AN INTRODUCTION TO TECHNOLOGICAL TOOLS AND PROCESS OF HERITAGE BUILDING INFORMATION MODELING (HBIM)

Junshan Liu*[a] ⓘ, Danielle S. Willkens[b] ⓘ, Graham Foreman[c]

[a] McWhorter School of Building Science, Auburn University, USA. liujuns@auburn.edu
[b] School of Architecture, Georgia Institute of Technology, USA. danielle.willkens@design.gatech.edu
[c] McWhorter School of Building Science, Auburn University, USA. gaf0029@auburn.edu

Abstract

Heritage Building Information Modelling (or HBIM) is a multi-disciplinary process and a promising tool for the management and documentation of heritage structures. HBIM can record the significant historic events that have taken place in the built environment and is used to track the aging process of the built asset. However, the digital re-construction procedures for HBIM development associated with historic buildings are very challenging: the objects of the historic models consist of components whose heterogeneous, complex, and irregular characteristics and morphologies are not represented in the existing BIM software libraries. Unlike conventional BIM workflows for new constructions, the tried and tested tools and methods must be adapted, and even reinvented, for HBIM applications. This article introduces the basic concept of HBIM, a set of technological tools of data capture for HBIM model development, and a feasible HBIM workflow.

Keywords: 360-degree Photography; Cultural Heritage; LiDAR; Photogrammetry.

1. INTRODUCTION

Using Building Information Modeling (BIM) in the historical field has been introduced as a new method during the past few years (Baik 2017). Heritage Building Information Modelling (Heritage BIM, or HBIM) has been defined as the recording and modelling of existing buildings, generating BIM geometry from documentation data of the building, such as 3D point clouds (Dore and Murphy 2017). HBIM normally includes highly protected buildings that usually requires broader intervention projects and a careful life cycle management (Jordan-Palomar et al. 2018). BIM technology is an appropriate for cultural heritage, and particularly heritage buildings matters (Fai et al. 2011; Jordan-Palomar et al. 2018). Researchers started to realize that BIM can become an invaluable decision-making and management tool for historical assets (Gromova 2019), especially with the ability of BIM to store attributes, model objects and make queries about their relationships (Rodríguez-Moreno et al. 2018).

HBIM can be used to draw from legacy data and the development of current metric data to accurately model historic structures for the purposes of renovation, preservation, and research (Janisio-Pawłowska 2021). HBIM allows for the creation of a central repository for all historical assets, including both geometric and non-geometric information such as archives, operational data, maintenance plans, condition surveys, archaeological investigations, material analysis, and other surveys. Presenting a holistic view of the building, HBIM is capable of retaining different information in different formats - tables, graphs, images, texts, links, etc. (Gromova 2019). The theme of HBIM is to provide intelligent data (Fai et al. 2011) and as "as-built" digital 3-D models (Baik et al. 2014), as well as for documentation, conservation, and management.

The main requirements for the beneficial integration of BIM into the documentation and interpretation of historic architecture are the quality of the model and its geometric reliability. Another condition involves the creation of a comprehensive database of historical notes regarding each component about materials and changes during the time. If models can meet these requirements and avoid hard computing processes, in the near future then HBIM will play a key role in the restoration, representation, and

communication of cultural built heritage (Quattrini et al. 2015).

This article introduces the basic concept and practices of HBIM, presents a set technological tools that are used for collecting data for HBIM development, and explains a feasible HBIM workflow through two use cases.

2. LITERATURE REVIEW

2.1 BENEFITS OF HBIM

There are significant inefficiencies on heritage structure interventions - documentation, conservation, rehabilitation, restoration and reconstruction. There is also an increasing interest in the adoption of new methodologies by heritage organizations and work groups, aiming to improve those inefficiencies (Jordan-Palomar et al. 2018). Hence, there is a need to develop solutions aimed at improving the management of heritage building projects. Considering the management of architectural heritage information, HBIM offers a distinctive factor which does not exist in any other field: a multi-layered spatial character in three dimensions that can be extended to four dimensions when the historic phases of the building are considered. 3D digital models are semantically enriched by integrating heterogeneous datasets, making them very useful for management and conservation purposes (Saygi and Remondino 2013).

