focus on the most recent advancements. However, a limited number of selected works dating back to 2015 were intentionally included to provide the necessary historical context on the evolution of these methodologies.

To illustrate the volume of available literature and the impact of the filtering process, a search in the Web of Science (WoS) using the query ("architectural heritage" OR "built heritage" OR "historic building") AND "HBIM" initially retrieved a total of 29,662 entries. This number was reduced to 11,765 after applying the aforementioned inclusion and exclusion criteria. From this point, the selection process prioritised qualitative relevance over quantitative impact metrics or citation counts. However, given the practical impossibility of reviewing the entirety of the results, the initial screening was capped at the first 150 articles returned for each specific keyword combination.

Next, a conscious effort was made to ensure a balanced thematic representation across the field. For instance, given the vast quantity of recent literature on HBIM, the review intentionally curated these references to avoid over-saturation, thereby allowing space for a broader spectrum of emerging tools, such as AI-driven defect detection or IoT integration. Finally, a total of 62 articles were selected for detailed analysis based on the aforementioned criteria.

3.2. Keyword Analysis and Categorisation

To structure the critical review, a comprehensive analysis of the keywords associated with the selected 62 articles was performed. Initially, a total of 108 active keywords were identified in the descriptive data of each of the papers selected. However, given the lack of standardisation in the terminology used across different publications, a data normalisation process was necessary to obtain a clearer picture of the research landscape.

This process involved the correction of orthographic variations and the consolidation of synonymous or highly interconnected acronyms. For instance, terms such as "BIM", "HBIM", and "IFC" were grouped under a single category to reflect their interchangeable use in the context of heritage management. Similarly, "digital twin" and "physical twin" were merged to represent the broader concept of dynamic modelling.

The methodological step from 108 individual terms to a concise set of analytical categories was achieved through a process of thematic coding based on semantic affinity. Keywords were clustered not merely by their literal meaning but by their operational function within the heritage conservation workflow (e.g., terms related to "LiDAR", "UAV", and "point cloud" were clustered under "digital documentation"). The resulting frequency analysis highlights the dominance of specific technologies and concepts. As shown in Table 1 and Figure 2, apart from the expected general terms like "architectural heritage", the field is heavily driven by HBIM workflows (25 occurrences) and conservation strategies (18 occurrences), with a rapidly growing interest in digital twins and AI-driven methods.

Table 1. Normalised keywords by frequency of appearance in the selected literature.

Keyword (Normalised)	Frequency
Architectural heritage	26
HBIM and BIM	25
Conservation and preservation	18
Cultural heritage	18
3D modelling and data	15
Digital twins	9
AI and deep learning	7
Semantics and ontology	6
Integrated survey	5
Laser scanning and LiDAR	5
Sustainability	4
Visualisation and VR/AR	4
Knowledge systems	4
UNESCO	3
Digital technologies	3

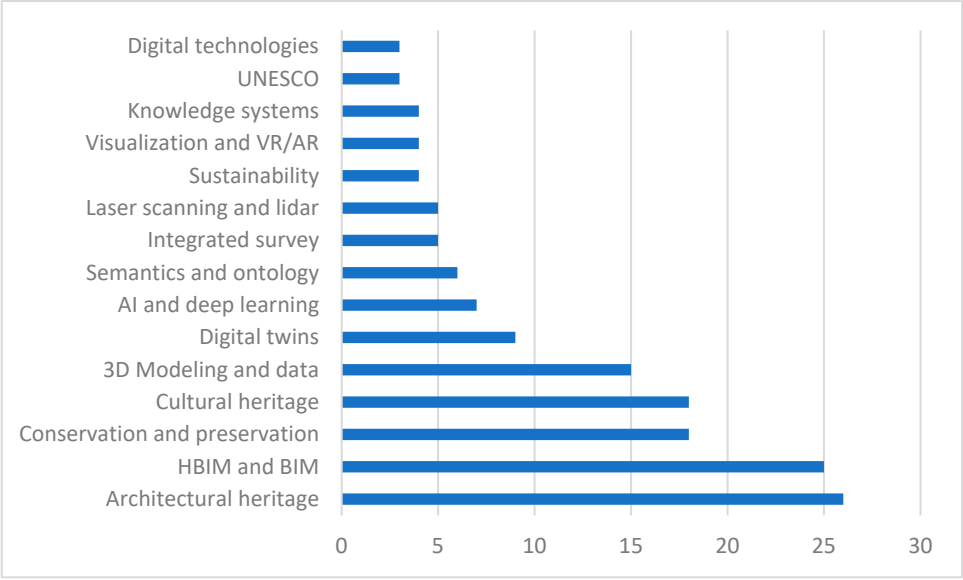


Figure 2. Normalised keywords identified in the selected literature.

