heritage

Review

Recording of Historic Buildings and Monuments for FEA: Current Practices and Future Directions

Francesca Turchetti [1,*], Branka Cuca [1], Daniela Oreni [1] and Athos Agapiou [2]

[1] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy; branka.cuca@polimi.it (B.C.); daniela.oreni@polimi.it (D.O.)
[2] Department of Civil Engineering and Geomatics, Faculty of Engineering and Technology, Cyprus University of Technology, Saripolou 2-8, Limassol 3036, Cyprus; athos.agapiou@cut.ac.cy
* Correspondence: francesca.turchetti@polimi.it

Abstract: Cultural heritage (CH) sites and monuments share significant historical and cultural value, but at the same time, these are highly vulnerable to deterioration due to age, construction methods, and materials used. Therefore, stability studies for CH structures through numerical analyses allow researchers and stakeholders to safeguard them against time and exposure to hazards. To obtain reliable results for stability studies, detailed and accurate geometric documentation is needed prior to any modeling or simulation. In this context, geomatics technologies like LiDAR and photogrammetry can offer great support in documenting their structural integrity, providing efficient, non-invasive data collection methods that generate 3D point clouds. Nevertheless, despite the benefits, geomatic methods remain underutilized in structural engineering due to limitations in converting 3D point clouds directly for use in finite element modeling (FEM) analysis. The paper aims to review current approaches for the generation of FE models for structural analysis employing data obtained from 3D digital surveys. Each approach is described in detail, providing examples from literature and highlighting its advantages and disadvantages. Studies show that analysis accuracy depends strongly on point cloud level of detail, underlining the importance of precise geomatic surveys. Emerging workflows and semi-automated methods enable point clouds to be integrated with BIM (building information modeling) and FEM, thereby enhancing the contribution that laser scanning techniques and 3D modeling provide for the analysis of the stability of structures belonging to cultural heritage.

Keywords: point cloud; cultural heritage; FEM; 3D modeling; BIM

Received: 11 December 2024
Revised: 15 January 2025
Accepted: 24 January 2025
Published: 28 January 2025

Citation: Turchetti, F.; Cuca, B.; Oreni, D.; Agapiou, A. Recording of Historic Buildings and Monuments for FEA: Current Practices and Future Directions. *Heritage* **2025**, *8*, 55. https://doi.org/10.3390/heritage8020055

1. Introduction

Nowadays, the preservation and maintenance of cultural heritage (CH) buildings and monuments is critical, especially in countries exposed to seismic risk. These structures are particularly vulnerable due to their age, construction techniques, past restoration or structural modifications, and materials [1]. When disasters strike CHs, the damage often extends beyond physical destruction, resulting in the loss of artistic and historical materials and an intangible loss of memory for the communities connected to that heritage. Preserving these structures not only protects their aesthetic and historical value but also sustains the identity and continuity of communities.

Over the past years, there have been remarkable advancements in documenting the structural integrity of CH structures. When structural aspects are involved in the conservation of the building, specific numerical analyses must be performed that involve the development of three-dimensional models. In numerical simulation studies, the structural response of a historical building is usually investigated with respect to several load conditions (e.g., horizontal movements induced by earthquakes, etc.) that are probable to affect the structure. Due to the intricate and complex geometry that usually characterizes CH buildings, the structural analysis of these structures is challenging. This process is further complicated by the lack of archive documents with information on geometry and materials, as engineers must rely on non-invasive methods and educated assumptions.

Since the early 2000s, architects and engineers have increasingly relied on laser scanning technology (also known as LiDAR, which stands for Light Detection and Ranging) for the design, the management, and the monitoring of projects [2]. Geomatics techniques like LiDAR and photogrammetry offer the advantage of rapidly capturing data remotely about the geometry and current condition of the surveyed objects. The final output is the creation of a point cloud that represents the very first version of a three-dimensional digital twin of the object. These technologies are particularly valuable for geomatic documentation of architecture and built cultural heritage in general, creating models that help preserve their design for future generations, and in structural engineering for assessing the condition of existing structures, enabling engineers and architects to perform detailed analyses without physical contact.

Despite their potential, geomatic technologies are still underutilized in structural engineering research, and the direct exploitation of point clouds for structural purposes remains very limited [3–6]. The current standard process involves manually creating CAD (computer-aided design) solid models from the point clouds and then discretizing these models with solid finite elements (FEs). Thus, these models usually derive from a manual remodeling process performed by the user. This manual process is prone to errors and aims at simplifying complex geometries, which can further affect the fidelity of the models [7].

Significant advancements in automated 3D mesh model generation from point clouds contributed to the reduction of reliance on manual interventions, with numerous commercial tools now available that can automate the meshing process for a variety of geometries. However, as things stand at present, no single software exists that can seamlessly manage the entire process from geomatics survey to modeling and subsequent transformation into an object usable in finite element modeling (FEM) applications. The graphics data exchange standards used in reverse modeling [8] differ from those of common FEM software, complicating the integration of these technologies. From a structural perspective, point clouds, which consist of numerous discrete points defined by three-dimensional coordinates, cannot be directly (re)used for numerical analyses. To utilize the geometric data derived from 3D laser scanning effectively, it is necessary to convert the point cloud into a continuum model [9]. This gap underscores the role of high-quality geomatics surveying in constructing precise 3D models. The higher the quality and detail with which a point cloud is built, the more suitable it will be for implementation within FEM software, resulting in more reliable structural analyses [10].

In Giaccone et al. [11], the authors demonstrated that analysis results are strongly dependent on the level of geometric detail of the digital model. They tested an existing column, belonging to a monumental fountain. The column was modeled in five different ways, from “stylized” to extremely “detailed”, modeling also cracks. The comparison among these models was carried out by performing static and dynamic analyses. They verified that a “stylized” model generates wrong estimations in terms of volume, mass, stress values and patches, and modal shapes, concluding that a “detailed” model is to be preferred. Likewise, in the work of Antòn et al. [12], the authors highlight the importance of accurate and detailed modeling for CH architecture preservation. Having performed numerical simulations on three models with different levels of geometrical details (specifically: ideal model, simplified model, and as-built model), they found remarkable differences in the responses of the models in terms of stress and displacement. Only remote sensing techniques allow to achieve the necessary level of geometric accuracy.

Several point cloud-based workflows for BIM (building information modeling) and FE modeling of historic buildings have been developed recently, exploiting either automatic or semi-automatic meshing of the point clouds. Barazzetti et al. [13] proposed a cloud-to-BIM-to-FEM workflow for the generation of an accurate historic BIM based on point clouds, taking into consideration the geometrical irregularity of a castle. The BIM model was automatically converted into FEM for structural simulations. In the same year, Castellazzi et al. [14] validated a semi-automatic procedure to transform point clouds into finite element models. The procedure exploits voxelization methodology, the process of converting a 3D object into a discrete grid of "voxels". In [10], Pepe et al. presented a scan-to-FEM pipeline to create digital models to be used in structural analysis. All techniques are further analyzed in Section 3 of this paper.

The paper is organized as follows. Section 1 presents an introduction to the study, with a focus on 3D point clouds obtained using advanced techniques for digital geometric recording. The aims and objectives of the study are also enlightened. Section 2 describes the methods and the materials used to carry out the study. The following Section 3 presents a detailed description of the various methodologies for the transformation of point clouds to FEM. The final remarks and possible future developments are exposed in Sections 4 and 5.

1.1. Advanced Products of Heritage Recording and Digitalisation Techniques: 3D Point Clouds

Over time, documenting built heritage has progressively evolved in terms of instrumentation used, speed, and quantity of data collected. In fact, the adoption of advanced digital survey technologies—such as laser scanning, close-range, and aerial photogrammetry—has greatly enhanced documentation practices [15]. For purposes of this paper, authors consider two main technologies, terrestrial laser scanning (TLS) and photogrammetry, that can produce point clouds, i.e., a set of distinct data with geometric information and very suitable for further surface or volume modeling.

Technological shifts that enabled extensive recording of heritage using advanced surveying technologies have also contributed to an increased popularity of this topic across different fields of application. Digitalization of heritage has in fact been incorporated within some of the most significant public policy recommendations [16] and internationally shared scientific principles [17]. Traditionally, charters do make a reference to non-destructive methods for data acquisition [18]. However, it is only in 2006 that a UNESCO report [19] on climate change and world heritage acknowledges the need for "remote sensing" approach relying on the use of satellite technology, non-destructive techniques, biosensing to assess biological damage to materials, and the use of simulation tools to predict the impact of climate change on the behavior of cultural heritage materials that are needed for the development of professional monitoring strategies. Geomatics technologies usually do not enter into direct contact with the object of survey, thus minimizing disturbance to fragile sites. In addition, they produce outputs of high levels of geometric accuracy and are very suitable for repetitive measurements; all these characteristics have enabled their extensive employment in the recording of cultural heritage monuments and sites over the past few decades.

Although the communities of scientists, scholars, and stakeholders agree on the advantages of geomatics technologies, there are no true common protocols for digitalization for further use of recorded data, for example, for purposes of FEM analysis. There are several examples of principles on 3D digitalization of heritage [20,21], proposed at the international level in the past, while experts suggest that specific guidelines should be resorted to, relying on good practices and on the manuals edited at the national level [22].

The surveying methods have evolved with the advent of tools like total stations, which integrate electronic distance measurement (EDM) and angle measurement for precise, automated remote sensing data collection. Global navigation satellite systems (GNSS), including GPS (global positioning systems), have revolutionized surveying by providing accurate geospatial coordinates from satellite signals, while the use of topography techniques and geodetic networks allows a correct georeferencing of ground survey collections. Modern surveying increasingly utilizes remote sensing technologies such as LiDAR (light detection and ranging) and photogrammetry, which create 3D models by collecting dense point clouds from laser or photographic data. Out of all possible products of an advanced surveying procedure, this paper will focus on the generation, properties, and use of point clouds as a starting point for 3D modeling, further discussed in Section 3.

According to Yang et al. [23], photogrammetry and laser scanning have become the best approaches for the acquisition of point cloud data in the field of cultural heritage. TLS is an advanced form of LiDAR technology applied from the ground and used to capture detailed 3D representations of structures and landscapes. TLS systems come in two primary forms: static TLS (STLS) and mobile TLS (MTLS). STLS uses a tripod-mounted scanner that collects 3D data from fixed positions [24]. MTLS, on the other hand, is mounted on moving platforms, allowing for data collection across larger areas, though at a slightly lower resolution [25]. For heritage documentation, STLS is more widely used to capture the geometric information through multiple scans taken from different points in space and hence different points of view. During processing, these scans are aligned, co-registered, and georeferenced in software to form a unified point cloud project that represents the structure's overall geometry. This technology can capture current geometric conditions of built heritage, potentially supporting structural assessment analysis [13] and damage detection [26]. It can also be explored for virtual reality (VR) and augmented reality (AR) applications such as for educational and interpretive purposes [27]. TLS is particularly useful for documenting and monitoring deteriorating sites or unstable conditions [28]. However, the advanced technology such as TLS comes with challenges. The equipment and software are usually costly, data processing is complex, and the technology requires skilled operators. Environmental factors like lighting and weather, as well as reflective, transparent, or obscured surfaces, can affect data quality. Additionally, TLS can struggle to capture colors and textures.

The other prominent remote sensing surveying technique is photogrammetry, a method for creating stereoscopic models, starting from photographs taken from multiple angles and positions in space [2]. There are two main types of photogrammetry: close-range and aerial. Close-range photogrammetry is often performed with handheld or tripod-mounted cameras and is suitable for artifacts, architectural features, or interiors. Aerial photogrammetry typically uses aircraft and is ideal for mapping large areas, creating topographic maps, and documenting landscapes or structures from above. In the past decade, several examples have relied on the use of drones and unmanned aerial vehicles (UAVs) integrated with digital cameras for surveying of historical structures and built environments and their surroundings. Photogrammetry is also relatively accessible, as it only requires a digital camera, software, and sufficient lighting to capture images [29]. Advances in software have made it possible to use even standard digital cameras or smartphones for initial data capture. The accuracy of a photogrammetric survey depends on factors such as camera settings, operator skills, the quality of the images, and environmental conditions. Additionally, photogrammetry may struggle to capture surfaces with no distinct visual features (texture), while challenges might be encountered in situations with no natural light and in which artificial lighting results in complex surveying (e.g., narrow areas such as tombs, caves, and underground chambers).

The outcomes of these advanced surveying methodologies are point clouds that can be visualized in 3D modeling environments. A point cloud is a collection of discrete points in three-dimensional space that represents the geometry of objects or environments. Each point in the cloud has coordinates (X, Y, Z) and, in some cases, additional attributes like color, intensity, or normal vectors that provide contextual information about the surfaces being scanned [2]. The goals of a detailed point cloud can be many, depending on the different needs. In the field of CH, the key advantage of point clouds is their ability to provide accurate information that can be further used to correctly represent complex surfaces and environments through technical drawings (two-dimensional products) and 3D models. Photogrammetric point cloud data, for example, are mostly used for orthophoto image production, especially in archaeology and architecture [30]. Other applications explored in recent literature include further data processing for models that can facilitate damage detection, provide geometry information for complex HBIM (historical building information modeling), and support further FEM techniques [31].