HBIM is essentially a virtual prototype of the real historical building, a building database containing its geometrical, historical and archaeological information. This provides a great advantage, since it is possible to consult it according to stakeholders' needs in order to discover possible relationships that might otherwise be hidden under the enormous amount of existing information associated with the architectural reference (Rodríguez-Moreno et al. 2018). HBIM also provides appropriate alphanumerical and graphical outputs for strategic decision-making on the major guidelines of heritage management: research, protection, conservation and dissemination (Castellano-Román and Pinto-Puerto 2019).

The possibility of HBIM to manage a model that can serve different outcomes is another great strength. The same model can not only be used for the generation of a large amount of diverse

information in both qualitative and quantitative formats: 2D drawings, 3D representations with different levels of detail (Rodríguez-Moreno et al. 2018), but also a listing of objects such as 3D printing, VR demonstrations, etc.

2.2 IMPLEMENTATION OF HBIM

HBIM is a multi-disciplinary process that requires the contribution and collaboration of professionals with very different skillsets. The role of HBIM is to provide archives for information management from a long-term perspective. In addition, it is necessary to consider accessibility for those outside of Architecture, Engineering and Construction (AEC) industries so that materials conservationists or cultural property managers can easily use information from archives. This has always been an essential consideration in improving the usability of HBIM, and it is important to make the database lighter to solve this problem (Ham et al. 2020). It is necessary to define a proper method in order to model a historic building (Chevrier et al. 2009). For HBIM, the whole comprehension of the building through its history is the director in the building modelling strategy (Rodríguez-Moreno et al. 2018).

Historic England has published "*BIM for Heritage*" to guide in the development of HBIM. This publication proposed a lifecycle principle for the implementation of HBIM, depicted in Fig. 1

(Antonopoulou and Bryan 2017; Castellano-Román and Pinto-Puerto 2019).

The documentation of heritage requires a large amount of resources, time, and effort. The process of digitizing the built heritage is developed upon the workflow of data acquisition, semantics, 3D modelling, and data entry. In general, HBIM can be implemented in two steps: data collection and model development. The process is complex and includes a series of operations that start with physical surveying, reality data capture, data analysis, drafting, modelling and monitoring the post - construction results (Rodríguez-Moreno et al. 2018; Fadli and AlSaeed 2019).

2.3 DATA COLLECTION FOR HBIM

Both historical data and existing conditions of the heritage are collected during this first step of HBIM process. The historical data should cover not only the structure, such as drawings and specifications, but also information about significant events associated with the structure. Through HBIM, information can be stored within the digital model, such as photographs, videos, reports, etc. Some of the information to be stored in HBIM models can be obtained through research into historical records and archives, but the other information, especially the structure's existing condition data, must be captured though on-site visits and surveys.
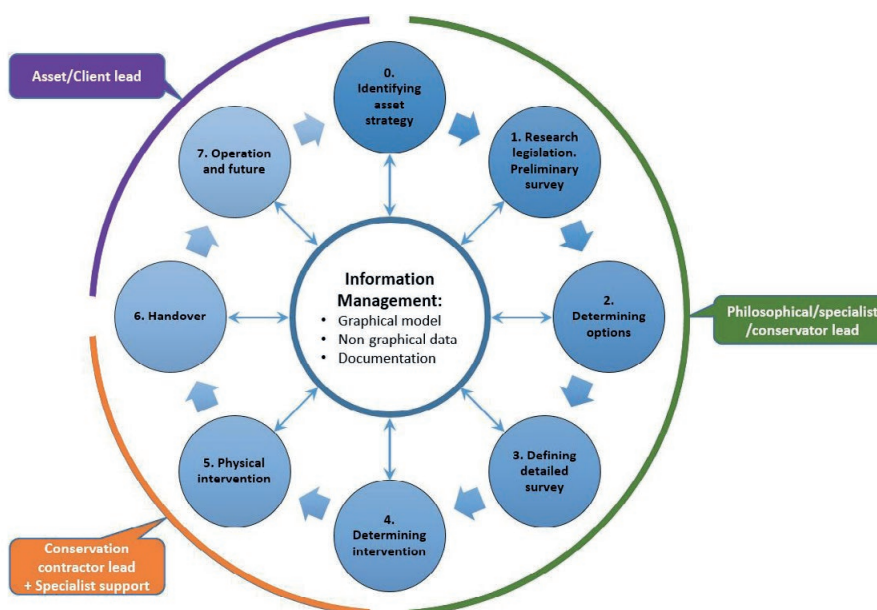