The inherent limitations and potential biases of this qualitative approach are acknowledged. Firstly, the language constraint (English-only) introduces a geographic bias, potentially underrepresenting significant advancements published in local languages, particularly from Italy or Spain, where there are strong academic traditions in architectural restoration. Secondly, the qualitative curation of the final 62 articles relies on the authors' expert judgement to select the most "representative" works, which diverges from the strict reproducibility of a systematic PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) review. Consequently, this sample should not be viewed as an exhaustive statistical review but rather as a highly curated cross-section designed to identify and explain the current technological frontiers and operational trade-offs in sustainable heritage preservation.

Following quantitative filtering, the keywords were not merely treated as isolated statistics but were analysed qualitatively to detect recurring themes. The identified terms were clustered into six main thematic domains that reflect the operational workflow in heritage conservation, from initial data capture to final sustainability assessment. This conceptual categorisation, detailed in Table 2, serves as the backbone for the critical review presented in the subsequent sections.

Table 2. Definition of thematic domains for the critical review.

Thematic Domain	Associated Keywords (Selection)	Focus Analysis
1. Digital documentation	Architectural heritage, cultural heritage, 3D modelling, photogrammetry, laser scanning, UAV	The evolution of data acquisition techniques and the shift towards multisource integration.
2. Information modelling	HBIM, BIM, IFC, parametrisation, scan-to-BIM	The consolidation of HBIM as the central repository for geometry and information.
3. Knowledge and Semantics	Ontology, semantics, knowledge systems, semantic segmentation	The challenge of structuring unstructured data to represent historical and material complexity.
4. Structural health monitoring and risk assessment	FEA, masonry structures, pathology cracks, safety assessment, structural integrity	The application of digital tools for structural health monitoring and risk assessment and management.
5. Advanced analysis (AI and DT)	Digital twin, artificial intelligence, deep learning, machine learning, simulation	The emergence of predictive tools and dynamic models for real-time monitoring.
6. Sustainable conservation	Conservation, preservation, sustainability, energy efficiency, CO_2, life cycle	The application of digital data to drive sustainable interventions and environmental resilience.

3.3. Literature Review

The evolution of digital tools applied to architectural heritage conservation is a complex ecosystem of converging technologies. Based on the qualitative analysis of the selected literature, this review is organised into six thematic domains. These domains trace the data lifecycle: from its initial acquisition and quality assurance to its structuring in HBIM, its

application in structural health monitoring, its evolution into AI-driven digital twins, and finally, its critical role in sustainable conservation strategies.

1. Digital documentation

The foundation of any heritage intervention is accurate documentation. However, the recent literature indicates a paradigm shift from sporadic surveying to continuous monitoring and rigorous quality assurance [18,19]. Early contributions, such as [20], highlight the necessity of adhering to standard specifications, the most common the ISO, specifically ISO 19131 to ensure that photogrammetric products are not merely visual representations but reliable metric databases. This focus on accuracy remains central in current research. References [21,22] demonstrate that the integration of terrestrial laser scanning (TLS) with digital photogrammetry is no longer just about coverage but about cross-validating geometric reliability in complex historic environments.

Furthermore, the scope of documentation has expanded to include the territorial scale. Tsifodimou et al. [19] proposes frameworks using unmanned aerial vehicles (UAVs) to monitor the impact of urban growth on archaeological sites, effectively turning documentation into a tool for change detection. Similarly, ref. [23] emphasises the need for multisource data fusion to capture not just the geometry but the "state of health" of the building fabric, establishing a baseline for detecting material degradation over time.

2. HBIM for heritage management

While documentation captures reality, heritage building information modelling (HBIM) organises it. The literature reflects a maturation of HBIM from a modelling exercise to a management methodology. Hou [24] lays the groundwork for using digital protection designs, but recent studies tackle the complexity of managing these models throughout the building's lifecycle. Maiezza [25] discusses the challenges of translating the singularity of heritage assets into parametric environments without losing information.

A critical barrier identified is interoperability. References [26,27] argue that for HBIM to serve as a true repository for asset management, it must overcome the rigidity of proprietary software. The trend is towards open standards (Industry Foundation Classes—IFC) that allow data to be accessible for non-geometric queries. Nieto-Julián et al. [28] further stresses that the reliability of the "as-built" model is paramount; if the information model does not accurately reflect the physical reality, including its imperfections, it cannot serve as a valid tool for decision-making or heritage management.

