Heritage Building Information Modelling (HBIM): A Review of Published Case Studies

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ABSTRACT:

This paper presents a systematic review of published case studies on Heritage Building Information Modelling (HBIM) since 2018, and identifies research gaps in the subject matter. Building upon the foundational work of Ewart and Zuecco (2019), this research aims to reveal the latest trends in HBIM implementation, identify recent developments of HBIM technologies, changes in the purpose of HBIM programs and stakeholder roles and responsibilities, and uncover knowledge gaps that provide avenues for future research. Utilizing the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) approach, two major academic databases, Scopus and Web of Science (WOS), were searched, resulting in a rich and diverse dataset for analysis. The paper reports findings on the status of reality capture techniques used to acquire data for HBIM development, focusing on terrestrial laser scanning (TLS) technology. The review highlights the benefits and limitations of TLS for data acquisition in HBIM, as well as the integration of TLS with other reality capture technologies, such as Structure from Motion (SfM) and photogrammetry. The paper further outlines the typical workflow for processing TLS scan data and explores the integration of multiple point clouds for comprehensive heritage site modeling. In addition to the state of the art, this systematic review also uncovers several research gaps in the field of HBIM that offer opportunities for future research and innovation, including the lack of guidelines for data acquisition in HBIM programs, the predominantly manual development process of HBIM from TLS point cloud data, and the under-utilized capacity of TLS for long-term monitoring and change detection. This comprehensive review provides valuable insights into the current landscape of HBIM, offering guidance for future research and development in the heritage sector and highlighting areas in need of further investigation to advance the field.

1. INTRODUCTION

In recent years, the adoption of Building Information Modelling (BIM) has been a topic of significant interest in the architecture, engineering, and construction (AEC) industries. The application of BIM to heritage buildings, known as Heritage Building Information Modelling (HBIM), has emerged as a valuable tool for managing and preserving cultural heritage (Murphy et al., 2013). The paper "Heritage Building Information Modelling (HBIM): A Review of Published Case Studies" (Ewart & Zuecco, 2019) serves as a critical examination of the state of HBIM in the heritage sector, providing valuable insights and analysis that warrant its inclusion in the anthology of papers capturing the state-of-the-art understanding of HBIM 5 years after its creation. Ewart's and Zuecco's paper is a significant scholarly work that provides a methodology to examine the adoption and application of HBIM in the heritage sector. The authors conducted an extensive analysis of 52 case studies published before October 2017 and explored the state-of-the-art, trends, purposes, stakeholder involvement, and knowledge gaps in the implementation of HBIM.

Building upon the foundational work of Ewart and Zuecco (2019), the researcher proposes new research that conducts a systematic review of HBIM case studies published since 2018. The intention of this research is to reveal the latest trends in HBIM implementation, identify the latest developments of HBIM technologies, changes in the purpose of HBIM programs and stakeholder roles and responsibilities, and discover knowledge gaps. Due to the page limit, this paper only presents findings in the state-of-the-art technologies used for capturing data for HBIM development, specifically terrestrial laser scanning (TLS).

2. RESEARCH DESIGN AND METHODOLOGY

2.1 Search Method

The Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) approach was selected for this study because of its acceptance, comprehensiveness, and wide variety of applications in numerous academic disciplines (Fobiri et al., 2022). Using the PRISMA approach, this research has commenced with a comprehensive literature search, targeting two major academic databases, Scopus and Web of Science (WOS). The query string deployed for search in Scopuc is as follows

"(TITLE-ABS-KEY(hbim OR historic AND bim OR heritage AND bim) AND TITLE-ABS-KEY(case AND stud*)) AND (LIMIT-TO (PUBYEAR,2023) OR LIMIT-TO (PUBYEAR,2022) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018)) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (DOCTYPE,"ar"))."*

As a result, 118 journal articles published between January 1st 2018 and February 9th 2023 have been identified for inclusion in this review article, providing a rich and diverse dataset for analysis. Figure 1 illustrates the PRISMA approach for this study.

