AI and Digital Twin Applications in 3D Information Models for Heritage Buildings: A Systematic Review

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ABSTRACT
The recent emergence of technology as digital tools has provided architects with possibilities for 3D modelling and simulation of built environments. Currently, the "digital twin" and Building Information Management (BIM) techniques enable analytical tools like connection analysis and energy performance modelling in tandem with the ideation of realistic 3D illustrations. These methods are now seen emerging in managing and documenting heritage structures. A Heritage Building Information Management (HBIM) platform is a multi-disciplinary process and a valuable tool to automate, manage, and document heritage structures. However, making the final product in an HBIM platform involves several laborious steps of processing, segmenting, and integrating raw data from different sources, such as laser-scanned point data and image data. Hence, an expedited, streamlined platform is necessary to facilitate conservation architects and other agencies involved in documenting, maintaining and interpreting heritage buildings and structures. Newer technologies like Artificial Intelligence can enhance previously unavailable opportunities to automate specific tasks and uncover paradigms through predictable simulations. For this, the researchers reviewed the literature on two fronts:
i) Investigating process flow and identifying the issues and challenges in gathering digital data of the existing building effectively.
ii) Reviewing the literature to understand the models and tech solutions that revolutionized building heritage building information models for practical use.
This study unravels workflow patterns and challenges based on these two sections of this literature review. Further, this research explores and analyses the trends and techniques employed in a typical heritage Building Information Management (HBIM) platform. The focus is on AI's capabilities as a digital tool in different stages of documentation and interpretation, performance measurement and simulation of heritage buildings, such as energy performance modeling, 4D (3D+Time) for projects planning, cost solutions, and simulating the historical significance to propagate the importance of HBIM. This study referred to the progress in the scientific literature on HBIM after the initial studies of C. Dore, and M. Murphy (2009).
Keywords— AI, Digital Twins, Design Process and Workflow, Heritage Buildings, 3D modelling

1. Introduction

With the advent of computational tools in the AEC (Architectural Engineering and Construction) industry, digital means of conception, production, and documentation extended the capacity of traditional practices while challenging and changing the conventional standards and praxis. Technological advancements like Building information modelling (BIM) **[1]** have enabled the transition from 2D CAD drawings to 3D models supporting various processes and collaborating with many AEC disciplines to store, record, and exchange heterogeneous content. Consequently, in the domain of conservation architecture, heritage organizations and work groups are becoming more interested in adopting innovative approaches to address the preservation of tangible and intangible cultural heritage worldwide. Various computational platforms have equipped conservation architects and historians with efficient ways of documenting, interpreting and disseminating cultural knowledge

[2]. The acquisition of quantitative and qualitative data is included in creating digital 3D models and simulations of the built environment that digitize cultural heritage assets and locations [**3**]. A Heritage Building Information Modelling (HBIM) platform is a multi-disciplinary process and a valuable tool to automate, manage, and document heritage structures, as defined by M. Murphy et al, 2009. HBIM software uses immersive and interactive settings to gather and display information that architects and users find helpful **[4].** Concepts of "digital twin" and Building Information Management (BIM) techniques enable analytical tools like connection analysis and energy performance modelling in tandem with the ideation of realistic 3D illustrations.

HBIM platforms incorporate spatial data gathered from 3D scanning and photogrammetric technologies. In particular, laser scanners can quickly and accurately create geometric replicas of three-dimensional objects in the form of millions of points with (X, Y, Z) coordinates.[6] Furthermore, internal or external calibrated cameras can add or map colour data to the 3D model, enhancing realistic imagery.

2. Uses of Heritage Building Information Modelling [5]:

A building information model can be used for the following purposes, amongst many others:

• *Visualization:* Realistic illustrations can be created that can further be used as AR/VR and MR models
• *Semantic Information:* Elements can be attributed to rich semantic data that can describe materials, year of construction, history etc
• *Forensic analysis:* This platform can illustrate potential failures, leaks, weathering etc.
• *Facilities management*: It can be used by facilities management departments for space planning and maintenance tasks.
• Fabrication/shop drawings for improvements and adaptive reuse
• *Code reviews:* These models may be used by fire departments and other agencies to examine construction projects.
• *Cost estimating:* There are cost estimating tools embedded into BIM software. Material quantities are automatically retrieved and updated when modifications are made to the model.
• *Conflict, interference, and collision detection:* all significant services can be cross-checked for interferences. For example, this process can verify that piping does not intersect with structural elements, ducts etc.