3. Knowledge representation: semantics and ontologies

Geometry alone is insufficient for heritage conservation; it requires meaning. This domain explores how unstructured data is converted into structured knowledge. Acierno et al. [29] was among the first to propose ontologies to represent the conservation process, a concept that has evolved significantly. Current research focuses on semantic enrichment. References [30,31] explore automated classification methods where architectural elements are not just drawn but "understood" by the system. Sbrogiò [32] highlights the use of semantic segmentation to link geometric primitives with historical documents and material data. This semantic layer is crucial for what [33] describes as knowledge graphs, which allow conservators to query the model for historical relationships, decay patterns, or construction techniques.

Regarding practical applications, recent research highlights how ontologies and semantic models actively streamline the scan-to-BIM process. For instance, ref. [34] presents a classification-driven workflow, where semantic richness is used to semi-automate the conversion of raw point clouds into BIM-ready geometry, significantly reducing manual interpretation. Along similar lines, ref. [35] demonstrates the successful use of machine

learning algorithms for the semantic segmentation of architectural components, while [23] comprehensively reviews point cloud segmentation techniques essential for automated semantic extraction. Furthermore, as noted by [36], the application of ontologies facilitates the integration of multimodal data. This ensures that digital archives are not merely static storage systems but active, queryable environments that facilitate data reuse, interdisciplinary analysis, and the long-term transmission of cultural heritage.

4. Structural health monitoring (SHM) and risk assessment

A specific and highly technical application of these digital workflows is structural health monitoring (SHM). Unlike general documentation, SHM focuses on safety and resilience, particularly against seismic threats. Aroquipa et al. [37] presents a methodological framework integrating digital twins for seismic assessment, using the Basilica Maria Auxiliadora in Peru as a case study. Their work illustrates how finite element analysis (FEA) can be fed directly by accurate HBIM geometry.

The reliability of sensor data is also a key theme. Pirrotta et al. [38] introduces advanced coherence analysis for vibration monitoring in high-variability environments, such as the Castello Ursino, proving that robust data processing is essential to avoid false positives in damage detection. References [35,39] reinforce this, showing that the interoperability between the architectural model (BIM) and the structural model (FEA) is the weak link that current methodologies aim to address, ensuring that structural safety assessments are based on the actual, current condition of the building.

5. Advanced analysis (AI and DT)

The most advanced domain represents the strategic shift from static models to dynamic digital twins (DTs), with artificial intelligence (AI) serving as the computational engine. References [40,41] define the heritage digital twin not as a file, but as a living system connected to the physical asset via IoT sensors.

AI is the tool that makes these twins predictive. References [42,43] demonstrate the use of deep learning and convolutional neural networks (CNNs) for the automated detection of cracks and surface pathologies. Instead of manual inspection, these AI-driven models can process vast amounts of image data to identify defects early. Jamil et al. [44] extends this to structural prediction. The convergence of DT and AI moves conservation from a "reactive" approach (corrective conservation) to a "predictive" one (intervening before failure occurs).

6. Sustainable conservation

The integration of digital technologies in architectural heritage has transcended traditional preservation, increasingly positioning environmental sustainability as the central objective of modern interventions. Data, models, and simulations now serve as critical tools to ensure the environmental resilience of historic structures. References [45,46] discuss the urgency of adapting heritage to climate change, employing digital tools to simulate environmental stressors. From a broader management perspective, ref. [47] emphasises the necessity of implementing sustainable management plans that rely on continuous digital monitoring to safeguard both physical and cultural values.

Energy efficiency has emerged as a primary driver within this domain. References [48,49] present workflows for the energy retrofitting of historic buildings, demonstrating how HBIM can balance performance improvements with the preservation of heritage significance. To achieve concrete reductions in environmental impact, the integration of building energy modelling (BEM) has proven essential. For instance, ref. [50] illustrates how BIM-based analytical workflows can quantify operational carbon and simulate thermal and lighting impacts to guide the eco-retrofitting of mid-20th-century buildings. Taking this a step further, ref. [51] highlights the transformation of heritage buildings into "liv-

ing laboratories" through dense sensor networks designed to continuously monitor and optimise energy consumption in real time.

Beyond operational energy, the literature underscores the importance of minimising the embodied carbon and material impact of restoration works. Puerto et al. [52] introduces the integration of life cycle assessment (LCA) into the heritage workflow, enabling the precise calculation of the carbon footprint associated with restoration materials. As further discussed by [53], these data-driven approaches not only aid in selecting low-impact materials but also significantly reduce construction waste by preemptively identifying and resolving design errors in the virtual environment before physical execution.

This domain highlights that sustainable conservation must be strictly data-driven. By translating abstract sustainability goals into measurable indicators, such as operational energy consumption, carbon footprint, CO_2 emissions, and waste reduction, digital documentation becomes a key tool for aligning historic preservation with the tangible targets of the European Green Deal.