Fig. 1. BIM for the Heritage Life Cyclical Principle. (Source: Antonopoulou and Bryan 2017; Castellano-Román and Pinto-Puerto 2019).

Multiple instruments can be used to collect information for HBIM thought on-site surveys. They include:

• Analog survey

• Terrestrial laser scanning (TLS)

• Photogrammetry

• 360-degree virtual tour

2.3.1 Analog survey

Getting dimensions of a window using a tape measure, capturing photos of a decorative column, or taking small material samples from a concrete foundation for lab testing are tried and true survey methods. Over the last few decades, however, a technological revolution brought with it new tools to improve and accelerate the topographic techniques of spatial data acquisition to help create accurate HBIM models. Today's most influential techniques are TLS, photogrammetry, and 360-degree photography (Logothetis et al. 2015; López et al. 2018).

2.3.2 Terrestrial laser scanning (TLS)

TLS technology has been adopted for its ability to expedite the spatial data collection of existing buildings or complex surfaces, as well as for its accuracy and precision (López et al. 2018). TLS can obtain a precise and detailed geometric reproduction of three-dimensional objects in a short time, in the form of millions of points (a cloud of points or point cloud), with geometric coordinates (X, Y, Z) as shown in Fig. 2, in a digital environment. TLS can play a very important role in a wide range of purposes that can be directly extrapolated to cultural heritage, including the follow-up of an intervention, defect detection, or the reproduction of existing models (López et al. 2018).

2.3.3 Photogrammetry Aided by UAVs

When collecting data of the parts of a building that are difficult to reach by TLS, such as the rooftop, photogrammetry aided by UAVs can be deployed to complete the task (Liu et al. 2016). Photogrammetry is a relatively precise, non-invasive, and contactless 3D measurement technique where high-quality image captures facilitate the collection of semantic and spatial data of a building or object to be accelerated (López et al. 2018). However, due to the intensive requirement of manually processing of data, photographic reconstruction via photogrammetry can be disadvantageous when the texture of the object is poor, or its shape is very complex (López et al. 2018).

2.3.4 360-degree Virtual Tour

Another technology for data collection is 360-degree photography that uses 3D-degree images, often called photo spheres (or photospheres) (How 360° Images Take Construction Documentation to the Next Level, no

Fig. 2. A 3D colorized high-density point cloud captured using TLS. (Source: authors).

date). A 360-degree camera captures one photo through each of its two (or more) lenses at the same time. Then, the camera 'stitches' the photos together to one 360-degree photo. This way everything around the photographer is thoroughly captured. Thus, 360-degree technology fills the gaps for typical, single aperture, analogue, or digital photographic captures, providing more immersive documentation for a building or a site. The 360-degree photos can be uploaded online as a "virtual tour" of a built structure which allows public users to tour the building's interior and exterior. A main advantage of the virtual tour is that viewers can easily orient themselves within the site, understanding both where they are and what they are going to see next.

2.4 HBIM MODEL DEVELOPMENT

The BIM model development procedures associated with historic buildings are not straightforward: the elements of historic models consist of components whose heterogeneous, complex, and irregular characteristics and morphologies are not represented in the BIM software libraries. Therefore, it is essential to introduce the historical and technical approaches into the HBIM environment, to model the different virtual parametric components and achieve a "BIM as-is model" of the architectural heritage. Researchers have proposed a method to work in a 3D environment throughout the modelling process and to develop semantics during the construction phase, which enables geometric accuracy and reliability of visualization outputs (Liu and Willkens 2021).