Advanced surveying methodologies are often integrated and combined with traditional methods, such as manual measurements, measured drawings, photography, and hand-drawn sketches [32]. For example, manual measurements, which use tools like tape measures and levels and are often accompanied by hand-drawn sketches to capture architectural details, are effective for tasks requiring high precision in localized areas and allow close interaction with the structure. Traditional triangulation and trilateration, which rely on angle and distance measurements between control points to determine the positions of physical elements in space, are particularly valuable for enhancing precision and efficiency. Although these techniques have been superseded by modern advanced surveying methods due to their labor-intensive nature, slower speed, and susceptibility to human error, they remain historically valuable and useful for integration into contemporary practices.

It is important to mention that in the practice of heritage recording, advanced technologies usually do not completely exclude manual data acquisition. Quite the contrary, the integration of information and the confirmation of specific interpretations often rely on the in situ controls and manual data collection. For the purposes of the comparison review reported in this paper only, the authors decided to treat the outputs of manual data collection (simplified measured drawings) and that of advanced geometric survey (point clouds) as fully separate sets of data.

1.2. Aims of the Study

The aim of this work is to review existing methodologies to transform high-quality digital point clouds into finite element models. In particular, the following objectives were set:

- To review the methods capable of employing directly, or semi-directly, the data from point clouds for the generation of an FEM used for structural analysis.
- To propose a classification of these methods.
- To highlight the strengths and drawbacks of each method.
- To assess the direction of future research in this field.

The focus concentrated on the automation of the process and on the contribution that laser scanning techniques and 3D modeling may provide for the analysis of the structural stability of cultural heritage structures.

2. Materials and Methods

This paper is structured as a state-of-the-art review regarding different methods to obtain an FE (finite element) model from a point cloud. The searching workflow followed these steps: (i) determine the initial field of inquiry; (ii) select search engines and provide a set of keywords to search for publicly available and indexed methods-related publications; (iii) discard the publications that are not related to the topic; (iv) read and analyze each article, identifying the principal techniques. The topic of the review is the generation of FE models of CH structures from surveyed point clouds. The inclusion criteria identified studies that address methods for the transition from point clouds to FEM, that highlight applications in the structural assessment or conservation of CH buildings, and provide detailed insights of the methodology used, including level of automation, geometric accuracy, or challenges in data processing. Exclusion criteria were applied to studies that only focus on data acquisition or documentation without addressing FEM generation and studies with limited relevance to CH, such as those centered on modern or industrial buildings. Works that discuss BIM mainly for non-structural purposes, such as data management or heritage visualization, were also excluded.

Web of Science (WoS) and Science Direct were the main search engines employed in the initial searching phase. Table 1 shows the steps followed when searching in Web of Science. The terms “point cloud”, “fem”, “structural model” and “cultural heritage” were combined using Boolean operators and seven different searches were conducted. The research was performed for “Topic”, “Author Keywords” or “All Fields”. A total of 393 documents were selected from step 1. The second step involved the decimation of the previously collected documents by filtering for language and categories. Duplicates were also removed. A total of 57 topic-related publications were eventually selected at the end of step 3.

Table 1. Steps of the search procedure in WoS.

Step 1—Collection		
Search	**N. of Publications**	**Webpage**
“point cloud” (Topic) AND “fem” (Topic)	89	https://www.webofscience.com/wos/woscc/summary/3068e755-84ac-4fe4-9906-ce2276ecaffb-010dac2add/relevance/1 (Accessed on 25 November 2024)
“point cloud” (Topic) AND “fem” (Topic) AND “cultural heritage” (Topic)	11	https://www.webofscience.com/wos/woscc/summary/94e7189a-1449-45cc-a3f8-9ac9f384be98-010dac1058/relevance/1 (Accessed on 25 November 2024)
“point cloud” (Topic) AND “structural model” (Topic) AND “cultural heritage” (Topic)	84	https://www.webofscience.com/wos/woscc/summary/6b2ac90f-44dc-4271-8e6d-1959f5dfb838-010dac5852/relevance/1 (Accessed on 25 November 2024)
“point cloud to structural model for cultural heritage” (Topic)	78	https://www.webofscience.com/wos/woscc/summary/fc0a4b84-fc7f-40ac-92f0-57524c6c67b7-010dac7fd1/relevance/1 (Accessed on 25 November 2024)
“point cloud” (Author Keywords) AND “fem” (Author Keywords)	11	https://www.webofscience.com/wos/woscc/summary/1161fb8d-c48e-4686-9b87-403d4b4b91d5-010dac37e4/relevance/1 (Accessed on 25 November 2024)

"point cloud" (Author Keywords) AND "structural model" (Author Keywords) AND "cultural heritage" (Author Keywords)	2	https://www.webofscience.com/wos/woscc/summary/348b3297-823f-43cf-89a3-b70e224ecc96-010dac7264/relevance/1 (Accessed on 25 November 2024)
"point cloud to structural model for cultural heritage" (All Fields)	118	https://www.webofscience.com/wos/woscc/summary/71c10e58-e933-4e10-925e-fc67dc44e2bc-010daca93f/relevance/1 (Accessed on 25 November 2024)
Total	393	
Step 2—Decimation		
Filter for language (English and Italian) and category (the selected categories were Architecture, Civil Engineering, Archaeology, Construction Building Technology, Computer Science, Mechanical Engineering)	386	
Remove duplicates	190	
Step 3—Definition		
Selection of papers dealing with the topic (i.e., generating FE model from point clouds for CH)	57	

The same procedure was followed when searching in the Science Direct engine (Table 2). The search from step 1 yielded 1964 documents, which were narrowed down to 18 after excluding those not specifically related to the subject of interest (i.e., the generation of FE models from point clouds for CH).

Table 2. Steps of the search procedure in Science Direct.

Step 1—Collection		
Search	**N. of Publications**	**Webpage**
"point cloud to structural model for cultural heritage"	1964	https://www.sciencedirect.com/search?qs=point%20cloud%20to%20structural%20model%20for%20cultural%20heritage (Accessed on 25 November 2024)
Step 2—Decimation		
Filter for language and subject area (Engineering, Environmental Science, Computer Science, Art and Humanities)	1093	
Step 3—Definition		
Selection of papers dealing with the topic (i.e., generating FE model from point clouds for CH)	18	

The research for references was further enriched by reviewing the papers and examining their cited references. Additional references were also found through searches using the Google search engine, resulting in 42 more references. The complete list of topic-related references, with duplicates removed, contains a total of 84 documents, and it can be found in Supplementary Materials.

3. Results

The 84 documents selected in the search procedure at Section 2 were analyzed using VOSviewer© software (version 1.6.20). Keywords play a key role in studies, capturing the main focus of the research. To get a better understanding of the current research trends, a keyword co-occurrence map was created, with nodes representing the keywords (Figure 1). As outlined in Figure 1 and in Table 3, keywords with the highest frequencies are "FEM", "Cultural heritage", "HBIM", "Point cloud", and "TLS". It is noteworthy that the concept of "HBIM" is relatively new and has only recently gained traction in the field. However, it has a strong correlation with the other keywords.

Table 3. Number of occurrences per keywords. Only keywords with more than 4 occurrences are shown.

Keyword	Occurrence
FEM	27
Cultural heritage	25
HBIM	13
Point cloud	12
TLS	11
Structural analysis	10
BIM	5
Interoperability	5
Mesh generation	4
Photogrammetry	4
3D modeling	4
NURBS	4
Voxelization	4

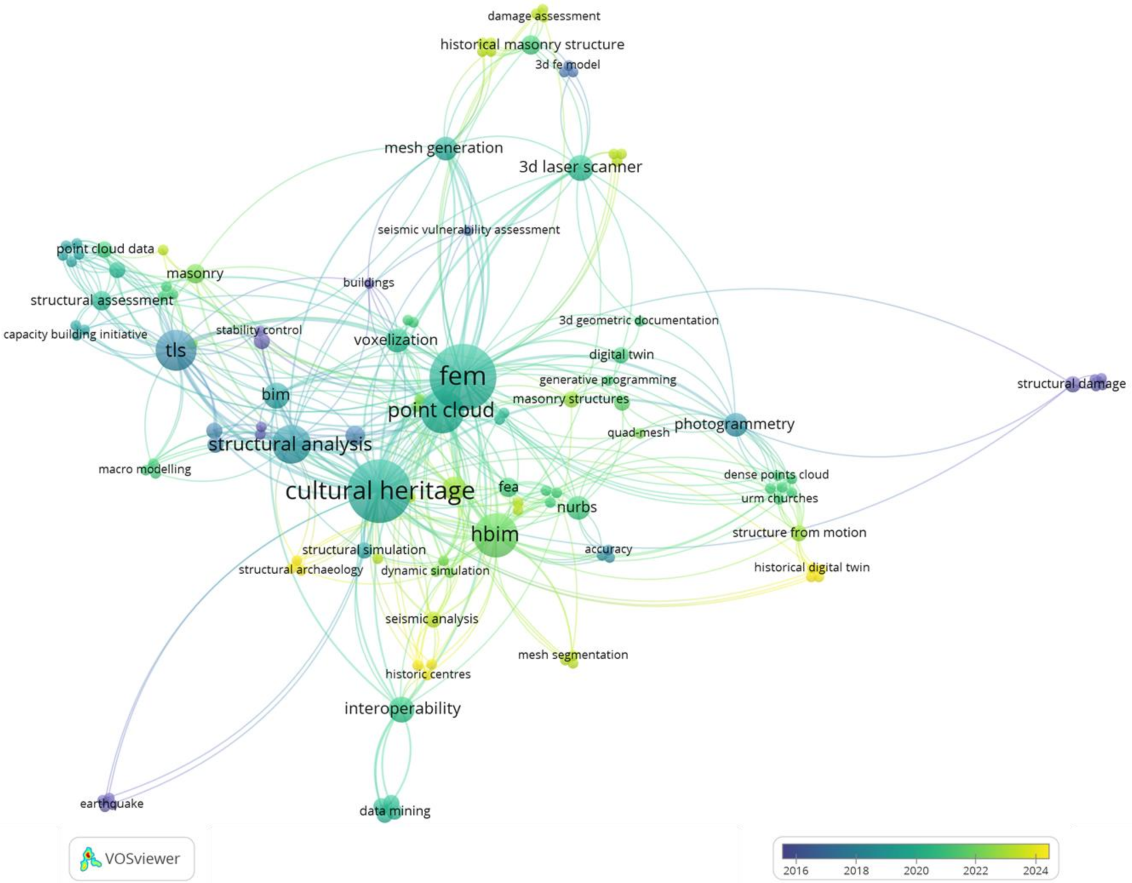

Figure 1. Overlay visualization by VOSviewer© of the number of citations for each keyword (represented by the size of the dots) with respect to the year of publication.

The selected literature was analyzed in terms of the publication date and geographical origin. The results are shown in Figures 2 and 3. The first studies on the generation of FE models from a point cloud date back to 2007 and have steadily increased in number since then. In 2023, 18 publications were released, indicating a growing interest and ongoing relevance in the field. It is noteworthy that the biggest contribution comes from the central European region, especially from Italy. Indeed, the highest number of publications was realized in Italy (35 documents). Outside Europe, the most active countries are China (6 documents) and the United States (3 documents). This demonstrates that this topic is discussed worldwide.

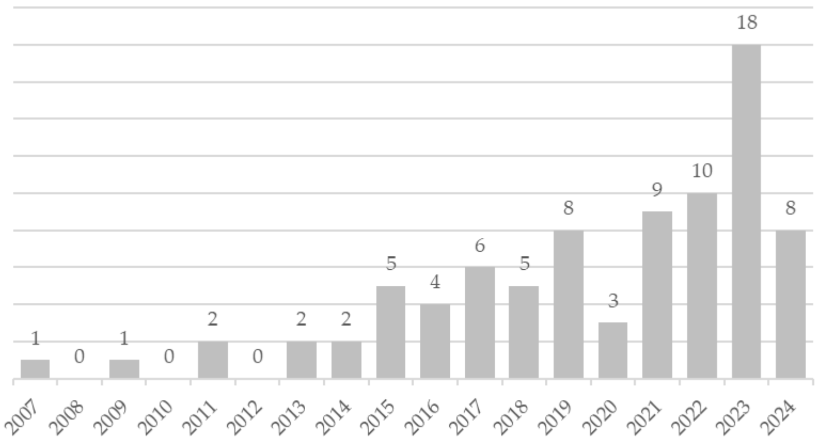

Figure 2. Distribution of publications over the years.