4. Environmental Cost of Digitisation

Beyond the reflections strictly related to historical background and a review of the literature, a critical issue that must be addressed is the fact that the digitisation of the capture, processing, and management results in higher resource consumption than traditional methods. To conduct this evaluation, a sustainability matrix [54] focused on environmental and social impacts is highly illustrative (economic costs being outside the scope of this review).

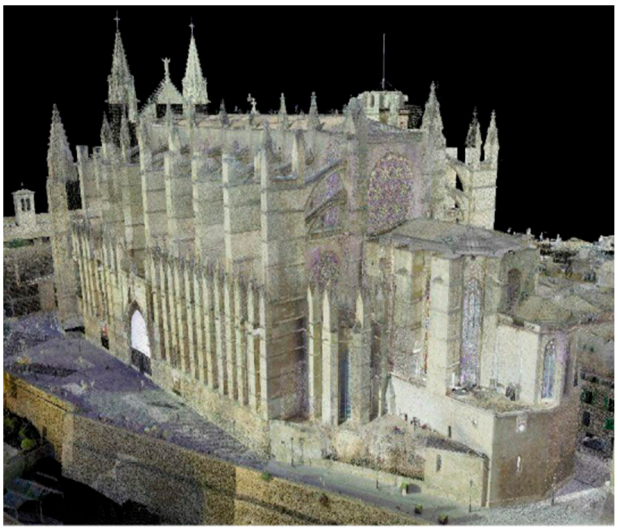
From an environmental perspective, quantification is based on the ecological footprint, specifically the volume of natural resources consumed. The use of digital tools inherently involves energy consumption by sensor batteries and high-performance computers, carbon dioxide emissions associated with cloud storage, and water consumption by the servers involved in data transmission and storage.

Ultimately, this consumption translates into carbon dioxide (CO_2) emissions, a key aspect of environmental impact.

Regarding the footprint of cloud storage systems, there is a wide range of possibilities. Most of the reviewed literature [55,56] estimates that 100 GB of data generates 0.2 tonnes of CO_2/year, a figure which is reduced to 0.1 tonnes when using an efficient network. Although there is a lack of empirical data to firmly confirm this point, it is suggested that more efficient servers from major providers, such as Google or Amazon, may result in lower emissions.

As an example, let us consider the digitisation of a large-scale heritage site, such as the Mallorca Cathedral, to identify the challenges ahead. The values presented in Table 3 (e.g., 5 kWh/GB, 5 L/kWh, and the conversion factor of 0.25 kg CO_2/kWh [57]) are indicative estimates based on the specific context of the average of companies in the Iberian energy market and local infrastructure. These parameters are highly dependent on regional energy mixes, data centre efficiencies, and local cooling technologies. Consequently, they should not be interpreted as universal standards but rather as a contextualised baseline to illustrate the methodological approach for quantifying the environmental footprint of digitisation.

Table 3. Example of the environmental impact of the digitisation of a historical building.

Environmental	
Data capture Sensor hours: 70 Battery consumption: 0.1 kWh Total energy: 1.75 kW **Data process** Total hours: 18 Average PC consumption: 0.2 kWh Total energy *: 3.6 kW Size during the process: roughly 965 GB Total energy *: 4800 kW **Data storage** Raw data: 400 GB Size final point cloud in cloud server: 700 Gb Total energy *: 3500 kWh Note: * **Considering 5 kWh per GB**	
Water resources Water consumption: 17,500 L **5 L per kWh is estimated to be consumed in a data centre, for cooling purposes**	
CO_2 footprint In capture, process and local storage *: 1201 kg CO_2 In cloud server storage **: 0.7 tonne CO_2/year **Note: * Conversion factors provided by the Spanish Ministry of Industry for non-renewal: 0.25 kg CO_2/kWh [57].** **** Considering an optimal network**	

5. Discussion

The analysis of the historical background and the literature reveals a state of deep transformation in the documentation of architectural heritage, characterised by a tension between technological capability and methodological implementation. While the "how" of data acquisition has been largely solved, with laser scanning and photogrammetry providing very accurate and fast surveys, the "why" and "what for" remain areas of intense development and debate.

This review highlights that the greatest bottleneck is no longer geometric capture but semantic enrichment. As identified in the "Italian school" of *Rilievo Critico*, a drawing was traditionally an interpretation of reality. In the digital era, this interpretation must be codified into ontologies and semantic data. The literature suggests that while we are capable of creating "digital doubles" (geometric copies), we often struggle to create true "digital twins" (functional replicas). Without proper semantic segmentation and knowledge representation, HBIM models are far from achieving their full potential.