Since BIM has been employed into the heritage field, almost all research projects use the manual methods of 3D modeling and some are more likely to use the semi-automatic methods spatially to model the MEP (mechanical, electrical, and plumbing) parts (Thomson and Boehm 2015; Baik 2017).

2.5 CHALLENGES OF HBIM

One of the main challenges in current HBIM methodology is the inability to quickly characterize complex non-homogenous architectural and structural features of historic structures, which conflicts with the benefit of standard BIM practice to utilize standardized procedures with common parametric objects. The most extensive method for HBIM segmentation of raw data into parametric objects is manual, requiring labour-intensive inputs to model non-standard heritage architectural and structural elements (Baik et al. 2014; Barazzetti et al. 2015; Green and Dixon 2016; Moyano et al. 2021). To overcome this challenge, Murphy (2012) applied HBIM by creating a parametric library for the building elements based on the TLS data using the architectural shape rules from the 18th century architectural pattern books.

Some other challenges that the stakeholders of HBIM have to face include:

- Heritage stakeholders have different needs than those of regular AEC professionals do when considering using BIM (Megahed 2015)

- Lack of standard guidelines/regulations for HBIM implementation (Apollonio et al. 2013)

- Limited standardization (Oreni et al. 2013; Dore and Murphy 2017; Rodríguez-Moreno et al. 2018)

- Multitude and complexity of details of historic structures to be replicated in models (Ham et al. 2020)

- Difficulty to represent the historic phases in an integrated way (Baik et al. 2014).

- A time consuming and error-prone process (Ham et al. 2020)

- Inconsistence of LoD requirements for different objects of HBIM models (Fai et al. 2011)

- High cost of hardware (for data collection), software and personnel cost (Kalyan et al. 2016; Ham et al. 2020)

The quality control of HBIM is another challenge. In spatial data, the quality of BIM involves several components (completeness, positional accuracy, thematic accuracy, etc.). As of now, there is no international standard that defines these components for BIM (Rodríguez-Moreno et al. 2018). The importance of geometric accuracy has been highlighted on many occasions as the English Heritage organization did in its Metric Surveys Specifications for Cultural Heritage publication (Bryan et al. 2013). Geometric accuracy is an important issue and some methods have been proposed, e.g. visual analysis, deviation analysis, image-based verification, etc. (Rodríguez-Moreno et al. 2018). Not only geometric accuracy

is important to document the current state of a historical building, but also is it necessary to validate the information attached to the model so it can be used to manage and conduct conservation tasks in a suitable way (Murphy 2012).

3. METHODOLOGY

In order to investigate the implementation of HBIM and technological tools utilized for data collection, the authors have performed extensive reviews of published literature and conducted thorough study of two HBIM projects. The literature review results are summarized and presented in the previous chapter.

The two HBIM projects include the Old Polk County Courthouse (OPCC) located in Bartow, Florida, USA and the Old Deport Museum (ODM) located in Selma, Alabama, USA. This research used OPCC project to test the technological tools and approaches for data collection for HBIM, while used the ODM project to exam the detailed process of HBIM model development.

3.1 OLD POLK COUNTY COURTHOUSE (OPCC)

The OPCC building, as shown in Fig. 3, as designed and constructed between 1908 and 1909, then expanded in 1926. Nowadays, this 3-story with a small basement, 50,000 square-foot history center is the county's history museum.

Fig. 3. The OPCC building. (Source: authors).

3.2 OLD DEPORT MUSEUM (ODM)

The ODM building (shown in Fig. 4) was built around 1890. It is a former Louisville and Nashville (L&N) Railroad Depot. The building has two main levels with approximately 5,000 square feet in total for exhibition, and a small basement and an attic for storage (Willkens et al. 2020).

Fig. 4. The ODM building. (Source: authors).

4. RESEARCH FINDINGS AND RESULTS

The study of OPCC project was focused on data acquisition utilizing reality capture technologies for HBIM development, and the ODM project concentrated on the process of developing the actual HBIM model. This chapter presents the results of the study.