The critical advantage of HBIMs over manual heritage management models is their accurate graphical representation of the parts of a building in an integrated data environment.
Other related benefits are as follows:

• *Quicker and more efficient:* Creates a common platform for sharing information
• *Efficient analysis*: Precise analysis of building proposals, fast simulations such as energy, finite element test etc.
• *Better output quality*: Documentation output can be dynamically manipulated
• *Automated structure*: structural systems for repair and rebuild can be better analysed and automated
• *Better Visual understanding*: The project can be understood further with AR/VR and MR technologies
• *Lifecycle data*: Requirements, operational cost and information can be used in facilities management

With this technological advancement, experts today employ a variety of BIM platforms such as ArchiCAD (Graphisoft), Tekla Structures, and Bentley System [6]. This software is commonly used to manage the incremental and integrated knowledge of architectural history through modelling and virtual visualisation. However, the process of making the final product in an HBIM platform involves several laborious steps of processing, segmenting, and integrating raw data from different sources, such as laser-scanned point data and image data [3,4].

HBIM uses a terrestrial laser scanner and digital cameras to collect raw survey data remotely. The image and scan data are cleaned and fused using various software applications. The point cloud is 'meshed,' and then the picture data is used to texturize the model, creating the framework for the 3D model. The final step in reverse engineering involves mapping BIM objects onto a 3D surface model. After this elaborate processing of the raw data, HBIM constructs complete 2D and 3D models that include information about the processes of construction and material composition of the historic structure. It is also crucial to note that the BIM platforms' libraries and tools concentrate on designing and constructing new structures with specific, regular, and standardized components. Due to this, some more BIM platform limitations come into the picture, including the absence of historical parametric object libraries and the need for more tools for managing complex, irregular, and uncertain shapes derived from point clouds. Further, although primarily factual, subsequent raw-data segmentation and interpretation make the final models again serve as the measure of an idea, working through an image in one's understanding of facts[10]. This study tries to understand the workflow process and its limitations in making an HBIM model, from its earliest beginnings to the technological progression it has made thus far into machine learning and Artificial Intelligence (AI). The emergence of Artificial Intelligence (AI) techniques in the architectural heritage domain is reshaping the approach of heritage experts towards the interpretation, recognition, and classification of building components on raw surveying information. In this respect, the study also explores the contributions of Artificial Intelligence (AI) to automate and optimize the technique at various stages of the process are understood. This study referred to the progress in the scientific literature on HBIM after the initial studies of C. Dore, and M. Murphy (2009). This research laid the foundation to define the paper's structure for investigating stages in creating an HBIM. A filter or bibliometric research identified the most important publications, the progression of interest in topics through time, and the connections between them. The many sources of contributions, including academic journals, proceedings, and commercial innovations, were searched using keywords for this purpose.