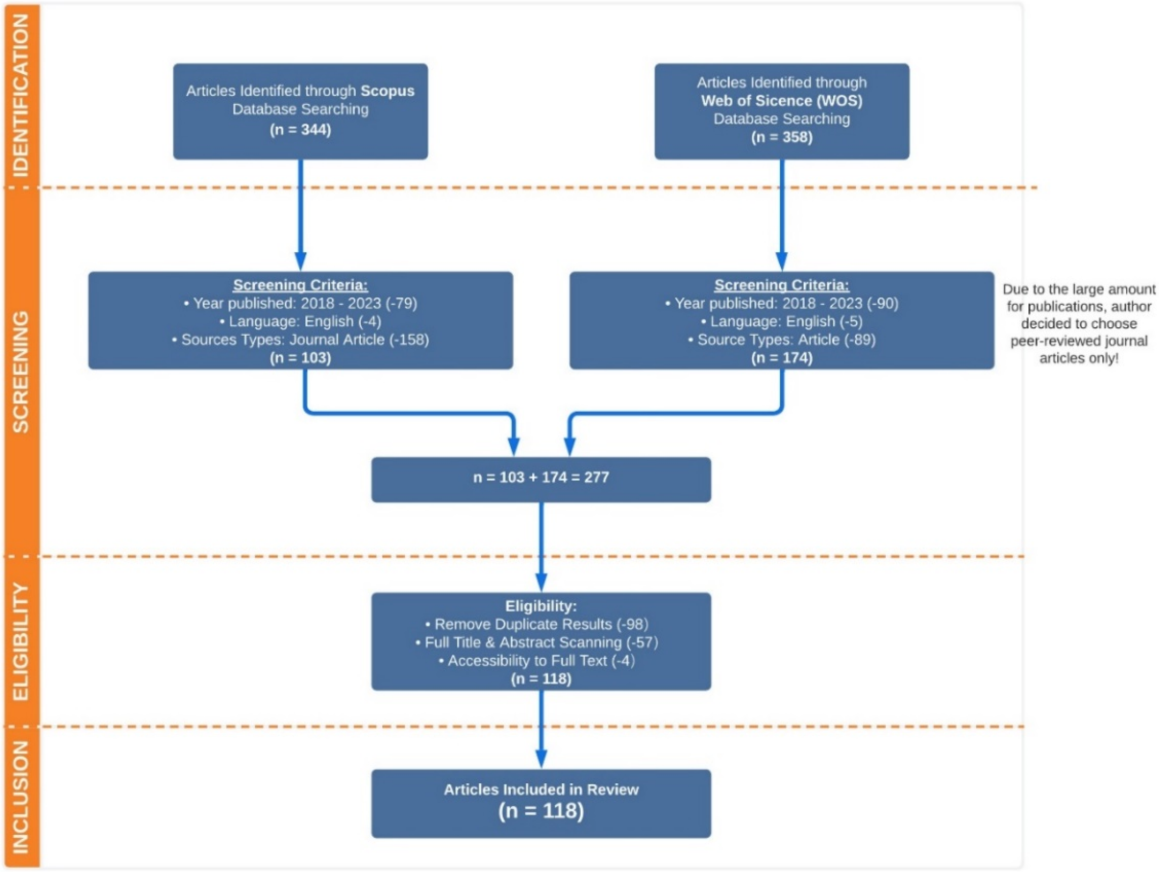
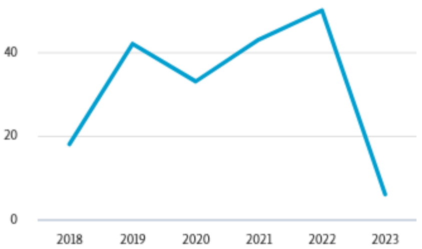


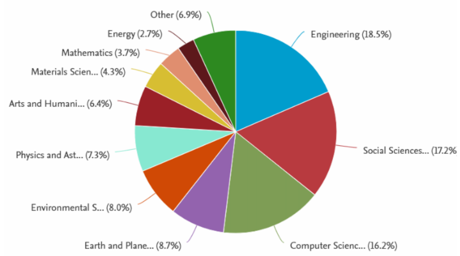
Figure 1. PRISMA approach was used for this study to identify 118 journal articles for the proposed review of HBIM case studies.

2.2 Search Results

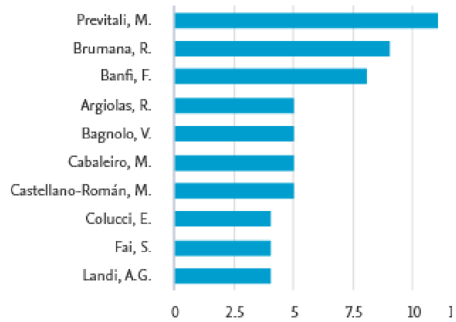
This section presents the major metrics of the found articles, including (1) the chronological evolution of the papers' publication (Figure 2a); (2) articles by subject area (Figure 2b); (3) the most active authors (Figure 2c); and (4) the origin country of co-authors (Figure 2d).