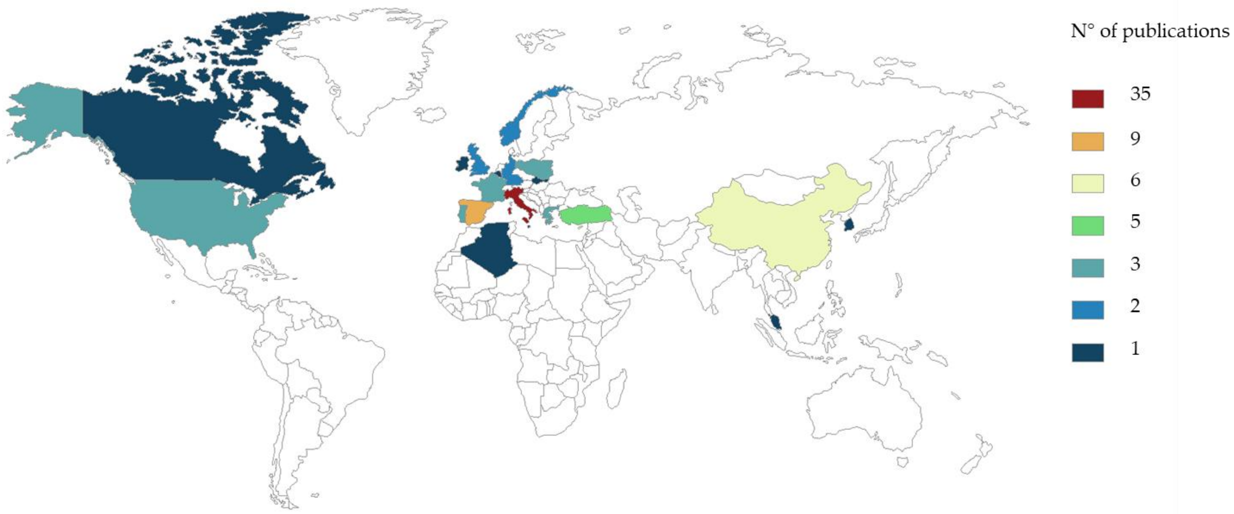

Figure 3. Geographic distribution of the first author's affiliation, referred to the publications from 2007 to 2024, on the topic "FEM generation from point cloud for CH".

3.1. FE Model Generation Approaches

The automated mesh model generation for FE analysis is a problem that has been studied for years, and much progress has been made so far, especially in terms of software and tools. Obtaining a finite element method (FEM) model from a point cloud involves several mathematical and computational steps. Indeed, point cloud data cannot be directly used for numerical analyses, as they are represented by discrete points, while a numerical model needs to be continuous and represented by mathematical equations. Different techniques exist nowadays that deal with the so-called scan-to-FEM process. A first attempt to classify the different methods for FEM generation from point clouds was given by Tognaccini [33] who identified three different techniques: (i) manually prepare the model in a CAD software, where the point cloud is used just as a guide; (ii) create a mesh model and convert it to a structural model using voxelization; and (iii) create non-uniform rational B-spline (NURBS) surfaces and convert them to solids.

Korumaz et al. [5] extended Tognaccini's [33] classification and divided the techniques into five groups, differentiating for different data acquisition approaches (manual survey or automatic survey via photogrammetry and TLS). A more recent classification was proposed by Quattrini et al. [34], categorizing the methods into four approaches. The first three approaches were the same as those introduced by Tognaccini [33]. The fourth approach intends to generate a mesh from the point cloud and convert it directly to a solid object.

An extended classification is proposed in this study, and it is shown in Figure 4. The classification involves five different methodologies to generate structural models starting from surveyed point clouds. The different methods are outlined in detail in the following Sections 3.1.1–3.1.5. It is noteworthy that the level of geometric accuracy of the final FE model increases from the first to the last approach. The level of geometric accuracy is closely related to the scale of representation and reflects the extent to which the surface geometry is represented, along with the ability to capture details and information. It can be computed as the deviation between the generated FEM and the actual geometry (e.g., root mean square error (RMSE)). An inadequate level of geometric accuracy can lead to inaccuracies in the FEM model. The purpose of exploiting point clouds is to lose the least amount of information from the survey and minimize operator interventions. Figure 5 shows the distribution of methods in terms of percentage, related to the analyzed publications. A list of the software used and cited in the articles can be found in Appendix A.

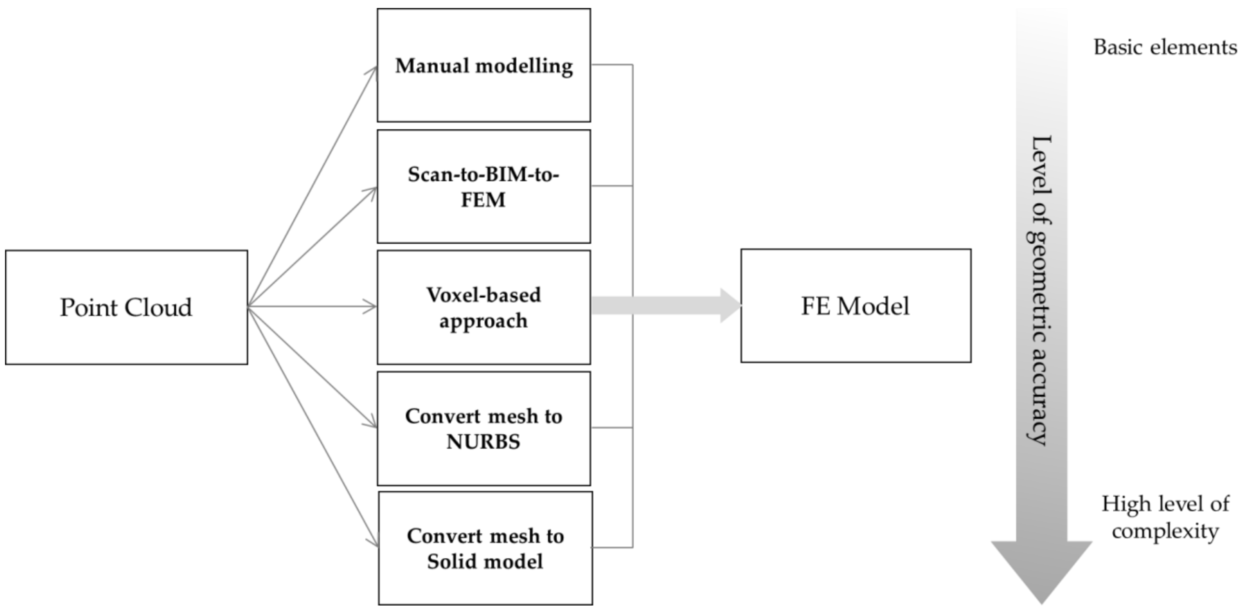

Figure 4. Classification of the methods for the development of FE models.

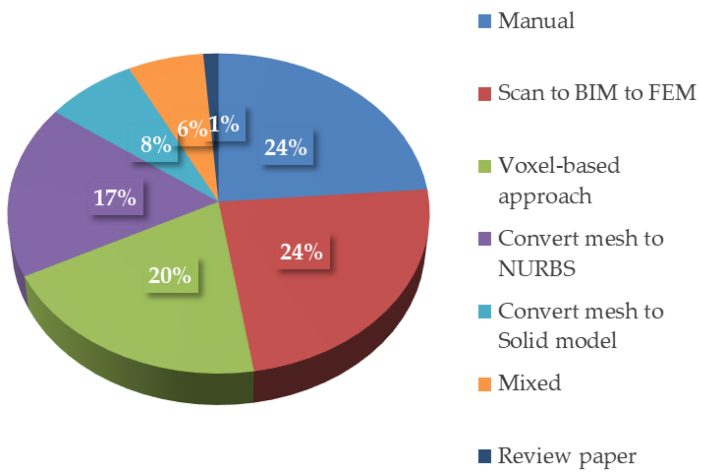

Figure 5. Percentage distribution of methods for the development of finite element models, related to publications from 2007 to 2024.

Figure 6 illustrates the generation of an FE model (Figure 6b) from a point cloud (Figure 6a). The example depicts a column from Tomb 7 at the archaeological site of the Tombs of the Kings in Paphos, Cyprus (Figure 7), used as a case study to outline the methodologies. The archaeological site of the Tombs of the Kings is included in the UNESCO World Heritage Site (WHS) list, which highlights its cultural importance and ensures its protection under international agreements. This protective status imposes constraints on interventions, making structural assessments particularly challenging. In addition, the site is susceptible to various risks, such as seismic activity and other environmental agents, issues that were not considered at the time of construction. Tomb 7 is particularly notable for its territorial, architectural, and structural characteristics. Being part of a larger complex, it integrates seamlessly with the landscape, and its soil-structure interaction is unique, as part of the structure is located underground. The colonnade is a fundamental load-bearing component of the monument. Other than being the most recurrent structural feature of the site, the column plays a critical role in ensuring stability and is thus selected as the representative element of the monument. The illustrative example of the column of Tomb 7 is used in the following sections to showcase the different types of meshes that can be generated when transitioning from a point cloud to an FE model in various approaches.

(**a**) Point cloud (**b**) FE model

Figure 6. Example of the conversion of a point cloud (**a**) into FE model (**b**). This example shows one of the columns of Tombs 7 in Tombs of the Kings in Paphos, Cyprus.

Figure 7. Localization of Tomb 7, Tombs of the Kings, Paphos, Cyprus.

3.1.1. Manual Modeling

The most employed method to date to obtain FE models is manual modeling. It typically involves creating a CAD model and then discretizing it into solid FEs. This process is often prone to errors in FE meshing due to geometric imprecisions and tolerances introduced during manual modeling [7]. Drawing in a CAD environment involves the combination of primitive solid shapes through unions, subtractions, intersection commands, and boolean operations, using point cloud just as a reference guide. Indeed, point clouds can be imported directly into CAD software, and plans, sections, and elevations can be easily visualized. Measures and distances are evaluated from the point cloud. Figure 8 illustrates an example of a possible workflow for manual modeling.

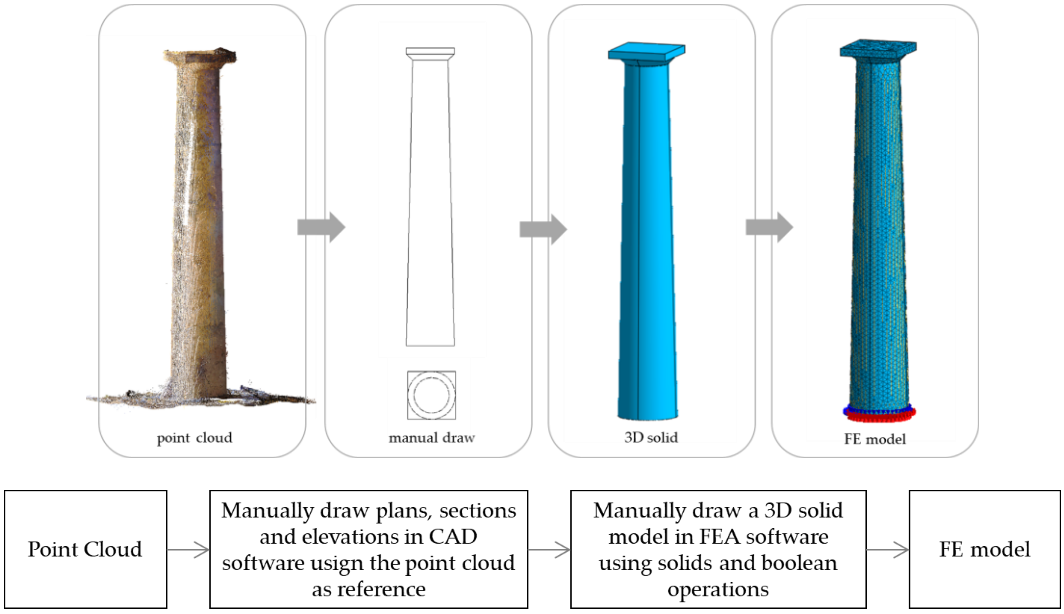

Figure 8. Example of a possible workflow for manual modeling.

This approach generally results in an approximation of the geometry since imperfections or relative inclinations that characterize historical buildings are discarded. Thus, many original characteristics of the geometry can be lost. Additionally, the high reliance on manual input increases the risk of human error, making the process labor intensive for complex projects. The operator must be well experienced and trained on different modeling software programs, and they need to know about the history of the analyzed object. This approach is time-consuming, considering all the steps involved, like the definition of the level of geometric detail, the meshing, the choice of sections, etc. A positive aspect of this approach is that the transformation to numerical models is relatively easy for simple shape geometries. Table 4 summarizes the PROs and CONs of this methodology.

Table 4. PROs and CONs of the "Manual modelling" methodology.

PROs	CONs
Easy process for simple models	Simplification of the geometry
Relatively easy to convert to FEM	Many characteristics of the original geometry can be lost
Does not require multiple software	Cumbersome to reach a high level of detail
The most employed method	Well-experienced and trained operator

3.1.2. Scan to BIM to FEM

A viable option for obtaining FE models from point clouds is by creating a BIM model. The so-called scan-to-BIM-to-FEM methodology has been gaining ground in recent years thanks to the advantages offered by BIM models in the preservation of CH buildings.