4.1 OPCC PROJECT

4.1.1 HBIM Execution Plan

The crucial first step of developing a HBIM workflow is identifying the goals of the program and developing the steps required to achieve these goals. Historic significance, accessibility to legacy information, and partnership with the building tenants are critical parameters that set the standard for the workflow. The current HBIM literature indicates a tendency to perform research study and on-site surveys to gather both geometric and non-geometric data to develop a HBIM repository of historic structures (Pocobelli et al. 2018). As shown in Fig. 5, the HBIM workflow developed for OPCC utilizes techniques identified from the literature review, tailored for a local context.

4.1.2 Data Acquisition for HBIM

Legacy (historic) records of the OPCC for HBIM were collected through archival research and collection of operational and maintenance plans, and physical samples (for building materials). The researchers discovered the original design and construction plans, as shown in Fig. 6 (1908 Basement Floor Plan).
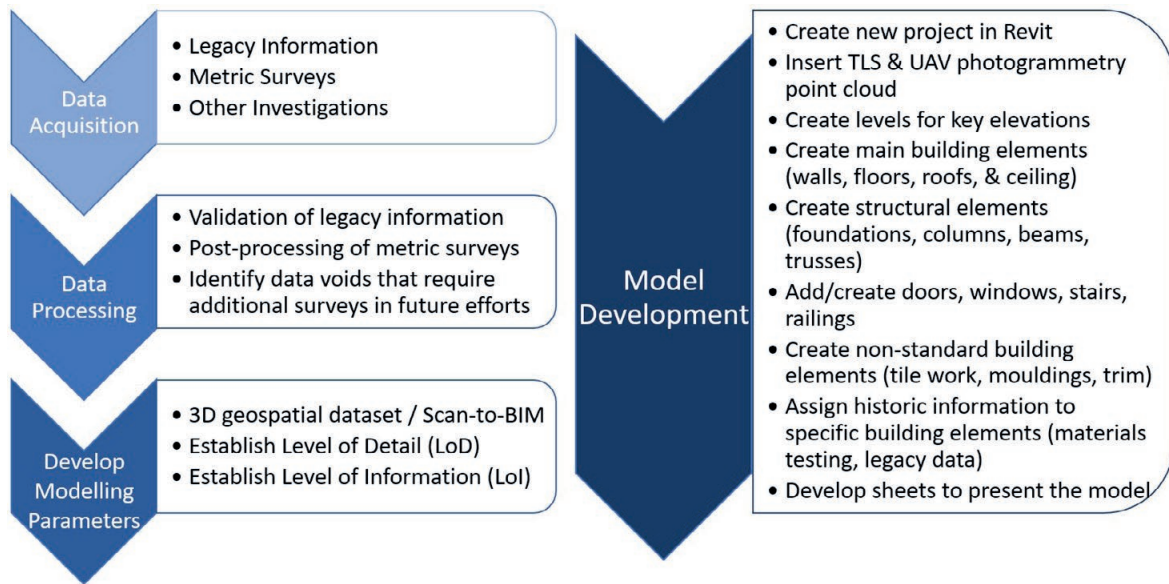
Data Acquisition
- Legacy Information
- Metric Surveys
- Other Investigations

Data Processing
- Validation of legacy information
- Post-processing of metric surveys
- Identify data voids that require additional surveys in future efforts

Develop Modelling Parameters
- 3D geospatial dataset / Scan-to-BIM
- Establish Level of Detail (LoD)
- Establish Level of Information (LoI)

Model Development
- Create new project in Revit
- Insert TLS & UAV photogrammetry point cloud
- Create levels for key elevations
- Create main building elements (walls, floors, roofs, & ceiling)
- Create structural elements (foundations, columns, beams, trusses)
- Add/create doors, windows, stairs, railings
- Create non-standard building elements (tile work, mouldings, trim)
- Assign historic information to specific building elements (materials testing, legacy data)
- Develop sheets to present the model