3. Data Capture and processing

3.1 Laser scanners

Laser scanning data is the primary spatial data to Create an HBIM model. Laser scanning technology uses laser beams that travel toward the scanned region; it can measure angles and distances with millimetre-level accuracy [8]. The scanner returns data consisting of millions of points, each with geospatial information of x,y,z dimensions. Colour can also be incorporated into digital models later by overlapping geospatial coordinates [11]. Laser scanners can be classified based on the type and technology they use. Each one has a range and level of precision appropriate for the purpose for which it will be used. There are two kinds of laser scanners- Ariel and Terrestrial; short-range and long-range scanners. As the name suggests, they are used based on where a scanner can be positioned on the ground or by drone technology, near or far. Terrestrial Laser Scanners (TLS) [3] have better accuracy than drones but cannot be used to get scans of the entire site or the roof from an elevated position. There are 3 types of TLS instruments-triangulation, phase comparison and time of flight scanners. [3, 6, 7]. Triangulation scanners determine 3D coordinate measurements by triangulating the spot or stripe of a laser beam on an object's surface captured by one or more charge-coupled device cameras. Based on the difference in phase between the wavelengths that are being transmitted and returned, phase comparison systems determine range. The time it takes for a laser pulse to travel from its source to an object and then be reflected time-of-flight scanners use a receiving detector to calculate range or distance. Due to their long range, time-of-flight scanners, such as LiDARs, are preferable to triangulation and phase comparison systems and better suited for recording smaller objects [12, 13]. However, with all terrestrial scanners, it is only ideal for capturing some geometric information of external surfaces from a single scanning location. Therefore, data is extracted by positioning scanners in different areas. The point cloud's x, y, and z coordinates from various positions are interpolated, and a final set of the point cloud is gathered in a process called *registration*

[14, 18]. Therefore, scanners are positioned to have adequate overlap, metric accuracy, similar density and resolution (scale) for registration and stitching.[19]

3.2 Combining laser scanning and digital imaging

Photogrammetry was coined by the Prussian architect Albrecht Meydenbauer [16] in 1867. The essence of photogrammetry is in extracting three-dimensional measurements and colour ranges of surface geometries from 2-D images. Imagery can be obtained from various cameras ranging from large format metric cameras, where high accuracy and archival value are essential, to smaller format 35mm cameras which are helpful where access is restricted. Compared to standard aerial (orbital) photogrammetry, close-range photogrammetry collects images taken at a closer range [14, 15]. One major drawback of photographic reconstruction is the need for post-processing. This is because the technique requires a lot of manual labour and takes a long time, especially when the object's texture is poor, and its shape is intricate [17]. Machine learning and computer vision (structure for motion algorithm) is starting to make pre-processing semi-automated.) [18]. In applications for documentation, structure evaluation, texture mapping, feature extraction, etc., the most efficient way to capture complex heritage sites is by combining TLS and photogrammetric techniques.

4. Processing laser and image survey data

4.1 Pre-processing of laser survey data

After collecting the raw geometry of the scanned structures, a point cloud, the data set with x,z, and z coordinates, needs to be cleaned, sorted and registered for a final point cloud data set.[3].

4.1.1 Data cleaning and re-sampling.

Pre-processing of data starts by cleaning up errors in the collected data. Erroneous data or objects, such as reflections from scanned objects, are cleaned and removed during the initial pre-processing stage so that point clouds can be created. Many factors can lead to inaccuracies in data, such as instrumental errors, positional errors [22], duplicated data, varying point density, human error, inconsistent formats, and reflections on scanned objects. Once identified, they can be re-sampled or significantly eliminated by introducing digital range limits or using graphical CAD software tools. Outliers and missing data are imputed statistically. Nowadays, this is done through specialised TLS software such as [20,21,29]

- ESRI ArcGIS
- Innovmetric Polyworks
- Riegl RiSCAN PRO
- Autodesk ReCap Pro
- Leica Cyclone
- FARO SCENE
- Artec Studio
- 3D Zephyr®
- Trimble Realwoks

Functions of TLS software may include [20,21,29]:
- Noise filtration
- Target identification
- Tagging
- Geo-referencing
- Report generation
- Error reporting
- 3D modeling
- Texturing
- Sharing files to the cloud
- Registration of point cloud data (automatic or manual)

4.1.2 Point Cloud Registration

Given two sets of point clouds in arbitrary coordinate systems, the goal is to precisely estimate geometric transformations between them to align these data under the same coordinate frame, called point registration [18]. The registration process becomes colossal as the data volume, quality, scale, and scene complexity vary.[19]

In general, most of the point cloud registration process typically takes on a two-step process, 1) a *coarse registration* establishing an initial geometric transformation between the two datasets using sparse feature-based correspondences, and 2) *a fine registration* to refine the geometric transformation using more and denser correspondences, also known as cloud-to-cloud (C2C) registration.[18] Many algorithms are now analysed based on their performance analysis on key point detection & description algorithms[25], and statistical outlier-removal algorithms for estimations [26]. As pointed out earlier, registration application requires the robust performance of all these technical components on sufficiently complex and diverse datasets. Moreover, many early evaluations do not consider recently developed methods, especially those developed under deep learning paradigms.