The general scan-to-BIM-to-FEM methodology starts with the generation of point clouds by 3D scanning technologies. These point clouds are the reference for constructing building information models (BIM), which are parametric models including not only geometric data but also metadata regarding materials, mechanical properties, and other building systems. From this stage, BIM models can be converted into finite element method (FEM) models for structural simulations and performance assessments under various conditions. An example of a possible workflow for this approach is shown in Figure 9.

This approach offers the great advantage of integrating a variety of data into the 3D model (metadata), which includes not only physical and functional properties but also geolocation and spatial data, maintenance information, the relationship between different components of the structure, and environmental data, offering a source for the entire lifecycle of a structure. However, modeling historical buildings with complex shapes in a BIM environment can be a complicated task. BIM software often lack the capacity to handle certain shapes and forms, necessitating the creation of custom parametric libraries. Furthermore, the conversion from BIM to FEM, though automated in some cases, frequently requires manual intervention, especially when dealing with complex or irregular geometries, with time-consuming manual corrections in the 3D mesh. Specialized tools, such as those in DIANA (www.dianafea.com, DIANA FEA B.V., Delft, Netherlands), are available to remove small entities and optimize the geometric model, but these still require significant investment in both time and expertise. Another critical aspect to consider is the import/export operations between BIM and FEM software. For instance, not all types of elements, sections, materials, or even loads and constraints may be recognized during the transfer process. It is important to verify whether any information is lost during the transition between software and not to assume that all data will always be correctly interpreted. However, once these limitations are understood, especially in large, complex models, the advantages of leveraging interoperability can be significant. Advancements in interoperability standards, such as the use of industry foundation classes (IFC), are helping to ensure data exchange across platforms. Unfortunately, not all FEM platforms are able to read files in IFC format. For example, Tekla® Structural Designer (www.tekla.com, Trimble Solutions Corporation, Espoo, Finland) and Robot Structural Analysis (www.autodesk.com, Autodesk, Inc., San Francisco, California, US) can read IFC files directly, while ABAQUS (www.3ds.com, Dassault Systèmes, Vélizy-Villacoublay, France) and Midas (www.midasoft.com, MIDAS Information Technology Co., Ltd, Gyeonggi-do, South Korea) require data conversion to compatible formats like STEP or STL.

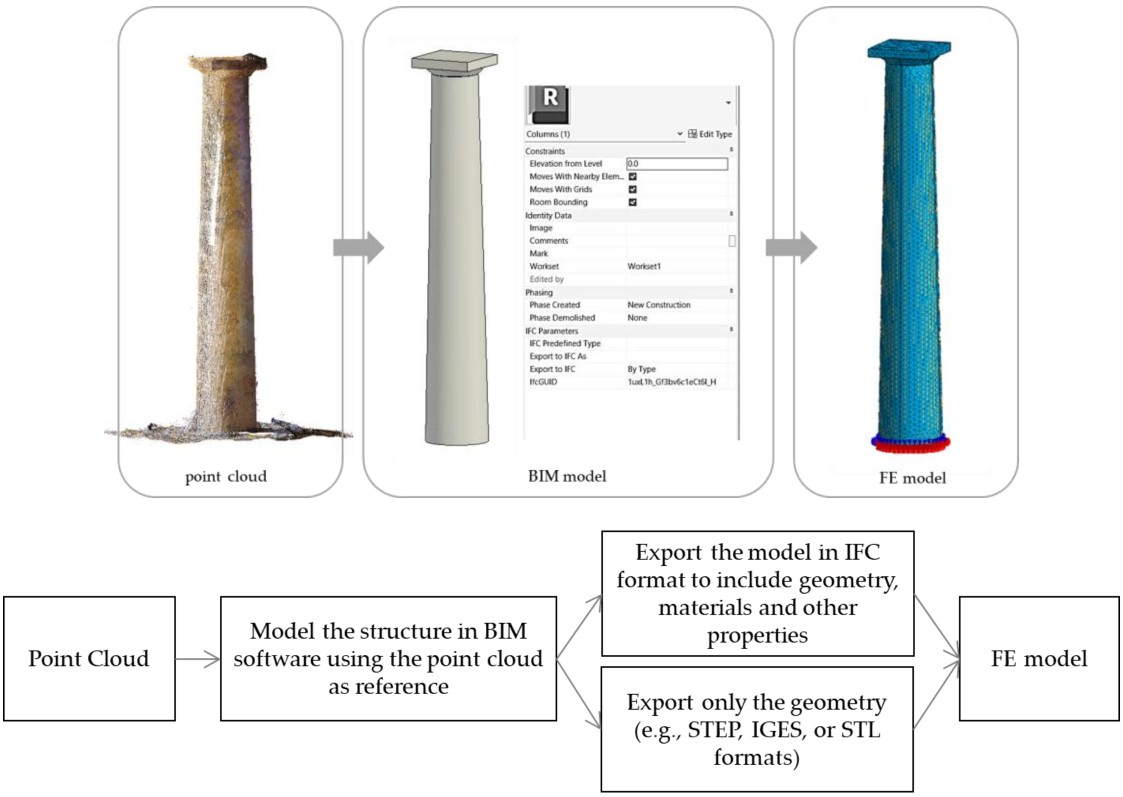

Figure 9. Example of a possible workflow for the scan-to-BIM-to-FEM approach.

Barazzetti et al. [13] applied the cloud-to-BIM-to-FEM methodology to the case study of Castel Masegra, located in Italy. The BIM model was built in Autodesk Revit®

(www.autodesk.com) from the 2D drawings extrapolated from the point cloud. It was possible to model simple and regular elements directly in Revit, while complex shapes were modeled through NURBS curves. Despite the necessity to design complex objects in a separate environment and the cumbersome manual edit of the auto-meshing process in the BIM-to-FEM phase, the authors managed to obtain a numerical model that reflected the geometric complexity and irregularity of the historic construction without an excessive simplification of the structure and with a limited processing time.

The application of this methodology to the field of heritage reconstruction depends on the peculiarities of each building, due to the irregularities it may present in its morphology. Recently, historic building information modeling (HBIM) has been introduced as an advanced approach that merges the principles of BIM with the specific needs of historic preservation and cultural heritage management. In 2009, Murphy et al. [35] proposed a new system of modeling historic structures, aiming to develop a novel prototype library of parametric objects. The design and details of these parametric objects were derived from architectural manuscripts, ranging from the works of Vitruvius and Palladio to the pattern books of the 18th century. However, many authors have emphasized that the unique forms of historical buildings represent a significant value that should be preserved and transmitted [36,37]. The lack of existing object libraries can be overcome through the development of specific 3D objects using advanced modeling tools (AMT), enabling the accurate representation of actual geometry.

In Ursini et al. [38], the authors tested the scan-to-HBIM-to-FEM process, examining the interoperability of HBIM models to be used for structural analysis and the representation of complex geometries within the HBIM models. They encountered many issues during the process, such as inconsistencies in the interchange between BIM software and FEA (finite element analysis) software and gaps in Autodesk Revit (www.autodesk.com, Autodesk, Inc., San Francisco, California, US) in the representation of historical masonries. Despite the issues and the involvement of numerous software, the authors were able to build not only a detailed HBIM model but also a structural analytical model, concluding that the workflow offers advantages both for structural investigations and for management, conservation, and maintenance of existing architectural heritage.

Santini et al. [39] highlighted major challenges with using historical BIM for sharing information between different disciplines. They found issues with representing irregular shapes, collapsed elements, deteriorated materials, and damaged surfaces. They also pointed out difficulties in transitioning from geometric surveys to structural modeling when including a BIM methodology.

New technologies are experimenting with the automation of the process from 3D scanning to 3D parametric modeling in BIM platforms. The work by Thomson and Boehm [40], although not specifically focused on CH, reviewed scientific literature on automating the process. Rolin et al. [41] proposed a workflow for achieving the semi-automatic transformation of a 3D point cloud, surveyed through a terrestrial laser scanner, into a 3D geometrical HBIM-oriented model, exploiting the functionalities of Rhino® (www.rhino3d.com, Robert McNeel & Associates (TLM, Inc.), Seattle, Washington, USA). The workflow also allowed for the creation of a consistent 3D finite element mesh suitable for structural analysis.

The scan-to-BIM-to-FEM approach is still developing but is becoming increasingly relevant for governments and public institutions, especially in the context of public procurement. As this methodology continues to evolve, it holds great promise for enhancing the precision, efficiency, and versatility of structural design and analysis in both new construction and the retrofitting of existing structures. Table 5 summarizes the PROs and CONs of the "Scan to BIM to FEM" methodology.

Table 5. PROs and CONs of the "Scan to BIM to FEM" methodology.

PROs	CONs
Easy process for regular shapes	Cumbersome process for complex shapes
It allows the use of metadata	The automation of the process is still not available
It allows interoperability through IFC standard format	Cannot be used for statues (elements cannot be simplified to beam, truss or shell)

3.1.3. Voxel-Based Approach

A voxel-based approach is based on the voxelization of data, which is the process of discretizing geometric or volumetric objects (curve, surface, solid) into volumetric data stored in a 3D array of voxels [42]. A voxel is a volumetric pixel, a 3D cube that represents a discrete part of the space within the object. This voxel-based representation of the 3D object can then be processed and converted into a finite element mesh for simulation and analysis.

The voxelization method has its origins in computer graphics and digital imaging, dating back to the early developments in 3D modeling and volume rendering during the 1960s and 1970s [43]. Voxels were introduced as a natural extension of the 2D pixel concept to represent 3D space. Early research in voxelization was aimed at creating volumetric representations of objects for medical imaging, scientific visualization, and computer-aided design (CAD). One of the earliest applications of voxelization was in medical imaging, particularly for CT (computed tomography) and MRI (magnetic resonance imaging) scans, where 3D anatomical structures needed to be visualized [44,45]. In the 1980s and 1990s, as computer graphics and computational power advanced, voxelization became more widely adopted for applications like volume rendering, collision detection, game development, and 3D simulations. Since then, voxelization has become a foundational technique in various fields such as CAD modeling, 3D printing, and physics-based simulations [46,47].

Voxelization techniques can be distinguished into point-based or surface-based. Point-based voxelization directly assigns points from the cloud to specific voxels within a 3D grid. A regular and uniform grid is first established over the spatial bounds of the data. The size of each voxel, which determines the resolution of the grid, is defined during this step. Next, the points in the cloud are mapped to their corresponding voxels based on their spatial coordinates. This mapping process identifies which voxel contains each point within the 3D grid, so each voxel is classified corresponding to binary values based on the sample points within that voxel. Hinks et al. [42] and Dogan and Gullu [48] propose different methods based on the point-based voxelization. The methods proposed are fast and offer a high degree of automation in reconstructing models from point cloud data. The resulting solid models can be imported into FEM programs for mesh generation and structural analysis.

Most existing voxelization techniques are surface based, where the focus is on capturing and discretizing the outer surface of an object, rather than its entire volume. Castellazzi et al. [14] introduced a surface-based semi-automatic voxelization procedure to transform 3D point clouds into 3D FEM models. A summary of the methodology is illustrated in the following paragraph and in Figure 10.

The process starts with the 3D scanning of the object, building, or environment to generate a dense point cloud. Having obtained the 3D point cloud, a first operation is producing a more regular cloud in density using a sampling algorithm. The second phase involves the cleaning of the cloud to delete unnecessary points. This phase is not automatic but requires the supervision of an operator. A polygonal mesh is then computed to obtain a continuous surface. The next operation is the slicing, which consists of creating planes (slices), parallel to a reference plane, at regular distances between each other until the whole structure is covered. The distance is arbitrary, and it defines the resolution of the model. The intersections between each slice and the polygonal model generate lines. Points are then distributed along these lines and cleaned to remove geometric irregularities. A boundary polygon that includes the points can then be computed using a concave or convex hull algorithm. Once the slices have been created, they are discretized and converted into digital images using the CT approach. Each digital image, with a certain resolution, is composed of pixels, so the stacking of them creates the volume elements (voxels). In this way, the reconstruction of the original 3D geometry can be realized by stacking all the slices. The creation of an FE model is then straightforward: each voxel is automatically converted into an eight-node hexahedral element. It is noteworthy that different pixel values can be assigned to represent various materials.