Fig. 5. HBIM workflow for OPCC. (Source: authors).
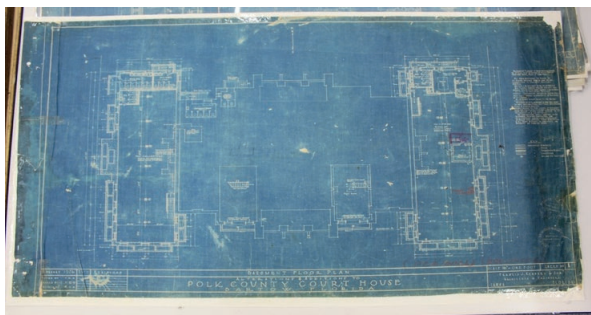
Fig. 6. The original blueprint of the Basement Floor Plan. (Source: OPCC Archive).

Next, the researchers conducted an on-site survey to document the existing fabric. A list of digital documentation technological tools utilized by the research team during the survey includes:

- *TLS.* to capture 3D point cloud and panoramic photographs

- *360-degree Virtual Tour.* to provide high-quality supplemental imagery of the building interior to assist HBIM model development

- *UAV Aerial Photography.* To complement TLS scans and capture the condition and character of the complex multi-domed roofline and other parts of the building that were hard to capture via TLS scanning

TLS Scanning. The TLS capture was carried out with two LiDAR scanners: a FARO Focus3D X130 HDR and a FARO Focus S-350. A scanning route was developed using the building's floor plans to establish adequate scanning coverage for the interior and exterior surfaces. Developing the scanning route also provided the research team an effective method to cover the majority of the building within the time constraints allotted. A total of 241 scans were captured by the two scanners in 13 hours (Fig. 7). Those scans were performed using a predefined medium resolution profile. Panoramic photos (non HDR) were also taken by the scanners for colourizing the point clouds. On average, each scan took about seven minutes including scan station setup, laser scanning, and panoramic photos taking. Field notes (Fig. 8) of scan routes were maintained to corroborate scan locations for post-processing.

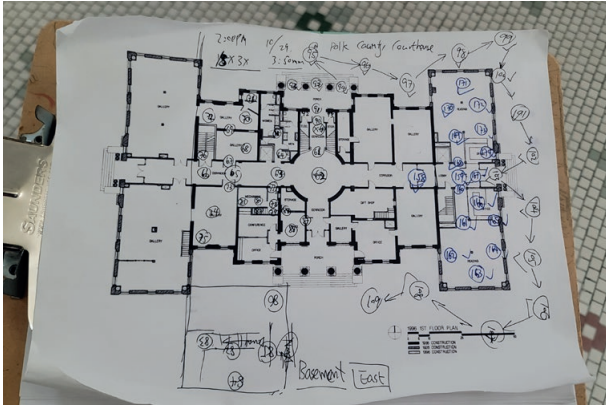Fig. 7. A FARO Focus S-350 scanner scanning the interior of OPCC building. (Source: authors).

Fig. 8. Field notes for tracking scan locations. (Source: authors).

Fig. 10. The locations of the Matterport scans on the first floor shown on an Apple iPad mini. (Source: authors).

360-degree Virtual Tour. The capture of a 360-degree virtual tour was carried out using a Matterport Pro2 3D Camera assisted by an Apple iPad mini. A total of 470 scans were captured to create a 3D immersive space that covered the full levels of the first and second floors, and a partial of the third floor. Images of capturing the virtual tour are shown in Fig. 9 and Fig. 10.

Fig. 11. The setup of a drone's remote control (RC) and a cell phone for pre-programed flight over OPCC. (Source: authors).

Fig. 9. Matterport Pro2 3D Camera. (Source: authors).