Furthermore, interoperability remains a critical barrier. The reviewed studies consistently point to the friction between the irregularity of historic shapes and the rigid, standardised libraries of BIM software. The transition from "scan-to-BIM" to "scan-to-twin" requires overcoming these proprietary limitations and advocating for open standards (IFC) that allow data to flow seamlessly between acquisition tools, structural analysis software (FEA), and energy simulation engines.

Finally, the emergence of AI and IoT changes the temporal dimension of conservation. Documentation is no longer a snapshot in time but a continuous stream of data. This shift from reactive repair to predictive maintenance is the most significant contribution of digitisation to sustainability. By predicting structural failure or optimis-

ing energy performance in real-time, digital tools are not just saving data; they are extending the physical lifespan of the building itself, which is the ultimate definition of sustainable conservation.

Nevertheless, despite these technological advances, there is a fundamental risk: overreliance on digital models can reduce the focus on physical conservation. A highly detailed digital twin might create a false sense of security, distancing conservators from the actual decay of the historic structure. Therefore, digital tools must remain a means to an end. The virtual model should never replace the physical building. Instead, it must actively guide real, on-site material interventions to ensure the authentic preservation of the heritage.

As frequently observed in the literature, the latest technology with the greatest possible detail is often used even when it is not strictly necessary for the preservation or retrofitting work. To ensure the sustainability of digital technologies, the balance between the required accuracy/resolution and the environmental cost must be integrated into the decision-making process. Processing and storing information locally, rather than relying exclusively on cloud infrastructures, can also considerably reduce this footprint.

Furthermore, the implementation of these digital tools is not globally uniform. Particularly in non-European and developing contexts, relevant adoption barriers persist, including the prohibitive initial costs of advanced geomatics equipment, a shortage of specialised technicians, and the absence of localised operational frameworks. As a consequence, these constraints currently limit the universal applicability of these techniques.

However, this environmental and economic cost must be weighed against the social aspect of sustainability. From a social perspective, the digitisation of projects facilitates the democratisation of access to information. Historically, we have transitioned through several phases: from information being reserved exclusively for scholars or the wealthy to relocating heritage to museums (where it was preserved but often lost its original context) to once again prioritising the in situ preservation of our heritage.

6. Conclusions

Based on the historical background and the critical review of the evolution of geomatics data acquisition and its integration into heritage workflows, the following key conclusions can be drawn:

From surveying to monitoring: Documentation has evolved from a static event to a continuous process. Modern workflows integrate multisource data to monitor changes, turning the digital model into a dynamic baseline for preventive conservation.

Semantics over geometry: The geometric precision of a model is less critical than its semantic quality. The value of HBIM lies in its ability to structure knowledge (historical, material, and constructional), making ontologies essential for managing the complexity of heritage data. Thus, to advance this paradigm, subsequent research must explicitly address methodologies for embedding culturally grounded narratives, intangible heritage values, and contextual significance into the development and structuring of these information models.

Interoperability and AI integration: Sustainable management requires simulating possible scenarios (energy performance, structural behaviour, risk assessment, etc.) and processing massive datasets. This is only possible if data is highly interoperable. Furthermore, artificial intelligence is shifting the paradigm from manual interpretation to automated analysis. In this context, the adoption of open standards is not merely a technical preference but a fundamental necessity to guarantee the accessibility and long-term survival of the data, transparency, and cross-disciplinary exchange of heritage information.

Sustainability: The ultimate purpose of digital documentation is to support decision-making. By facilitating life cycle assessment (LCA) and energy retrofitting without com-

promising historical value, geomatics data becomes a primary tool for the sustainable preservation of the built environment.

In addition, regarding what may be termed digital sustainability, while digital tools are essential for modern preservation, their deployment carries a significant and often overlooked environmental footprint, including energy consumption, CO_2 emissions, and water usage associated with data processing and cloud storage. Future interventions must adopt a fit-for-purpose approach, critically evaluating the balance between the highest possible digital resolution and its ecological cost. Furthermore, this environmental impact must be weighed against the profound social benefits of digitisation, which democratises access to knowledge and can play a key role in the development of sustainable preservation strategies for historic buildings.