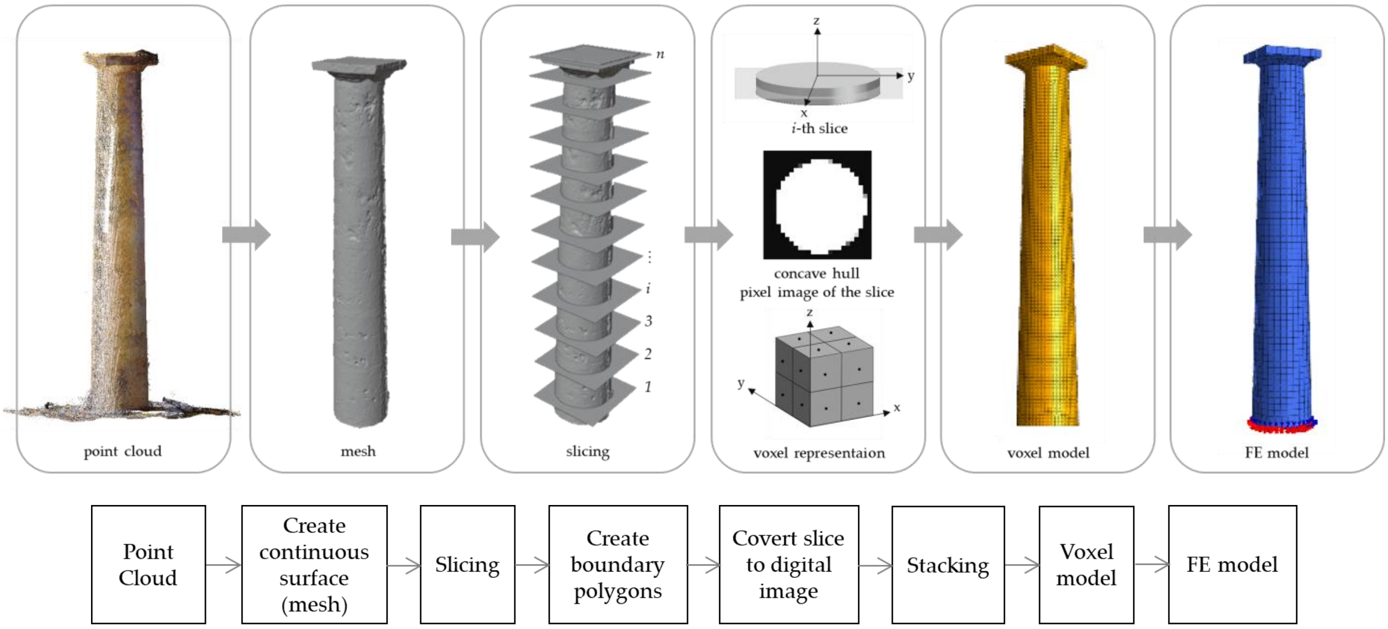

Figure 10. Flowchart of the voxel-based method.

The authors also developed an open-source software program called CLOUD2FEM based on the depicted workflow. The description of the open-source software can be found in Castellazzi et al. [7]. The software is developed in Python and integrates open-source libraries on the back-end to facilitate processing and modeling tasks. It features a user-friendly graphical interface, making it accessible to users without advanced structural skills. As an independent workflow, it does not rely on any specific software, which offers significant advantages over traditional CAD methods.

Bitelli et al. [49] applied the Cloud2FEM procedure to the surveyed Fortress of San Felice sul Panaro (Italy), which was severely damaged by the earthquake in 2012. The partial collapse of the perimeter walls of the North Tower, as well as the presence of debris and discontinuities, highly affected the point cloud obtained through TLS surveying. The Cloud2FEM process allowed the development of a detailed 3D numerical model that accounted for complex elements and damaged structures. The authors were able to perform an FEM analysis on the damaged structure but also on the undamaged structure, obtained by processing the voxel model manually, slice by slice.

The methodology, as well as the software code, can be easily improved, as evidenced by several studies found in the current literature. Bitelli et al. [50] enhanced the method by proposing a new approach that automatically computes the minimum necessary number of slices to efficiently describe the entire structure. It is a recursive process that reduces time and minimizes operator intervention. A further improvement of the methodology was proposed by D'Altri et al. [51], where the authors integrated 3D documentation data from virtual tours to handle non-comprehensive point clouds (e.g., when only the outer surface of the building is included in the point cloud). Lo Presti et al. [52] exploited the Cloud2FEM procedure to transform point clouds into BIM models. The data were converted to IFC format (the standard for BIM software) after the slicing phase, and BIM model generation showed a good efficiency and a high level of automation.

It has been shown that the automated voxel model approach offers a flexible and efficient way to convert point cloud data into a volumetric model. The process is robust, accommodating point clouds of any complexity or completeness, making it particularly useful for modeling complex structures. The process minimizes operator intervention, with user input required only during the slice cleaning and splitting phases, which results in significant time savings. The overall processing time is determined by the number of slices. The accuracy of the result is tied to the resolution of the voxel grid. A higher resolution will produce a more detailed model but will also require more computational resources. Compared to CAD, where material properties must be assigned to a partition of the entire model, the voxel-based method allows for property assignment to individual voxels, providing detailed and accurate structural description [53].

However, the methodology does have some challenges. Kaushal et al. [54] tested the Cloud2FEM software, investigating three different meshes for the same case study. They concluded that different meshing produced different results in terms of stress concentrations, showing the necessity of selecting an appropriate mesh and the urgency to assess this problem. The quality of the FEM mesh generated from voxel models is critical for accurate results. Poor mesh quality can lead to inaccurate simulations or excessive computational cost. Furthermore, the voxel-to-FEM process can be computationally expensive, particularly for high-resolution voxel models or large structures, requiring powerful software and hardware. A summary of the PROs and CONs of the "Voxelization" methodology is presented in Table 6.

Table 6. PROs and CONs of the "Voxelization" methodology.

PROs	**CONs**
Relatively easy and speedy procedure	Rasterization
Valid for complex structures	Poor mesh quality of the voxel model can lead to inaccurate results
It allows for property assignment to individual voxels	Computationally expensive for high-resolution voxel models or large structures
Semi-automated procedure	
Independent of any commercial software	

3.1.4. Convert Mesh to NURBS

A fourth method of converting 3D scanned data into numerical models relies on the use of non-uniform rational B-splines (NURBS). NURBS stands for non-uniform rational B-splines. It is a mathematical model for generating and representing curves and surfaces [55]. NURBS prevents the oversimplification of complex shapes and offers a more accurate representation of reality. The decimation and feature preservation capabilities of modern alignment algorithms make them particularly suited for simplifying reality-based models for finite element analysis (FEA).

A general workflow of this methodology (Figure 11) starts from the automatic creation of a continuous surface mesh from the scanned point cloud. If the mesh thus created is satisfactory and valid, which is usually the case for simple regular models and high-resolution point clouds, it can be directly converted into NURBS. Some CAD packages offer automatic conversion of polygonal models to NURBS, but this often results in a higher number of small patches, especially when the original mesh is topologically disorganized [56]. In most cases, it is convenient to clean the mesh or re-mesh it, using specific tools that simplify and reduce the number of elements in the mesh, before transforming it into NURBS. The NURBS model is then imported into an FEA environment where it can be automatically converted into a volumetric solid mesh and exploited for structural analyses.

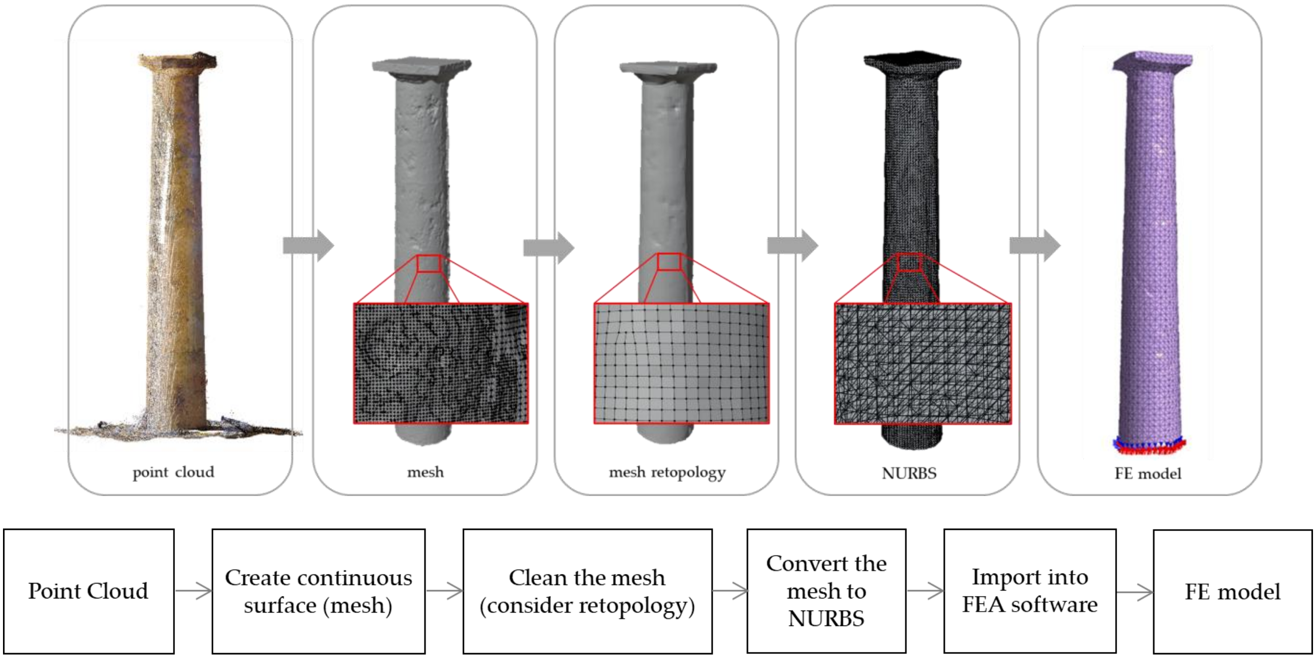

Figure 11. Workflow of the method "Convert mesh to NURBS". A zoomed-in view of the mesh texture is evidenced in the red box.

As seen in Section 3.1.2, NURBS can also be converted into parametric BIM objects. The main FEA software has meshing tools that can convert NURBS models, which only represent outer surfaces, into a 3D volumetric mesh. The difference between a volumetric mesh and a surface mesh is that the first has nodes spread in the outer surface and within the internal volume, connected by simple shapes like tetrahedrons, pyramids, prisms, or hexahedrons [57].

Optimizing the initial topology of the mesh is useful to minimize the number of NURBS patches. However, simplifying meshes, creating volumes, and fixing topological issues require several manual steps and multiple software platforms. Additional challenges include overcoming sparse or missing data and minimizing accuracy loss during conversion.

Automated conversion into FEM models is not always straightforward and may require dividing the geometry into sections and using Boolean operations to make the geometries congruent. Furthermore, distinguishing between structural and non-structural components is critical, as laser scanning does not make this distinction. In the modeling phase, non-structural components should be removed to avoid unnecessary applied masses and loads in the structural model.

Pepe et al. [10] proposed a semi-automated procedure to obtain 3D models for FEM and also for HBIM environments. The method involved importing the point cloud into Rhino® and processing it, exploiting the plug-ins available in the software. In particular, the *EvoluteTool PRO* (www.evolute.at, Evolute GmbH, Düsseldorf, Germany) plug-in allows the generation of complex NURBS surfaces, particularly suitable in case of irregular geometries. After having transformed the NURBS surfaces into solids directly in Rhino®, the model can be imported into the software for structural analysis. Although the process required several manual steps and the use of different software, it represents an advancement in the field.

Alfio et al. [58] tested the following pipeline: generate a triangular surface mesh (TIN), transform it into a quad mesh, convert the quad mesh model into an NURBS surface, and eventually import the model into the FEM environment. As quad meshes allow for a reduction in the approximation error and the number of elements, they are usually preferred for FE analyses.

The workflow presented in Lei et al. [59] includes the following steps: conversion of point cloud to triangular mesh, import of the model into Hypermesh® (www.altair.com/hypermesh, Altair Engineering, Troy, Michigan, US) to accomplish mesh generation, and import of the meshed model, using .inp format, into ABAQUS for analysis. The same pipeline was followed by Almac et al. [60].

In Fortunato et al. [61], the NURBS modeling method was carried out involving the following steps: (i) generation of a polygonal model in Geomagic (www.3dsystems.com, 3D Systems, Rock Hill, South Carolina, US); (ii) construction in Rhino of the geometric model based on NURBS; (iii) import of the NURBS model into Hypermesh® tool for the generation of high-precision mesh; and (iv) import of the model into ABAQUS for structural analysis.

Quattrini et al. [34] presented a semi-automatic methodology to transform TLS point cloud into 3D FEM. Geomagic was used to clean the point cloud, mesh it, and correct the mesh; Rhino® was used to transform the mesh into a single closed polysurface; Midas FEA was employed to model the solid mesh and perform structural analysis. A sufficient level of interoperability between tools was obtained. However, the model could not be subdivided into elements in Midas FEA due to its high complexity, and another model was thus created inside Midas FEA software. It this way it was possible to assign different materials to different elements.

Many studies have experimented with retopology, the process of recreating the surface geometry of a 3D model by generating a new simplified mesh with optimized topology. The retopologized mesh is usually composed of quadrangular elements (quads), which can be better distributed on the surface compared to triangular. The process leads to a reduction in the number of final polygons and consequently in the computational cost of FE simulations. The retopology process is available for open-source software such InstantMeshes (github.com/wjakob/instant-meshes) or Blender (www.blender.org, Blender Foundation, Amsterdam, Netherlands), or in commercial software such as ZBrush (www.pixologic.com, Pixologic Inc., Los Angeles, California, US). In Gonizzi Barsanti et al. [56], a retopologized model of the Fabrica Solimene in Vietri sul Mare (Campania, Italy) was created in ZBrush. This mesh was then transformed into polysurfaces (NURBS) in Rhino®, using the *MeshToNurb* tool, and exported in .stl or .step format to produce a volumetric model suitable for FEA.