UAV Aerial Photography. The capture of aerial photos was carried out using a DJI Mavic Pro-2 drone. This drone followed a pre-programed path generated in DJI Pilot app, at an altitude of 150 feet that captured a total of 950 aerial photos of the building: 200 from a bird's-eye view (i.e. 90-degree vertical) and 750 at a 60-degree oblique angle. An image of capturing the aerial photos using a DJI drone system is shown in Fig. 11. Fig. 12 shows a captured aerial photo of the roof.
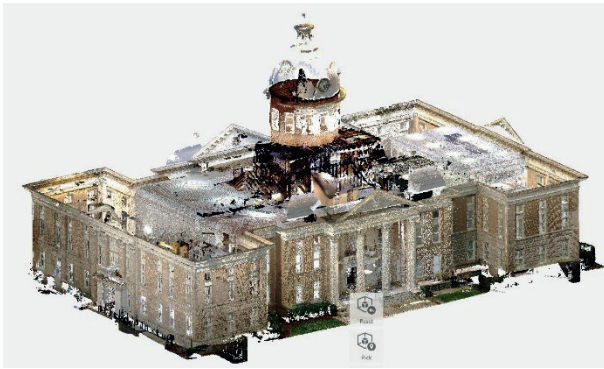

Fig. 12. An aerial photo of OPCC. (Source: authors).

Multiple software programs were used to process the captured data, including:

- FARO SCENE (SCENE) and Autodesk Recap Pro (Recap) for processing of the TLS data.
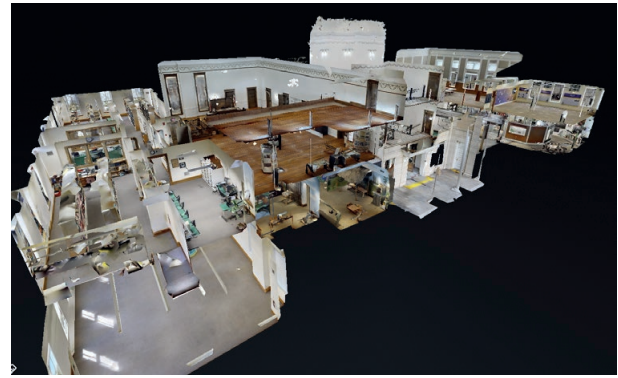
(a) Façade.

(b) Section cut to expose the inside.

(c) First floor plan view.

Fig. 13. Photos of the OPCC point cloud. (Source: authors).

(a) A 3D "doll house" view.


(b) The second floor plan view.

Fig. 14. The virtual tour created using 360-degree photography technology. (Source: authors).

With the large number of scans (241) captured, the initial 3D point cloud created using SCENE had over 1.7 billion points. This "raw" point cloud was transferred to Recap where it was further cleaned, manipulated and then unified (to decrease the number of points), before the 3D point cloud data becoming ready to serve as the primary dataset for HBIM modelling in the next stage. Fig. 13 shows a set of photos of the processed OPCC point cloud.

- The 470 captured 360-degree photos were processed via Matterport's cloud service before a 360-degree virtual tour was made available. Due to its relatedly low accuracy, this virtual tour was to be used as a supplemental dataset for HBIM modelling. It would mainly provide visual and non-geometrical information of the building. Fig. 14 shows screen shots of this virtual tour.

- The UAV captured aerial photos were processed via a photogrammetry software named AgiSoft Metashape. All of the 950 photos were first aligned and then further processed to generate a 3D point cloud and mesh (surfaces) for the building's exterior. This set of data was intended for assisting the modelling of the roof and dome. Fig. 15 shows the photogrammetry process.

4.1.3 Discussion

Although the research team has utilized a variety of techniques to collect the historical and current-condition data of the OPCC building, many of
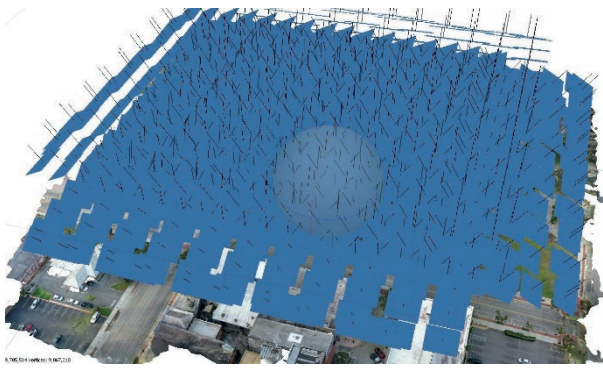
(a) Alignment of the aerial photos.