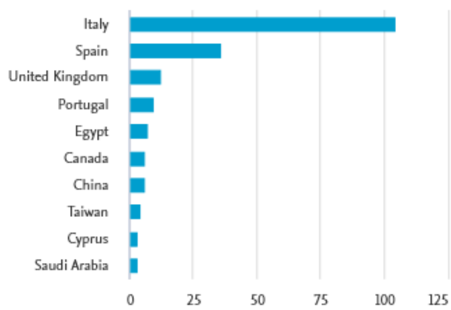
(a)



(b)



(c)



(d)

Figure 2. Major metrics of the 118 selected articles for this research

2.3 Data Extraction

The study employed a systematic approach to data collection and analysis to comprehensively assess the current state of HBIM in the heritage sector. The process involved six steps: 1) full-text scanning to ensure relevance and gain context, 2) data extraction focusing on a set of variables related to HBIM projects, 3) data organization using a structured format and database, 4) descriptive analysis to identify trends and patterns, 5) comparative analysis to explore relationships between various aspects of HBIM projects, and 6) synthesis and interpretation to draw conclusions and provide recommendations for future research and development.

3. RESULTS

Due to its page limit, this paper only reports the findings of the status of reality capture techniques used to acquire reality data for HBIM development, focusing on terrestrial laser scanning (TLS) and photogrammetry technologies.

3.1 Terrestrial Laser Scanning (TLS) for Data Acquisition for HBIM

The literature highlights that Terrestrial Laser Scanning (TLS) has become a crucial technique for studying heritage assets and is now considered essential for HBIM development (Moyano, Nieto-Julián, et al., 2022). TLS offers several advantages over other methods in HBIM, such as high accuracy (Martín-Lerones et al., 2021; Moyano, Gil-Arizón, et al., 2022), rapid data capture relative to the time invested (Rocha & Mateus, 2021), and comprehensive non-invasive object capture (Abbate et al., 2022; Franco et al., 2020) that eliminates the need for follow-up field surveys (Palcak et al., 2022). Al-Bayari and Shatnawi's study (2022) found that using TLS for heritage documentation can reduce field survey time by 25–30%.

3.2 Challenges and Limitations of TLS for HBIM

However, TLS also presents several challenges when used for data acquisition in HBIM. Firstly, it is expensive, with laser scanners often costing tens of thousands of USD. Additionally, it necessitates specialized software, robust hardware, and skilled professionals to manage and process the scanned data (Alshawabkeh, Baik, & Fallatah, 2021; Martín-Lerones et al., 2021). Conducting a TLS survey can be time-consuming (Mammoli et al., 2021), particularly when capturing large or intricate heritage sites, and is sensitive to environmental factors such as lighting conditions, dust, fog, and rain (Palcak et al., 2022). The duration of a TLS survey depends on the area's complexity, required accuracy, and the processing software utilized. Various factors, including data acquisition time, environmental conditions, and data processing time, contribute to the overall survey time:

- Data acquisition time: TLS entails collecting numerous high-density point clouds from multiple perspectives to cover the entire area of interest, which can be time-consuming, especially for larger or more complex areas requiring multiple scanning setups;
- Environmental conditions: Weather conditions, sunlight, and shadows can influence data quality, potentially necessitating additional scanning time to compensate;
- Data processing time: Processing the acquired data to produce a usable point cloud can be time-consuming, particularly for large datasets with high point densities.

Surfaces that are shiny/reflective, black, or transparent can also pose difficulties. TLS cannot capture objects that are hidden or not in the line-of-sight (Massafra et al., 2020). Accurately capturing color is another challenge for most LiDAR scanners used in heritage studies (Alshawabkeh, Baik, & Miky, 2021).

3.3 Other Reality Capture Technologies Assisting TLS for Data Acquisition

Given the intricate geometry of built heritage and the limitations of laser scanning technology, TLS alone is insufficient for comprehensive data acquisition. As a result, other tools and techniques are often employed to gather additional information about the heritage structure, supplement the TLS survey, or enhance its accuracy and coverage (Alshawabkeh, Baik, & Fallatah, 2021; Fryskowska & Stachelek, 2018; Rocha et al., 2020). These tools and techniques can be grouped into the following categories:

- Structure from Motion (SfM) or photogrammetry, either ground-based or mounted on an Unmanned Aerial Vehicle (UAV) platform (Abbate et al., 2022; Barrile et al., 2022; de la Plata et al., 2021; Reinoso-Gordo et al., 2018);
- Mobile or handheld LiDAR and photogrammetry scanners (Banfi et al., 2022; Nieto-Julián et al., 2020);
- Devices for error control and data quality verification, including total stations (TS) and global positioning systems (GPS) (Brumana et al., 2018; de la Plata et al., 2021; Grillanda et al., 2021).