Barsanti et al. [57] proposed the same approach based on retopology procedures and transformation of this retopologized model into NURBS surfaces. The model thus obtained was imported into the FEM environment to obtain a volumetric mesh. Lucidi et al. [62] also implemented the retopology procedure. They concluded that retopology allows for many advantages, such as achieving a high level of detail (LoD) model, reducing software interoperability issues and computational time, and the possibility of discretizing the model in different parts depending on the materials.

All these studies highlighted that the key to obtaining a volumetric model for FEA is to have a clean, closed mesh that can be converted into a closed NURBS. See Table 7 for a review of the PROs and CONs of the "Convert mesh to NURBS" method.

Table 7. PROs and CONs of the "Convert mesh to NURBS" methodology.

PROs	CONs
The process can be partially or fully automated	The process usually involves adopting multiple software
NURBS can be easily converted into BIM objects	The process often requires several manual steps
Great geometrical accuracy	

3.1.5. Convert Mesh to Solid Model

The last approach involves the generation of a mesh from the point cloud and the direct transformation of the mesh into a solid model suitable for numerical analyses. This process is feasible only for software that supports this conversion. According to [5,34], this is a useful approach that requires the minimum involvement from the operator. Figure 12 describes the steps of the generic flowchart for the application of this approach.

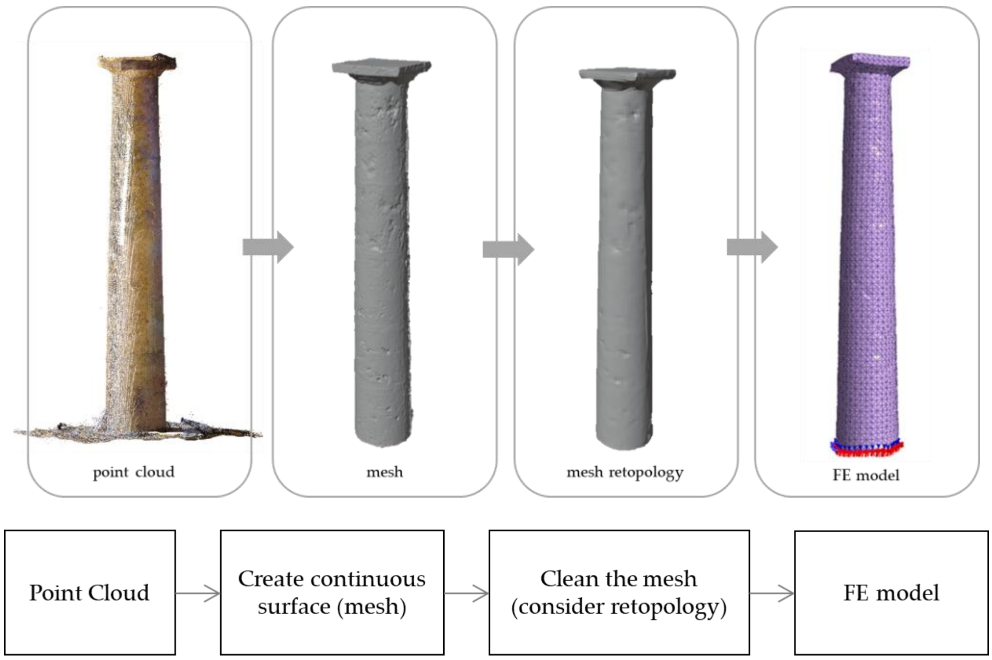

Figure 12. Flowchart of the method "Convert mesh to Solid model".

Bagnéris et al. [63] applied this methodology to study the mechanical behavior of a marble statue characterized by cracks and fractures. The authors chose open-source tools, both for 3D acquisition and numerical analysis, to guarantee the reproducibility of the process. Having generated the 3D point cloud of the statue, they generated a tetrahedral mesh with Gmsh (gitlab.onelab.info/gmsh/gmsh) to be directly used in the same software for mechanical analysis.

Likewise, Tucci et al. [64] developed a 2D mesh model of the case-study vault derived directly from point cloud and compared it with a 3D idealized geometry model. The models were analyzed in open-source FE software Salome (www.salome-platform.org, CEA, EDF and Open Cascade), without the need to transform them into NURBS. The numerical analyses confirmed the same cracking pattern for all the models, assessing the benefits of meshes generated directly from point cloud data.

There are tools able to use meshless methods or operate directly on 3D models without requiring traditional FE meshing. These tools perform structural analysis directly on geometry. For example, the *Scan&Solve* plugin for Rhino® is a powerful tool designed for structural analysis that performs simulations directly on polygonal models. The advantage is the elimination of complex and time-consuming finite element meshing. On the other hand, only linear stress analysis can be executed, and no complex nonlinear problems, like dynamic simulations, can be handled. While they are powerful for quick analyses, they cannot replace specialized FEA software like ANSYS (www.ansys.com, ANSYS, Inc., Canonsburg, Pennsylvania, US) or Abaqus for detailed or complex simulations. Visintini et al. [65] analyzed the statue of Emperor Claudius preserved at the National Archaeological Museum of Aquileia in Italy. The mesh model obtained from the point cloud was filtered, simplified, and repaired through automatic commands in MeshLab (github.com/cnr-isti-vclab/meshlab), a process that required multiple operations. The model was then imported into Rhino® where, thanks to the plug-in *Scan&Solv*, it was possible to directly perform numerical simulation in this modeling environment.

This approach is promising for the analysis of homogeneous objects; this class includes statues, as well as other monolithic architectural/artistic elements. It does not need the use of many different programs, and it can rely on open-source software. It is convenient for early-phase analyses where speed is prioritized. Starting with the analysis of these simple objects, this approach could be extended, with appropriate advancements, to larger and more complex elements. Table 8 summarizes the PROs and CONs of the "Convert mesh to Solid model" methodology.

Table 8. PROs and CONs of the "Convert mesh to Solid model" methodology.

PROs	CONs
High level of geometrical accuracy	Feasible only if software supports the conversion
Minimum operator involvement	Feasible for small homogeneous objects
Fast and straightforward No FE meshing	Available for speedy analyses

4. Discussion

This paper presents a summary of various research works focused on the process of converting 3D scanned data into an FE model that can be used for structural analysis, simulations, and engineering purposes. Since 2015, the use of this technique has seen significant growth in the field of cultural heritage, due to the increasing possibility to structure the information in 3D modeling environments. Within this context, five different approaches to what can be called scan-to-FEM method can be highlighted, each with its advantages and specific application areas: (i) the manual modeling of 3D solid models in FEM environments based on drawings extracted from point clouds; (ii) the scan-to-BIM-to-FEM approach, which consists of exploiting point clouds to model in BIM software and automatically convert the BIM model to an FEM model; (iii) the voxelization method, a semi-automatic discretization technique that leads to the creation of a voxel model to be converted into a finite element mesh; (iv) the conversion of meshed point clouds to NURBS to solid models; and (v) the direct conversion of meshed point clouds to solid models in software that allows the numerical analysis of these models.

The first approach involves reconstructing the full 3D geometry in a CAD environment from point cloud data. Despite being the most used, this approach can be computationally expensive and time-consuming if dealing with complex or detailed structures and usually results in the loss of details and accuracy. On the contrary, it is easy and straightforward in the case of simple and small objects. Similarly, the scan-to-BIM-to-FEM approach implies reconstructing the full model in a BIM environment, with the complication that parametric families must be built from scratch if not included in the software. The achievable level of accuracy for this technique can be limited. However, BIM metadata models contain much information on structural characteristics, allowing easier collaboration and communication among different stakeholders (architects, engineers, contractors, and owners). Moreover, automatic scan-to-BIM procedures are developing lately.

In the voxel-based approach, point cloud data are voxelized, that is, converted into a 3D grid of voxels. The voxel model is then used as the basis for FEM mesh generation. This approach has the advantage of avoiding complex surface reconstruction, but the resolution of the voxel grid can limit the precision of the model, and the resulting FEM mesh may require additional refinement. It results in being particularly suitable for objects with irregular or fragmented shapes. The fourth approach involves several steps: the creation of a meshed model from a point cloud, the conversion of the mesh into NURBS, and the conversion of NURBS into a solid, volumetric model. This requires adopting multiple software programs and usually several manual adjustments. The main advantage of this approach is that the final model achieves the highest geometric correspondence to the original point cloud.

In the last approach, the triangular or tetrahedral mesh generated from the point cloud is directly used for FEM analysis. This is suitable for relatively small geometries. The difficulties arise when dealing with noisy or incomplete data, as the mesh may need significant refinement to meet FEM solver requirements. Table 9 summarizes the main features of the different methodologies.

All these methods can be combined, creating hybrid approaches where different parts of the scanned object can be processed using different techniques. For example, voxelization may be used for parts with complex or irregular shapes, while NURBS reconstruction might be applied to more regular areas. This can be particularly useful for large-scale or highly detailed objects where a single method may not be appropriate for the entire structure.

Table 9. Summary table of the main features of the five methodologies.

FEM Generation Approaches	Main Features
Manual modeling 	• Difficult to reach a high level of geometric accuracy • Low computational efficiency • High robustness (ability to handle noisy or incomplete data in the point cloud) • No automation • High capability to handle large and complex datasets
Scan-to-BIM-to-FEM 	• Difficult to reach a high level of geometric accuracy • Low computational efficiency • High robustness (ability to handle noisy or incomplete data in the point cloud) • Low level of automation • Good capability to handle large and complex datasets
Voxel-based approach	• Good level of geometric accuracy • High computational efficiency • Good robustness (ability to handle noisy or incomplete data in the point cloud) • High level of automation • Low capability to handle large and complex datasets

	
Convert mesh to NURBS 	• High level of geometric accuracy • High computational efficiency • Low robustness (ability to handle noisy or incomplete data in the point cloud) • High level of automation • Low capability to handle large and complex datasets
Convert mesh to solid model 	• High level of geometric accuracy • High computational efficiency • Low robustness (ability to handle noisy or incomplete data in the point cloud) • High level of automation • Low capability to handle large and complex datasets

5. Conclusions and Future Work

The intercommunication between geomatics and civil engineering can highly contribute to the field of cultural heritage. This is conceived as one of the objectives of the ENGINEER (“Geomatics and Civil Engineering Innovative Research on Heritage”) project, a European project that envisions the enhancement and extension of inter-departmental multidisciplinary research activities of the Department of Civil Engineering and Geomatics of the Cyprus University of Technology [66]. The ENGINEER project aims to bridge the gaps between geomatic and civil engineering, where cultural heritage is the research domain.

To address the objectives outlined in Section 1.2, a comprehensive state-of-the-art review was carried out, thoroughly examining 84 documents on the topic. The review focuses on methodologies developed to date for generating FE models from surveyed point clouds. These methodologies were classified into five groups, with the level of geometric accuracy of the final FE model increasing from the first to the last group. Each approach was analyzed to highlight its advantages and drawbacks, considering factors such as computational efficiency, ease of implementation, adaptability to complex geometries, and suitability for different types of cultural heritage structures. This classification helps understand the balance between accuracy and practicality when creating FE models. It also provides useful guidance for choosing the most appropriate method for conservation and structural assessment.

The aim of this work is also to contribute to the ENGINEER project, exploring different approaches in the generation of detailed FE models for the structural assessment of

CH buildings, exploiting surveyed point clouds. The results would boost the potential contribution of geomatics to structural engineering.

These are the key considerations drawn from the analysis:

- The approaches analyzed are suited to different project requirements and levels of complexity. The choice of an approach depends on the specific needs of the FEM analysis, including the complexity of the geometry, the accuracy needed, and the computational resources available.
- Voxel-based methods are a simple automatic procedure that do not require multiple software programs, but details may be lost.
- Direct meshing and voxel-based methods are faster and easier to automate, but more advancements need to be done to render the process fully automated.
- The operator plays a central role in the process. The various methods include multiple steps that require expertise in geomatics, architecture, geometry processing, finite element modeling, and structural analysis. Their expertise must ensure that the final model includes the essential features of the structure while being computationally suitable for simulation.

These approaches continue to evolve, becoming increasingly powerful tools in structural analysis. The process can be significantly enhanced by artificial intelligence (AI), which can improve various stages of this process by automating tasks and increasing the accuracy and efficiency of model generation and analysis. Future work will test all these methods on a real-world case study, comparing them to highlight the strengths of each approach, with the aim to find the most suitable workflow for each case study. One of the main goals will also be to tackle the interoperability issues, aiming to reduce calculation times and make the models more detailed and closer to reality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage8020055/s1.