Standard registration algorithms, such as the iterative closest point (ICP) or least squares three-dimensional (3D) surface matching method [25], require registering in diverse types of datasets, such as different-source low-overlap or metrically inaccurate datasets. According to Djahel et al., 2021, in 3D data assimilation and spatial referencing, it is essential to co-register multi-source datasets, such as registration between TLS scans to drone photogrammetry point clouds and between drones with satellite photogrammetry point clouds and between indoor scans with outdoor scans [27].

4.2 Data processing

The basic framework for capturing the geometry of a heritage structure is the point cloud created by the laser scanner from the range data. The associated image data is then projected onto this geometric framework, enabling more accurate identification of the texture and features of the structure on the final 3D model.

4.2.1 Surface meshing.

Point cloud sets have a considerable volume of data, often with redundant information. These enormous datasets quickly become challenging to analyse and work with. Most computers have a finite amount of memory, and operations must be completed in a few steps. The sheer size of a point cloud file can be significant; additionally, manipulating these scans can be challenging [28]. Hence, point clouds can be optimised with algorithms that can create surface triangulations. A process systematically selects a collection of points on the surface to provide the simplest surface representation. [23, 24] The created surface comprises triangles connecting the data to create a complete polygon. Textures and colours can then be attributed to surfaces that make the essential elements of the 3D model.

4.2.2 Texturing the point cloud.

After triangulating point data, the textures of the surfaces need to be re-assigned from the image information. For each triangle vertex on the 3D surface, associated image coordinates are determined. The RGB colour values are then added to the surface triangle after that. Recently, algorithms have been developed that are computationally inexpensive and automatically generate high-quality textures for planar segments based on coloured point clouds. [28] This data is further moved into a CAD or a VRML platform for further realistic rendering for visualisation. Here, image registration defines the location and orientation of all images with respect to one another in a single coordinate system. This process necessitates measuring points in many photos, which can be done manually or automatically in some situations. Each image is given to a particular point cloud set and utilised as a texture map after the points in the point cloud are typically connected via triangulation.

5. Challenges and Limitations of TLS and Photogrammetry for HBIM

The two most important attributes for 3D point cloud data are resolution (or accuracy) and quality since they determine the level of detail and precision of the HBIM models created from them.

Erroneous data can be accumulated at all three stages: data gathering, processing, and fusion. At the data gathering stage, while some errors are systematic within the workflow, some come inherent with the inaccuracies of the equipment. Mostly, equipment to record data in HBIM is through scanners and cameras. Some common errors that can occur from the TLS survey and photogrammetry are as follows [27,28,29, 30]:

• equipment must be appropriated for maximum coverage of the relevant surfaces, reduce self-occlusions and ensure a sufficient point cloud density with the least number of scans.

• The devices are expensive, and the processing of data gathered requires a specialised skill set.

• A TLS survey can also be time-consuming, especially for complex structures.

• There can also be atmospheric errors during the survey, e.g., weather conditions such as humidity, temperature, and visibility.

• The specification and limitation of the equipment, i.e., scanning range, speed, scan-station setting-up requirements, and the requirements for scanning targets.

• Equipment lack in reconstructing texture-less areas of scenes like walls or window glasses and the inability to generate point clouds of scenes that require high densities.

• camera principal point and principal distance, lens distortion coefficients, and imaging settings (i.e., shooting distance, baseline, percentage of photo overlaps, number of overlapping photos, camera intersection angles, and angles of incidence) affect the results. Errors can be caused by incorrect calibration of the external and internal parameters of the camera;

• practical constraints, such as the desirable distances and angles to place the camera or TLS devices not being accessible or some details of the target object being obstructed by other objects (e.g., supporting rigs).