Author Contributions: Conceptualization; methodology; investigation; writing—original draft preparation; writing—review and editing, A.C.-J., M.A.N.-A. and F.B.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Reviewed papers comes from the data base Web of Science available with subscription from https://clarivate.com/academia-government/scientific-and-academic-research/research-discovery-and-referencing/web-of-science/ (last access on 28 January 2026).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Desgodets, A. *Les Édifices Antiques de Rome*; Chez Iean Baptiste Coignard: Paris, France, 1682.
2. Stuart, J.; Revett, N. *The Antiquities of Athens*; John Haberkorn: London, UK, 1762.
3. Viollet-le-Duc, E.E. *Dictionnaire Raisonné de l'Architecture Française du XIe au XVIe Siècle*; B. Bance (A. Morel): Paris, France, 1854.
4. Baillargeon C. Anne de MONDENARD, La Mission héliographique: Cinq photographes parcourent la France en 1851, París, Monum, Éditions du patrimoine, 2002, 320 p., 350 ill. NB y col., cat. raisonné, ann., bibl., ind., 69 E. *Estud. Fotogr.* **2003**, *13*, 171–173.
5. Grimm, A. Albrecht Meydenbauer: Bauingenieur—Fotograf—Photogrammeter. *J. Photogramm. Remote Sens. Geoinf. Sci.* **2021**, *89*, 371–389. [CrossRef]
6. Pérez-Gómez, A.; Pelletier, L. *Architectural Representation and the Perspective Hinge*; The MIT Press: Cambridge, MA, USA; London, UK, 2000.
7. ICOMOS. The Athens Charter for the Restoration of Historic Monuments. In Proceedings of the First International Congress of Architects and Technicians of Historic Monuments, Athens, Greece, 21–30 October 1931.
8. ICOMOS. International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter). In Proceedings of the Second International Congress of Architects and Technicians of Historic Monuments, Venice, Italy, 25–31 May 1964.
9. ICOMOS. *Charter for the Protection and Management of the Archaeological Heritage*; International Committee for Heritage Management: Lausanne, Switzerland, 1990.
10. Consiglio Superiore per le Antichità e Belle Arti. *Carta del Restauro*; Ministero dell'Educazione Nazionale: Rome, Italy, 1932.
11. Docci, M.; Maestri, D. *Storia del Rilevamento Architettonico e Urbano*; Editori Laterza: Rome, Italy; Bari, Italy, 1984.
12. London Charter. *The London Charter for the Computer-Based Visualisation of Cultural Heritage (Draft 2.1)*; King's College: London, UK, 2009.
13. Ullman, S. The interpretation of structure from motion. *Proc. R. Soc. London Ser. B Biol. Sci.* **1979**, *203*, 405–426.
14. Hartley, R.; Zisserrman, A. *Multiple View Geometry in Computer Vision*; Cambridge University Press: Cambridge, UK, 2004.
15. Mingucci, R.; Garagnani, S.; Cinti Luciani, S. CAD versus BIM: The evolution of acronyms or a revolution in the world of design? *Disegnare Idee Immagin.* **2012**, *23*, 68–79.
16. Remondino, F. Heritage recording and 3D modeling with photogrammetry and 3D scanning. *Remote Sens.* **2011**, *3*, 1104–1138. [CrossRef]