Author Contributions: Conceptualization, F.T., B.C. and D.O.; methodology, F.T., B.C. and D.O.; software, F.T.; resources, F.T., B.C. and D.O.; data curation, F.T.; writing—original draft preparation, F.T.; writing—review and editing, F.T., B.C., D.O. and A.A.; supervision, B.C. and D.O.; project administration, B.C. and A.A.; funding acquisition, B.C. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by European Union's Horizon Europe Framework Programme (HORIZON-WIDERA 2021-ACCESS-03, Twinning Call) under the grant agreement No 101079377 and the UKRI under project number 10050486.

Data Availability Statement: No new data were created.

Acknowledgments: The authors would like to acknowledge the ENGINEER project. This project has received funding from the European Union's Horizon Europe Framework Programme (HORIZON-WIDERA-2021-ACCESS-03, Twinning Call) under the grant agreement No 101079377 and the UKRI under project number 10050486. Disclaimer: Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the UKRI. Neither the European Union nor the UKRI can be held responsible for them.

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

Nomenclature

Notation	Definition
AMT	Advanced modeling tools
AR	Augmented reality
BIM	Building information modeling
CAD	Computer-aided design
CH	Cultural heritage
CT	Computed tomography
EDM	Electronic distance measurement

FE	Finite element
FEA	Finite element analysis
FEM	Finite element model
GNSS	Global navigation satellite systems
GPS	Global positioning systems
HBIM	Historical building information modeling
IFC	Industry foundation classes
LiDAR	Light detection and ranging
LoD	Level of detail
MRI	Magnetic resonance imaging
MTLS	Mobile terrestrial laser scanning
NURBS	Non-uniform rational B-splines
RMSE	Root mean square error
STLS	Static terrestrial laser scanning
TLS	Terrestrial laser scanning
UAV	Unmanned aerial vehicles
VR	Virtual reality
WoS	Web of Science

Appendix A

This section presents a table (Table A1) listing the software used for managing point clouds, for FEM analysis, and for BIM and surface modeling in the articles analyzed.

Table A1. List of software for "Point clouds manage", "FEM analysis", "BIM modelling" and "Surface modelling" and the reference that cites it.

	References
Point clouds visualization and processing	
Agisoft Metashape (www.agisoft.com)	[56]
Autodesk ReCap (www.autodesk.com)	[39,67]
3D Studio Max (www.autodesk.com)	[39]
3D Reshaper (www.geodeticavolpe.com)	[68]
MeshLab	[5,59]
Geomagic	[59,69]
MeshMixer (www.autodesk.com)	[56]
CloudCompare (www.cloudcompare-org.danielgm.net)	[56]
Blender	-
InstantMeshes	-
Zbrush (Pixologic)	[56,57]
Artec Studio 10 professional (www.artec3d.com)	[12]
FEM analysis	
Abaqus	[59,70]
Midas FEA	[13,58]
Robot Structural Analysis	-
3D FEM professional (www.sofistik.com)	-
Ansys (www.ansys.com)	[68,71]
PRO SAP (www.2si.it)	[38]
SAP 2000 (www.csi-italia.eu)	[67]
DIANA FEA	[72]
Hypermesh®	[69]
Straus7 (www.straus7.com)	-
Solidworks (www.solidworks.com)	[73]
BIM modeling	
Autodesk Revit	[13,38,67,70]
ArchiCAD (www.graphisoft.com)	-
Tekla	-
Bentley MicroStation (www.bentley.com)	-
Dynamo (www.dynamosoftware.com)	[74]
Surface modeling	
Rhinoceros®	[13,38,58,70,75]
Hypermesh®	[59]
Blender	-
Maya (www.autodesk.com)	-

References

1. Fioravanti, M.; Mecca, S. *The Safeguard of Cultural Heritage: A Challenge from the Past for the Europe of Tomorrow*; COST Strategic Workshop; Firenze University Press; Florence, Italy, 2011.
2. Chen, L. Integration of Terrestrial Laser Scanning and Close-Range Photogrammetry for Documenting Built Heritage. PhD Thesis, University of Florida, Gainesville, FL, USA, 2020.

3. Truong-Hong, L.; Laefer, D.F. Validating computational models from laser scanning data for historic facades. *J. Test. Evaluation* **2013**, *41*, 481–496. https://doi.org/10.1520/JTE20120243.
4. Bartoli, G.; Betti, M.; Bonora, V.; Conti, A.; Fiorini, L.; Kovacevic, V.C.; Tesi, V.; Tucci, G. From TLS data to FE model: A workflow for studying the dynamic behavior of the Pulpit by Giovanni Pisano in Pistoia (Italy). *Procedia Struct. Integr.* **2020**, *29*, 55–62. https://doi.org/10.1016/j.prostr.2020.11.139.
5. Korumaz, M.; Betti, M.; Conti, A.; Tucci, G.; Bartoli, G.; Bonora, V.; Korumaz, A.G.; Fiorini, L. An integrated Terrestrial Laser Scanner (TLS), Deviation Analysis (DA) and Finite Element (FE) approach for health assessment of historical structures. A minaret case study. *Eng. Struct.* **2017**, *153*, 224–238. https://doi.org/10.1016/j.engstruct.2017.10.026.
6. Armesto, J.; Lubowiecka, I.; Ordóñez, C.; Rial, F.I. FEM modeling of structures based on close range digital photogrammetry. *Autom. Constr.* **2009**, *18*, 559–569. https://doi.org/10.1016/j.autcon.2008.11.006.
7. Castellazzi, G.; Presti, N.L.; D'altri, A.M.; de Miranda, S. Cloud2FEM: A finite element mesh generator based on point clouds of existing/historical structures. *SoftwareX* **2022**, *18*, 101099. https://doi.org/10.1016/j.softx.2022.101099.
8. Várady, T.; Martin, R.R.; Cox, J. Reverse engineering of geometric models-an introduction. *Comput. Des.* **1997**, *29*, 255–268. https://doi.org/S50010-4485(96)00054-1.
9. Funari, M.F.; Hajjat, A.E.; Masciotta, M.G.; Oliveira, D.V.; Lourenço, P.B. A parametric scan-to-FEM framework for the digital twin generation of historic masonry structures. *Sustainability* **2021**, *13*, 11088. https://doi.org/10.3390/su131911088.
10. Pepe, M.; Costantino, D.; Garofalo, A.R. An efficient pipeline to obtain 3D model for HBIM and structural analysis purposes from 3D point clouds. *Appl. Sci.* **2020**, *10*, 1235. https://doi.org/10.3390/app10041235.
11. Giaccone, D.; Fanelli, P.; Santamaria, U. Influence of the geometric model on the structural analysis of architectural heritage. *J. Cult. Heritage* **2020**, *43*, 144–152. https://doi.org/10.1016/j.culher.2019.12.001.
12. Antón, D.; Pineda, P.; Medjdoub, B.; Iranzo, A. As-built 3D heritage city modelling to support numerical structural analysis: Application to the assessment of an archaeological remain. *Remote. Sens.* **2019**, *11*, 1276. https://doi.org/10.3390/rs11111276.
13. Barazzetti, L.; Banfi, F.; Brumana, R.; Gusmeroli, G.; Previtali, M.; Schiantarelli, G. Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans. *Simul. Model. Pract. Theory* **2015**, *57*, 71–87. https://doi.org/10.1016/j.simpat.2015.06.004.
14. Castellazzi, G.; D'Altri, A.M.; Bitelli, G.; Selvaggi, I.; Lambertini, A. From laser scanning to finite element analysis of complex buildings by using a semi-automatic procedure. *Sensors* **2015**, *15*, 18360–18380. https://doi.org/10.3390/s150818360.
15. Willkens, D.S.; Liu, J.; Alathamneh, S. A Case Study of Integrating Terrestrial Laser Scanning (TLS) and Building Information Modeling (BIM) in Heritage Bridge Documentation: The Edmund Pettus Bridge. *Buildings* **2024**, *14*, 1940. https://doi.org/10.3390/buildings14071940.
16. European Commission (EC). EU-lex-2021/1970 of 10 November 2021 on a Common European Data Space for Cultural Heritage. 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021H1970 (accessed on 28 November 2024).
17. The London Charter for The Computer-Based Visualisation of Cultural Heritage Preamble Objectives Principles [WWW Document]. 2009. Available online: https://londoncharter.org/fileadmin/templates/main/docs/london_charter_2_1_en.pdf (accessed on 28 November 2024).
18. The Venice Charter. International Charter for the Conservation and Restoration of Monuments and Sites. 1964. Available online: https://www.icomos.org/en/participer/179-articles-en-francais/ressources/charters-and-standards/157-the-venice-charter (accessed on 28 November 2024).
19. Colette, A. (ed.). *Climate Change and World Heritage. Report on Predicting and Managing the Impacts of Climate Change on World Heritage and Strategy to Assist States Parties to Implement Appropriate Management Responses*; World Heritage Reports 22; UNESCO World Heritage Centre: Paris, France, 2006.
20. European Commission (EC). Study on Quality in 3D Digitisation of Tangible Cultural Heritage: Mapping Parameters, Formats, Standards, Benchmarks, Methodologies, and Guidelines VIGIE 2020/654 Final Study Report. 2022. Available online https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage (accessed on 28 November 2024).
21. Expert Group on Digital Cultural Heritage and Europeana. Basic Principles and Tips for 3D Digitisation of Tangible Cultural Heritage for Cultural Heritage Professionals and Institutions and Other Custodians of Cultural Heritage. 2021. Available online: https://digital-strategy.ec.europa.eu/en/library/basic-principles-and-tips-3d-digitisation-cultural-heritage (accessed on 28 November 2024).

22. Bochenska, A.; Kot, P.; Muradov, M.; Markiewicz, J.; Zawieska, D.; Hess, M.; Antoniou, A. Critical evaluation of cultural heritage architectual standard documentation methods across different european countries. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2023**, *XLVIII-M-2*, 251–258. https://doi.org/doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-251-2023.
23. Yang, S.; Hou, M.; Li, S. Three-Dimensional Point Cloud Semantic Segmentation for Cultural Heritage: A Comprehensive Review. *Remote. Sens.* **2023**, *15*, 548. https://doi.org/10.3390/rs15030548.
24. Bauwens, S.; Bartholomeus, H.; Calders, K.; Lejeune, P. Forest inventory with terrestrial LiDAR: A comparison of static and hand-held mobile laser scanning. *Forests* **2016**, *7*, 127. https://doi.org/10.3390/f7060127.
25. Che, E.; Jung, J.; Olsen, M.J. Object recognition, segmentation, and classification of mobile laser scanning point clouds: A state of the art review. *Sensors* **2019**, *19*, 810. https://doi.org/10.3390/s19040810.
26. Pathak, R.; Saini, A.; Wadhwa, A.; Sharma, H.; Sangwan, D. An object detection approach for detecting damages in heritage sites using 3-D point clouds and 2-D visual data. *J. Cult. Heritage* **2021**, *48*, 74–82. https://doi.org/10.1016/j.culher.2021.01.002.
27. Banfi, F. HBIM, 3D drawing and virtual reality for archaeological sites and ancient ruins. *Virtual Archaeol. Rev.* **2020**, *11*, 16–33. https://doi.org/10.4995/var.2020.12416.
28. Palčák, M.; Kudela, P.; Fandáková, M.; Kordek, J. Utilization of 3D Digital Technologies in the Documentation of Cultural Heritage: A Case Study of the Kunerad Mansion (Slovakia). *Appl. Sci.* **2022**, *12*, 4376. https://doi.org/10.3390/app12094376.
29. Sánchez-Aparicio, L.J.; del Blanco-García, F.L.; Mencías-Carrizosa, D.; Villanueva-Llauradó, P.; Aira-Zunzunegui, J.R.; Sanz-Arauz, D.; Pierdicca, R.; Pinilla-Melo, J.; Garcia-Gago, J. Detection of damage in heritage constructions based on 3D point clouds. A systematic review. *J. Build. Eng.* **2023**, *77*, 107440. https://doi.org/10.1016/j.jobe.2023.107440.
30. Arias, P.; González-Aguilera, D.; Riveiro, B.; Caparrini, N. Orthoimage-based documentation of archaeological structures: The case of a mediaeval wall in Pontevedra, Spain. *Archaeometry* **2011**, *53*, 858–872. https://doi.org/10.1111/j.1475-4754.2010.00566.x.
31. Yang, S.; Xu, S.; Huang, W. 3D Point Cloud for Cultural Heritage: A Scientometric Survey. *Remote. Sens.* **2022**, *14*, 5542. https://doi.org/10.3390/rs14215542.
32. Akboy, S. The Habs Culture of Documentation with an Analysis of Drawing and Technology. PhD Thesis. Texas A&M University, College Station, TX, USA, 2011.
33. Tognaccini, R. La Chiesa di Santa Maria del Mar a Barcellona: Dal Rilievo Tridimensionale All'analisi Strutturale. Master's Thesis, University of Pisa, Pisa, Italy, 2009.
34. Quattrini, R.; Clementi, F.; Lucidi, A.; Giannetti, S.; Santoni, A. From TLS to FE analysis: Points cloud exploitation for structural behaviour definition. The San Ciriaco's bell tower. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **2019**, *42*, 957–964. https://doi.org/10.5194/isprs-archives-XLII-2-W15-957-2019.
35. Murphy, M.; Mcgovern, E.; Pavia, S. Historic building information modelling (HBIM). *Struct. Surv.* **2009**, *27*, 311–327. https://doi.org/10.1108/02630800910985108.
36. Banfi, F.; Chow, L.; Reina Ortiz, M.; Ouimet, C.; Fai, S. *Building Information Modeling for Cultural Heritage: The Management of Generative Process for Complex Historical Buildings*; Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Springer Science and Business Media Deutschland GmbH: Cham, Switzerland, 2018; Volume 10605, pp. 119–130. https://doi.org/10.1007/978-3-319-75826-8_10.
37. Oreni, D.; Brumana, R.; Della Torre, S.; Banfi, F. Survey, HBIM and conservation plan of a monumental building damaged by earthquake. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2017**, *42*, 337–342. https://doi.org/10.5194/isprs-Archives-XLII-5-W1-337-2017.
38. Ursini, A.; Grazzini, A.; Matrone, F.; Zerbinatti, M. From scan-to-BIM to a structural finite elements model of built heritage for dynamic simulation. *Autom. Constr.* **2022**, *142*, 104518. https://doi.org/10.1016/j.autcon.2022.104518.
39. Santini, S.; Canciani, M.; Borghese, V.; Sabbatini, V.; Sebastiani, C. From Digital Restitution to Structural Analysis of a Historical Adobe Building: The Escuela José Mariano Méndez in El Salvador. *Heritage* **2023**, *6*, 4362–4379. https://doi.org/10.3390/heritage6050231.
40. Thomson, C.; Boehm, J. Automatic geometry generation from point clouds for BIM. *Remote. Sens.* **2015**, *7*, 11753–11775. https://doi.org/10.3390/rs70911753.
41. Rolin, R.; Antaluca, E.; Batoz, J.-L.; Lamarque, F.; Lejeune, M. From point cloud data to structural analysis through a geometrical hBIM-oriented model. *J. Comput. Cult. Heritage* **2019**, *12*, 1–26. https://doi.org/10.1145/3242901.
42. Hinks, T.; Carr, H.; Truong-Hong, L.; Laefer, D.F. Point Cloud Data Conversion into Solid Models via Point-Based Voxelization. *J. Surv. Eng.* **2013**, *139*, 72–83. https://doi.org/10.1061/(asce)su.1943-5428.0000097.
43. Kaufman, A.; Shimony, E. 3D Scan-Conversion Algorithms for Voxel-Based Graphics. In *Proceedings of ACM Workshop on Interactive 3D Graphics*; ACM Press: Chapel Hill, NC, USA, 1986; pp. 45–76.