• systematic error due to camera factors and systematic error due to poor planning of camera network geometry

• During the creation of the 3D model, each image must be correctly assigned for each corresponding point cloud; otherwise, errors occur

New methodologies are being researched extensively to automate and appropriate data collection at different stages of generating the HBIM process.

6. Creating engineering drawings from laser scan surveys
6.1 Mapping onto the point cloud – creating engineering drawings

Creating construction drawings from a 3d data set involves a process of reverse engineering. Plans, Elevations and Sections may have to be produced from dimensions, geometry, and material properties captured from the survey. Once the point cloud is exported to CAD software, the data must be adjusted to an orthographic plane. The point cloud must be segmented to overlap the required vectors. In order to identify the objects to be modelled, the integrated point cloud is manually subdivided and delimited for this stage (by following rules and historical patterns).

The analysed object or building is then parametrically modelled using the current BIM library and the externally created objects. Most CAD platforms' workflow is built towards building new objects from existing parametric libraries available through the software. By automatically adding simple 2D or 3D shapes to the point cloud, mapping vectors onto a 3D model can be accelerated. Numerous commercial and academic research projects have investigated the automated reconstruction of existing buildings from point clouds during the past few years.

Some 3D modellers commercially used nowadays are Revit Autodesk, Bentley Systems: Tekla Structures, and ArchiCAD (Graphisoft). The region-growing plane segmentation algorithm is suggested in the works of Wang et al. (2020) [21] and Liu (2020) [29] to separate the raw data into point cloud segments that are located on the same plane. They then provide a boundary detection technique that automatically determines the surface's size, position, and form and creates contour polygons for each recognised feature. According to Volk et al., 2014[32], these studied technologies do not fully automate the conversion of point clouds to BIM despite the advancement. Commercial software such as EdgeWise®, Scan-to-BIM®, from IMAGINiT Technologies for Autodesk Revit led

to the development of new solutions to automate BIM object segmentation and recognition. Although challenging and time-consuming, the semi-automatic procedure is the most efficient method for documentation projects and the parametric modelling of architectural heritage.[6]

6.2 HBIM or the digital twin

Three-dimensional (3D) geometric documentation is the first step in developing
the digital twin of heritage buildings. Tests like FE (Finite Element) tests are subsequently performed to check for Structural vulnerability assessment of heritage structures as a part of a risk mitigation strategy[33]. Shabani et al., 2022 used the industry foundation classes (IFC) format to export the 3D model to develop the 3D FEM in CAD exchanger software [33].

CONCLUSION

The Heritage Building Information Modelling (HBIM or H-BIM) approach creates intelligent BIM models that include, manage, and interpret architectural heritage information using 3D modelling and information management. HBIM is now a crucial tool for preserving and presenting cultural assets. The focus of current research on automated surveying systems for cultural heritage items has been on finding the best hardware and software platforms for data gathering and processing, with the end result being the precise 3D modelling of a historic structure.

(1) To make a 3D model, the acquired data must be processed and transformed. When converted into models, point clouds taken from complex structures, in particular, may be inaccurate or incomplete. It is possible to create plugins that will fix any issues that arise when turning point clouds into models. As a result, data processing can be made simpler.

(2) Careful consideration should be given to the characteristics of the data collection techniques. Variables may be considered before choosing a technique, including the topography, the size of the application area, and the degree of detail in the building.

(3) In modelled complicated structures, parametric object creation is complex. A Geometric Description Language (GDL) could be created to address this issue.

(4) Semantic data is typically manually incorporated into the model, which takes time. The model and data of the object in the computer environment can be automatically matched and integrated by the software.

(5) To increase awareness for analysis and interpretation, simple access, and preservation, developing an international and regional HBIM parametric library is crucial. The creation of specific parametric libraries can be made publicly accessible via free platforms.

(6) Emerging computational technologies, such as Artificial Intelligence (AI), can be used to study the use of HBIM. There is not much research that uses AI to analyse HBIM models. AI can support decision-making and evaluation processes for facility managers, structural engineers, restoration specialists, and conservation planners.

(7) Research using HBIM models in VR for visualisation, project management, and site management for architects and engineers is more common than research on MR and AR approaches.

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