3.4 SfM/Photogrammetry

TLS and photogrammetry can be combined to leverage the strengths of each technology (Costantino et al., 2021). While TLS is more expensive and requires more expertise than photogrammetric surveys, photogrammetry is a more cost-effective, flexible, and faster method that can still capture accurate and high-quality data for complex objects (Alshawabkeh, Baik, & Fallatah, 2021). By integrating these two technologies, the accuracy and dense point cloud capabilities of TLS can be combined with the adaptability of photogrammetry, which can operate even under exceptional conditions.

The combination of TLS and photogrammetric techniques has proven to be highly effective for documenting large and complex heritage sites, with applications in structural assessment, texture mapping, feature extraction, and more (Alshawabkeh, Baik, & Miky, 2021). Out of the 118 articles reviewed, most of them utilized photogrammetric point clouds and combined them with TLS point clouds for data acquisition. In their research, de la Plata et al. (2021) employed a DSLR camera to generate high-density terrestrial photogrammetric point clouds for building interiors and TLS for exterior facades. Costantino, Pepe, and Restuccia (2021) adopted a similar approach, using TLS for external facades, a DSLR camera for interiors, and a camera mounted on an unmanned aerial vehicle (UAV) for capturing the upper sections of the building.

3.5 TLS Scan Processing Workflow

The processing of TLS survey scans for HBIM development consists of three main steps: (1) scan registration, (2) point cloud data cleaning and optimization, and (3) point cloud dataset downsizing (Fryskowska & Stachelek, 2018).

1. Scan registration involves aligning individual scans into a single reference system to produce a unified point cloud of the entire heritage site. This can be done manually or automatically using pre-established targets (target-based registration) or homologous features (targetless registration).

2. Point cloud cleaning is essential to ensure the resulting model is accurate and useful for further analysis and documentation. Cleaning involves removing noise or unwanted data points captured during scanning and correcting errors or inaccuracies. This process typically combines automated and manual techniques, such as filtering, segmentation, and classification, to identify and remove unwanted points (Rocha et al., 2020).

3. TLS point clouds contain millions or even billions of points, resulting in massive file sizes. However, a higher number of points does not always guarantee a better dataset for HBIM development. The number of points should be reduced without losing essential geometric information. The ability to model building elements for HBIM using a 3D point cloud depends on cloud resolution, which is defined by the distance between points or the density of points captured by the scanner (Fryskowska & Stachelek, 2018). One approach to reduce point count and file size is subsampling (Garcia-Gago et al., 2022). Software programs like Autodesk ReCap Pro (Antón et al., 2018), CloudCompare (Mol et al., 2020), FARO SCENE (Barrile et al., 2022), and Leica Cyclone (Martín-Lerones et al., 2021), enable users to subsample point clouds by increasing the distance between points. This technique significantly reduces file size and enhances manageability for model development (Antón et al., 2018).

3.6 Integration of Multiple RC Point Clouds

As mentioned in Section 3.3, data acquisition for HBIM development of heritage sites often involves multiple technologies and techniques, which can result in multiple point clouds of the same structure. Many articles reviewed in this research included studies that captured at least one TLS point cloud and one photogrammetric point cloud. Integrating (or fusing) these separate point clouds into a single, comprehensive point cloud is crucial for creating a complete model and drawing final conclusions (Franco et al., 2020). Point cloud fusion can be achieved using the Iterative Closest Point (ICP) algorithm, which minimizes differences between two point clouds, transforms source points, and reassociates them (Lin et al., 2020). One of the most challenging aspects of point cloud integration is aligning all point clouds and converting them into the same coordinate system (Alshawabkeh, Baik, & Fallatah, 2021). To address this challenge, a common approach identified in the literature involves using established Ground Control Points (GCPs) as a shared reference for aligning and scaling all point cloud data (Barrile et al., 2022). Several software platforms have been used to perform point cloud fusion, including CloudCompare (Palcak et al., 2022), Autodesk ReCap Pro (Barrile & Fotia, 2022), and Agisoft Metashape (Santagati et al., 2021).

4. DISCUSSION

Reality capture (RC) technologies, particularly Terrestrial Laser Scanning (TLS), have become essential tools for data acquisition in HBIM development. TLS offers significant benefits such as high accuracy and comprehensive coverage, but it also has drawbacks like high initial investment, time-consuming processes for large or complex projects, and environmental sensitivity. To address these limitations, practitioners can implement a well-planned TLS survey and utilize complementary RC technologies.