44. Ma, M.; Buyyounouski, M.K.; Vasudevan, V.; Xing, L.; Yang, Y. Dose distribution prediction in isodose feature-preserving voxelization domain using deep convolutional neural network. *Med Phys.* **2019**, *46*, 2978–2987. https://doi.org/10.1002/mp.13618.
45. Joyce, T.; Buoso, S.; Stoeck, C.T.; Kozerke, S. Rapid inference of personalised left-ventricular meshes by deformation-based differentiable mesh voxelization. *Med Image Anal.* **2022**, *79*, 102445. https://doi.org/10.1016/j.media.2022.102445.
46. Ridzuan, N.; Ujang, U.; Azri, S.; Yusoff, I.M.; Choon, T.L. Voxelization techniques: Data segmentation and data modelling for 3d build-ing models. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2022**, *48*, 149–155. https://doi.org/10.5194/isprs-archives-XLVIII-4-W3-2022-149-2022.
47. Bergs, T.; Henrichs, O.; Wilms, M.; Prümmer, M.; Arntz, K. Development of a voxelization tool for the calculation of vector-based workpiece representations. *Procedia CIRP* **2021**, *100*, 7–12. https://doi.org/10.1016/j.procir.2021.05.022.
48. Doğan, S.; Güllü, H. Multiple methods for voxel modeling and finite element analysis for man-made caves in soft rock of Gaziantep. *Bull. Eng. Geol. Environ.* **2021**, *81*, 1–20. https://doi.org/10.1007/s10064-021-02489-8.
49. Bitelli, G.; Castellazzi, G.; D'altri, A.M.; de Miranda, S.; Lambertini, A.; Selvaggi, I. On the generation of numerical models from point clouds for the analysis of damaged Cultural Heritage. *IOP Conf. Series: Mater. Sci. Eng.* **2018**, *364*, 012083. https://doi.org/10.1088/1757-899X/364/1/012083.
50. Bitelli, G.; Castellazzi, G.; D'altri, A.; De Miranda, S.; Lambertini, A.; Selvaggi, I. Automated voxel model from point clouds for structural analysis of cultural heritage. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2016**, *41*, 191–197. https://doi.org/10.5194/isprsarchives-XLI-B5-191-2016.
51. D'Altri, A.; de Miranda, S.; Castellazzi, G.; Glisic, B. Numerical modelling-based damage diagnostics in cultural heritage structures. *J. Cult. Heritage* **2023**, *61*, 1–12. https://doi.org/10.1016/j.culher.2023.02.004.
52. Presti, N.L.; Castellazzi, G.; D'altri, A.M.; Bertani, G.; de Miranda, S.; Azenha, M.; Roggio, D.S.; Bitelli, G.; Ferretti, F.; Rende, N.; Mazzotti, C. Streamlining FE and BIM Modeling for Historic Buildings with Point Cloud Transformation. *Int. J. Arch. Heritage* **2024**, 1–14. https://doi.org/10.1080/15583058.2024.2330942.
53. Selvaggi, I. Surveying and Three-Dimensional Modeling for Preservation and Structural Analysis of Cultural Heritage. PhD Thesis, Università di Bologna, Bologna, Italy, 2017.
54. Kaushal, S.S.; Soto, M.G.; Napolitano, R. Structural analysis of post-disaster masonry structures modeled using CLOUD2FEM software. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2023**, *48*, 827–834. https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-827-2023.
55. Rogers, D.F. Rational B-spline curves. In *An Introduction to NURBS*; The Morgan Kaufmann Series in Computer Graphics; Elsevier: Amsterdam, The Netherlands, 2001, pp. 129–153.
56. Barsanti, S.G.; Guagliano, M.; Rossi, A. Digital (re)construction for structural analysis. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2023**, *48*, 685–692. https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-685-2023.
57. Barsanti, S.G.; Guidi, G. A New Methodology for the Structural Analysis of 3D Digitized Cultural Heritage through FEA. *IOP Conf. Series: Mater. Sci. Eng.* **2018**, *364*, 012005. https://doi.org/10.1088/1757-899X/364/1/012005.
58. Alfio, V.S.; Costantino, D.; Pepe, M.; Garofalo, A.R. A Geomatics Approach in Scan to FEM Process Applied to Cultural Heritage Structure: The Case Study of the "Colossus of Barletta." *Remote. Sens.* **2022**, *14*, 664. https://doi.org/10.3390/rs14030664.
59. Lei, Z.; Weitong, Y.; Desheng, L.; Ping, Z.; Yonghui, J.; Yin, X.; Yungang, H.; Xiaoxi, L.; Miaole, H.; Xi, C.; Qianli, F. A Complete Methodology for Structural Finite Element Analysis of Terracotta Sculptures Based on a 3D Scanned Model: A Case Study on the Terracotta Warriors (China). *Stud. Conserv.* **2022**, *68*, 761–772. https://doi.org/10.1080/00393630.2022.2156223.
60. Almac, U.; Pekmezci, I.P.; Ahunbay, M. Numerical Analysis of Historic Structural Elements Using 3D Point Cloud Data. *Open Constr. Build. Technol. J.* **2016**, *10*, 233–245. https://doi.org/10.2174/1874836801610010233.
61. Fortunato, G.; Funari, M.F.; Lonetti, P. Survey and seismic vulnerability assessment of the Baptistery of San Giovanni in Tumba (Italy). *J. Cult. Heritage* **2017**, *26*, 64–78. https://doi.org/10.1016/j.culher.2017.01.010.
62. Lucidi, A.; Giordano, E.; Clementi, F.; Quattrini, R. Point cloud exploitation for structural modeling and analysis: A reliable workflow. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2021**, *43*, 891–898. https://doi.org/10.5194/isprs-archives-XLIII-B2-2021-891-2021.
63. Bagnéris, M.; Cherblanc, F.; Bromblet, P.; Gattet, E.; Gügi, L.; Nony, N.; Mercurio, V.; Pamart, A. A complete methodology for the mechanical diagnosis of statue provided by innovative uses of 3D model. Application to the imperial marble statue of Alba-la-Romaine (France). *J. Cult. Heritage* **2017**, *28*, 109–116. https://doi.org/10.1016/j.culher.2017.05.002ï.

64. Tucci, G.; Rihal, S.; Betti, M.; Conti, A.; Fiorini, L.; Kovacevic, V.C.; Bartoli, G. Ground based 3d modelling (photogrammetry and tls)-survey, documentation and structural assessment of XX century cultural heritage in India-A case study of the masonry vaults in Dehradun. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2019**, *42*, 1105–1111. https://doi.org/10.5194/isprs-Archives-XLII-2-W11-1105-2019.
65. Visintini, D.; Spangher, A. Il contributo della Geomatica per l'analisi strutturale dei beni culturali: l'esempio di una statua romana lesionata. In Proceedings of the 18th Conferenza Nazionale ASITA, Firenze, Italy, 14–16 October 2014.
66. Agapiou, A.; Aktas, Y.; Barazzetti, L.; Costa, A.; Cuca, B.; D'ayala, D.; Kyriakides, N.; Kyriakidis, P.; Lysandrou, V.; Oreni, D.; et al. Geomatics and civil engineering innovative research on heritage: Introducing the "ENGINEER" project. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2023**, *48*, 27–32. https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-27-2023.
67. Martínez-Carricondo, P.; Casimiro-Bernández, J.M.; Agüera-Vega, F.; Carvajal-Ramírez, F. Structural weakness of the twenty eyes aqueduct in the wadi of carcauz (almeria, spain). *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* **2023**, *48*, 1021–1025. https://doi.org/10.5194/isprs-Archives-XLVIII-M-2-2023-1021-2023.
68. Bassier, M.; Hadjidemetriou, G.; Vergauwen, M.; Van Roy, N.; Verstrynge, E. *Implementation of Scan-to-BIM and FEM for the Documentation and Analysis of Heritage Timber Roof Structures;* In: Euro-mediterranean conference); Springer: Cham, Switzerland,2016; Volume 10058, pp. 79–90. https://doi.org/10.1007/978-3-319-48496-9_7.
69. Guarnieri, A.; Milan, N.; Vettore, A. Monitoring of complex structure for structural control using terrestrial laser scanning (Tls) and photogrammetry. *Int. J. Arch. Heritage* **2013**, *7*, 54–67. https://doi.org/10.1080/15583058.2011.606595.
70. Zouaoui, M.A.; Djebri, B.; Capsoni, A. From Point Cloud to HBIM to FEA, the Case of a Vernacular Architecture. *J. Comput. Cult. Heritage* **2020**, *14*, 1–21. https://doi.org/10.1145/3418039.
71. Tucci, G.; Bartoli, G.; Betti, M.; Bonora, V.; Korumaz, M.; Korumaz, A.G. Advanced procedure for documenting and assessment of Cultural Heritage: From Laser Scanning to Finite Element. *IOP Conf. Series: Mater. Sci. Eng.* **2018**, *364*, 012085. https://doi.org/10.1088/1757-899X/364/1/012085.
72. Shabani, A.; Skamantzari, M.; Tapinaki, S.; Georgopoulos, A.; Plevris, V.; Kioumarsi, M. 3D simulation models for developing digital twins of heritage structures: Challenges and strategies. *Procedia Struct. Integr.* **2022**, *37*, 314–320. https://doi.org/10.1016/j.prostr.2022.01.090.
73. Marinelli, A.; Kumari, M. From point cloud data to structural modelling: The case study of the Tusk at Spynie Palace, Scotland. *Procedia Struct. Integr.* **2023**, *47*, 205–212. https://doi.org/10.1016/j.prostr.2023.07.013.
74. Massafra, A.; Prati, D.; Predari, G.; Gulli, R. Wooden truss analysis, preservation strategies, and digital documentation through parametric 3D modeling and HBIM workflow. *Sustainability* **2020**, *12*, 4975. https://doi.org/10.3390/su12124975.
75. Oreni, D.; Brumana, R.; Banfi, F.; Bertola, L.; Barazzetti, L.; Cuca, B.; Previtali, M.; Roncoroni, F. *Beyond Crude 3D Models: From Point Clouds to Historical Building Information Modeling via NURBS*; In: Ioannides, M., Magnenat-Thalmann, N., Fink, E., Žarnić, R., Yen, AY., Quak, E. (eds) Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection. EuroMed 2014. Lecture Notes in Computer Science, vol 8740, pp. 166-175. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-13695-0_16.