17. Amoroso, G.; Appolonio, F.; Bacci, G.; Baldissini, S.; Benedetti, B.; Gaiani, M.; Manferdini, A.; Masci, M.E.; Remondino, F. *Modelli Digitali 3D in Archeologia: Il Caso di Pompei*; Scuola Normale Superiore: Pisa, Italy, 2010.
18. Dolińska, N.; Wojciechowska, G.; Bednarz, Ł. Integration of AI and IoT sensors for continuous monitoring and restoration of cultural heritage sites-determining critical factors. *Int. J. Conserv. Sci.* **2025**, *16*, 501–516. [CrossRef]
19. Tsifodimou, Z.E.; Skondras, A.; Stamou, A.; Skalidi, I.; Tavantzis, I.; Stylianidis, E. Monitoring the Impact of Urban Development on Archaeological Heritage Using UAV Mapping: A Framework for Preservation and Urban Growth Management. *Drones* **2025**, *9*, 669. [CrossRef]
20. Campos, M.B.; Tommaselli, A.M.G.; Ivánová, I.; Billen, R. Data product specification proposal for architectural heritage documentation with photogrammetric techniques: A case study in Brazil. *Remote Sens.* **2015**, *7*, 13337–13363. [CrossRef]
21. Moyano, J.; Nieto-Julián, J.E.; Lenin, L.M.; Bruno, S. Operability of Point Cloud Data in an Architectural Heritage Information Model. *Int. J. Archit. Herit.* **2022**, *16*, 1588–1607. [CrossRef]
22. Conti, A.; Fiorini, L.; Massaro, R.; Santoni, C.; Tucci, G. HBIM for the preservation of a historic infrastructure: The Carlo III bridge of the Carolino Aqueduct. *Appl. Geomat.* **2022**, *14*, 41–51. [CrossRef]
23. Zhao, J.; Hua, X.; Yang, J.; Yin, L.; Liu, Z.; Wang, X. A Review of Point Cloud Segmentation of Architectural Cultural Heritage. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *10*, 247–254. [CrossRef]
24. Hou, S.Q. A Design and Research on Protection of Architectural Heritage Based on Digital Technology. *MATEC Web Conf.* **2016**, *63*, 02038. [CrossRef]
25. Maiezza, P. As-Built Reliability in Architectural Hbim Modeling. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *42*, 461–466. [CrossRef]
26. Alshawabkeh, Y.; Baik, A. Integration of photogrammetry and laser scanning for enhancing scan-to-HBIM modeling of Al Ula heritage site. *Herit. Sci.* **2023**, *11*, 147. [CrossRef]
27. Turco, M.L.; Bono, J.; Parameters, A.T. Modeling and Taxonomy for an HBIM Baroque Facade. *Nexus Netw. J.* **2024**, *26*, 609–630. [CrossRef]
28. Nieto-Julián, E.; Bruno, S.; Moyano, J. An Efficient Process for the Management of the Deterioration and Conservation of Architectural Heritage: The HBIM Project of the Duomo of Molfetta (Italy). *Remote Sens.* **2024**, *16*, 4542. [CrossRef]
29. Acierno, M.; Cursi, S.; Simeone, D.; Fiorani, D. Architectural heritage knowledge modelling: An ontology-based framework for conservation process. *J. Cult. Herit.* **2017**, *24*, 124–133. [CrossRef]
30. Zhang, X.; Zhi, Y.; Xu, J.; Han, L. Digital Protection and Utilization of Architectural Heritage Using Knowledge Visualization. *Buildings* **2022**, *12*, 1604. [CrossRef]
31. Bevilacqua, M.G.; Russo, M.; Giordano, A.; Spallone, R.; Twinning, D.; Reality, V. 3D Reconstruction, Digital Twinning, and Virtual Reality: Architectural Heritage Applications. In *Proceedings of the 2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, VRW 2022*; IEEE: New York, NY, USA, 2022; pp. 92–96. [CrossRef]
32. Sbrogiò, L. Open Hbim: Ifc-Based Virtualization of Architectural Heritage. *Scires-It* **2024**, *14*, 91–106. [CrossRef]
33. Yang, X.; Lu, Y.C.; Murtiyoso, A.; Koehl, M.; Grussenmeyer, P. HBIM modeling from the surface mesh and its extended capability of knowledge representation. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 301. [CrossRef]
34. Salah, R.; Géczy, N. Architectural Heritage Digitization: A Classification-Driven Semi-Automated Scan-to-HBIM Workflow. *Buildings* **2026**, *16*, 21. [CrossRef]
35. Croce, V.; Caroti, G.; Piemonte, A.; De Luca, L.; Véron, P. H-BIM and Artificial Intelligence: Classification of Architectural Heritage for Semi-Automatic Scan-to-BIM Reconstruction. *Sensors* **2023**, *23*, 2497. [CrossRef]
36. Fu, X.; Li, M.; Li, X.; Chen, W.; Yu, L.; Chen, Z.; Wen, S.; Li, Y.; Du, J.; Wang, Y.; et al. Emerging Computing Technology for Digital Culture Heritage Preservation and Inheritance: A Literature Review. *IEEE Trans. Comput. Soc. Syst.* **2025**, 1–38. [CrossRef]
37. Aroquipa, H.; Hurtado, A.; Angel, C. Methodological framework for integrating structural health monitoring and digital-twin models for seismic assessment of heritage buildings: Case study of Basilica Maria Auxiliadora, Lima, Peru. *Structures* **2025**, *80*, 110115. [CrossRef]
38. Pirrotta, C.; Gueli, A.M.; Trigona, C.; Imposa, S. Coherence Analysis for Vibration Monitoring Under High Variability Conditions: Constraints for Cultural Heritage Preventive Conservation. *J. Sens. Actuator Netw.* **2025**, *14*, 45. [CrossRef]
39. Guzzetti, F.; Anyabolu, K.L.N.; Biolo, F.; Dell'orto, R. Bim and Castello Sforzesco in Milan. A Particular Approach to Digitization of the Architectural and Information Heritage. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.-ISPRS Arch.* **2022**, *46*, 115–122. [CrossRef]
40. Biolo, F.; Guzzetti, F.; Anyabolu, K.L.N. Integration of different types of survey output and the information asset in a 3d model of the castello sforzesco in milan. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.-ISPRS Arch.* **2023**, *48*, 219–226. [CrossRef]
41. Franco, P.A.C.; de la Plata, A.R.M.; Sendín, M.P. Investigating a Workflow for Obtaining Physical Models from Digital Twins Obtained through Photogrammetry and TLS: New Ways for a Sustainable Dissemination of Heritage. *Appl. Sci.* **2023**, *13*, 1057. [CrossRef]