A well-designed TLS survey plan ensures maximum coverage with sufficient point density, reduces self-occlusions, and minimizes on-site time. TLS is often combined with other RC technologies, especially SfM (Structure-from-Motion) or photogrammetry. Integrating TLS and photogrammetry allows for the combination of TLS's accuracy and photogrammetry's flexibility. As for TLS scanners, FARO and Leica are the two leading brands, each holding nearly half of the market share.
The typical workflow for processing TLS scan data involves three steps: scan registration, point cloud data cleaning and optimization, and dataset downsizing. In the reviewed literature, FARO SCENE and Leica Cyclone emerged as popular choices for TLS data processing and registration software, while Autodesk ReCap Pro is commonly used for point cloud cleaning, filtering, and downsizing.

To effectively use point cloud datasets for modeling in BIM platforms (e.g., Revit or ArchiCAD), large point cloud files must be downsized by reducing point density and increasing the distance between points while preserving essential geometric information. Many studied HBIM cases also employed other RC technologies, especially photogrammetry, for data acquisition; data processing in these cases involved fusing multiple point clouds into one. This is achieved by aligning and merging separate point clouds into the same coordinate system using the ICP (Iterative Closest Point) algorithm or with the help of pre-established reference points (i.e., GCPs). Autodesk ReCap Pro and open-source software CloudCompare are leading platforms for this task. The final step in TLS scan data processing is evaluating the accuracy and quality of the point cloud data.

5. CONCLUSIONS

This research presents a systematic review of Heritage Building Information Modelling (HBIM) case studies published since 2018, building upon the foundational work of Ewart and Zuecco (2019). The analysis reveals the latest trends in HBIM implementation, developments in HBIM technologies, and changes in the purpose of HBIM programs and stakeholder roles and responsibilities. Terrestrial Laser Scanning (TLS) has emerged as a vital tool for data acquisition in HBIM development, offering benefits such as high accuracy and comprehensive coverage. However, it also presents challenges like high costs, time-consuming processes, and environmental sensitivity. To address these challenges, practitioners can implement well-planned TLS surveys and utilize complementary RC technologies such as SfM/photogrammetry. The combination of TLS and photogrammetry enables the fusion of the accuracy of TLS with the flexibility of photogrammetry, resulting in more efficient and comprehensive HBIM models.

The review demonstrates that integrating TLS into HBIM workflows significantly enhances the accuracy, efficiency, and reliability of data collection and 3D modeling for cultural heritage sites (Aryan et al., 2021; Fryskowska & Stachelek, 2018). Incorporating high-resolution point cloud data derived from TLS enables researchers and practitioners to capture complex geometries and structural details, leading to more accurate and detailed HBIM models (Nguyen et al., 2022; Pepe et al., 2020). Moreover, combining TLS with other technologies like photogrammetry results in more robust and comprehensive datasets for HBIM model development (Banfi, 2021; Colucci et al., 2021).

This research has also identified gaps in the subject matter, presenting opportunities for future research and innovation:

- The lack of guidelines for data acquisition in HBIM programs poses a significant challenge. The absence of standardized methodologies and protocols for integrating TLS data into HBIM models hampers the adoption and implementation of these technologies within the cultural heritage domain (Rodríguez-Moreno et al., 2018). Practitioners often develop their own methods for capturing the existing condition of built heritage, based on project characteristics, available resources, and personal experience. Clear guidelines covering planning, implementation, and data processing and transferring can simplify the process, lower costs, and help practitioners establish data acquisition methodologies aligned with the Level of Development (LOD) of the proposed HBIM model.
- The development of HBIM from TLS point cloud data remains predominantly manual, necessitating substantial effort. Efficient and accurate processing and integration of large, complex datasets derived from TLS and other sources remain challenging (Nieto-Julián et al., 2022). Developing automated and semi-automated techniques for data processing, segmentation, and feature extraction can considerably reduce time and resources required for capturing built heritage data and creating models, streamlining the overall HBIM development process.
- The under-utilized capacity of TLS for long-term monitoring and change detection: Although TLS has been widely used for initial documentation and 3D modeling of heritage sites, its potential for long-term monitoring, change detection, and condition assessment remains underexplored (Moyano et al., 2020; Santagati et al., 2021). Future research can focus on developing methodologies and tools for systematically using TLS data to monitor and assess the conservation status of heritage structures over time.

This review provides valuable insights into the current state of HBIM technologies, methodologies, and applications, which can guide future research and development in the field. By identifying knowledge gaps and addressing the limitations of current technologies, the heritage sector can continue to leverage the potential of HBIM to better manage and preserve our valuable cultural heritage.

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