42. Arsalan, H.; Heesom, D.; Moore, N. From Heritage Building Information Modelling Towards an 'Echo-Based' Heritage Digital Twin. *Heritage* **2025**, *8*, 33. [CrossRef]
43. Bouchachi, M.; Jiménez-Delgado, A.; De-Gracia-Soriano, P.; Nemroudi, R. Architectural Heritage and Artificial Intelligence: Diagnosis and Solutions Proposed by ChatGPT for Algerian Historical Monuments. *Heritage* **2025**, *8*, 139. [CrossRef]
44. Jamil, O.; Brennan, A.M. Immersive heritage through Gaussian Splatting: A new visual aesthetic for reality capture. *Front. Comput. Sci.* **2025**, *7*, 1515609. [CrossRef]
45. Dionizio, R.F.; López-Chao, V. Integrating HBIM and WebGIS for the Documentation, Visualization and Management of Modern Architectural Heritage Sites. *Int. J. Archit. Herit.* **2025**, *19*, 3530–3549. [CrossRef]
46. Twumasi-Ampofo, K.; Oppong, R.A.; Quagraine, V.K. The state of architectural heritage preservation in ghana: A review. *Cogent Arts Humanit.* **2020**, *7*, 1812183. [CrossRef]
47. Arques, S.G.; Casasola, M.G.; Hidalgo, B.D.E. Towards sustainable management of the World Heritage in Spain: From identification to monitoring of cultural values. *Conserv. Patrim.* **2025**, *48*, 115–132. [CrossRef]
48. Vuoto, A.; Funari, M.F.; Lourenço, P.B. On the Use of the Digital Twin Concept for the Structural Integrity Protection of Architectural Heritage. *Infrastructures* **2023**, *8*, 86. [CrossRef]
49. D'Orazio, M.; di Giuseppe, E.; Mariotti, C.; Muccioli, M.F. Leveraging User-Generated Content to Enhance Heritage Monitoring Protocols and Resources Allocation Through Aspect-Based Sentiment Analysis. *J. Inf. Technol. Constr.* **2025**, *30*, 397–417. [CrossRef]
50. Bernardini, E.; Palmero-Sánchez, P.L.; De-Juan-Ripoll, C.; Rodrigo-Catalán, P. Integrating Eco-Design Strategies in the Energy Retrofitting of Mid-20th Century Heritage Buildings: The Case of Antonio Rueda's Housing Complex. *Appl. Sci.* **2026**, *16*, 564. [CrossRef]
51. Naya, C.; Dorregaray-Oyaregui, S.; Alonso, F.; Roquette, J.L.; Yoldi, J.M.; Martín-Gómez, C. Transforming a Heritage Building into a Living Laboratory: A Case Study of Monitoring. *Energies* **2025**, *18*, 3622. [CrossRef]
52. Puerto, A.; Castañeda, K.; Sánchez, O.; Peña, C.A.; Gutiérrez, L.; Sáenz, P. Building information modeling and complementary technologies in heritage buildings: A bibliometric analysis. *Results Eng.* **2024**, *22*, 102192. [CrossRef]
53. Cinquepalmi, F.; Tiburcio, V.A. Sustainable Restoration of Cultural Heritage in the digital era. *Vitruvio* **2023**, *8*, 76–87. [CrossRef]
54. Shanshan, Z.; Ahmad, A.; Heng, X. Analysis of Management Strategies for Urban Hotels in China Under the Sustainable Development Goals of Low-Carbon Tourism. *Int. J. Prof. Bus. Rev.* **2023**, *8*, e02995. [CrossRef]
55. Adamson, J. Carbon and the Cloud. Hard Facts About Data Storage. *Stanford Magazine*, 2017. Available online: https://stanfordmag.org/contents/carbon-and-the-cloud (accessed on 26 February 2026).
56. Melamedov, Z.M. Cómo Reducir el Consumo de Agua en los Centros de Datos en la Nube. Data Center Dynamics. 18 December 2024. Available online: https://www.datacenterdynamics.com/es/opinion/como-reducir-el-consumo-de-agua-en-los-centros-de-datos-en-la-nube/ (accessed on 26 February 2026).
57. Spanish Ministry of Industry. Factor Emission Conversion. Available online: https://www.miteco.gob.es/content/dam/miteco/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/factoresemision_tcm30-542746.xlsx (accessed on 25 February 2026).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.