(b) Low-density 3D point could generated from aerial photos.

(c) 3D mesh generated from point cloud data.

Fig. 15. The steps of photogrammetry for processing aerial photos. (Source: authors).

the building's elements were still excluded or only partially captured through the process, which created data voids for producing those elements in HBIM development. Due to time and accessibility constraints, the on-site survey only focused on the exterior fabric and interior spaces.. Significant data voids were identified after processing the initial TLS point cloud. These data voids are attributed to the unique geometries of the roofline, nonstandard building elements, and congested galleries of the history center. Initial data processing also indicated the registration of TLS scans in the basement, stairwells, and attic

space had relatively large errors due to the low scan overlap caused by cumbersome materials stored in the space and limited time to fully capture the stairwells and attic. The researchers believe that a more thorough data acquisition plan would have helped mitigate the challenge of data voids.

4.2 ODM PROJECT

4.2.1 Data Acquisition for HBIM

The data of the existing condition of ODM building was collected through on-site surveys assisted by both traditional Historic American Buildings Survey (HABS) methods (*Historic American Buildings Survey/Historic American Engineering Record/Historic American Landscapes Survey - Digitizing the Collections*, 1930) and technological tools. These tools include:

- TLS. This was carried out by using a FARO X-130 scanner taking a total of 84 scans. The scans were processed to create an initial point cloud consisting of 688 million points before being further processed in Recap for cleaning and downsizing. Fig. 16 shows the processed 3D point cloud.

- UAV photography. The aerial photos were captured using a DJI Mavic Pro-2 drone, with the intention to provide visual references of

(a) Front view.

(b) Elevation view.

Fig. 16. 3D point cloud of the ODM building captured via TLS and processed in SCENE. (Source: authors).

the roofline and architecture details of the dome.

- 3D virtual tours. Matterport technology was utilized to create a virtual tour of the building.

4.2.2 HBIM Model Development

Autodesk Revit was selected as the software program for developing the HBIM model. The approach adopted by the authors was to replicate the critical existing condition of this historical building, including the building's geometry and materiality. However, due to the limitations of Revit software, historical marks such as patina (i.e., wear and tear on the building), structural and aesthetic markings from settlement and renovations, and other damage to the structure might not to be fully addressed in the model. Also, it was the researchers' understanding that the information that was unable to be captured through data acquisition or not visually exposed would not be included in the model (e.g., floor joists, subfloors, foundations, concrete reinforcements, etc.). As a HBIM model, it is required that every object introduced is not only a geometric representation of real shapes or technical components as in the CAD system, but it is a multi-data collector on its own, with specific significance to the user of the model. These elements provide an abstract computer representation of a physical world: a wall, as an object, represents an actual wall in the physical world as well as a door as a digital object represents a real door, connected to the hosting wall (Rodríguez-Moreno et al. 2018).

The 3D point cloud captured via TLS was used as the primary source of information for modelling, assisted by the supplemental references, including the virtual tour, UAV aerial photos, the original floors plans and photos taken from the on-site surveys. The main steps of developing ODM's HBIM model are illustrated in Figgs. 17 and 18 shows a sets of 3D views of the completed model in Revit.

To achieve HBIM's full functionality, the researchers assigned additional information of historic fabric of the building such as photos and narratives to specific elements in the developed BIM model. This was accomplished through the creation of a set of new *Project Parameters* in Revit and then attaching information (i.e., materials and specific finish of walls, hardware, photos, notes, etc.) to these Project Parameters of the specific elements. Fig. 19 shows how this technique was utilized to attach photos to a type of window in the model.

4.2.2 Discussion

Due to the unique historic fabric and form of the structure, the researchers spent a large amount of time on creating individual model elements using Revit's '*Model In-Place Component*' command. The estimate for this project is that 70% of the modelling time was spent on those customized elements such as wall surface details and decorative elements such as trims, railings, and door/window frames which only account for less than 20% of the items in the model. One of the greatest advantages of Revit as a tool for the design of new buildings is its large library of standard model elements (Revit family files). Conversely, this becomes one of the BIM
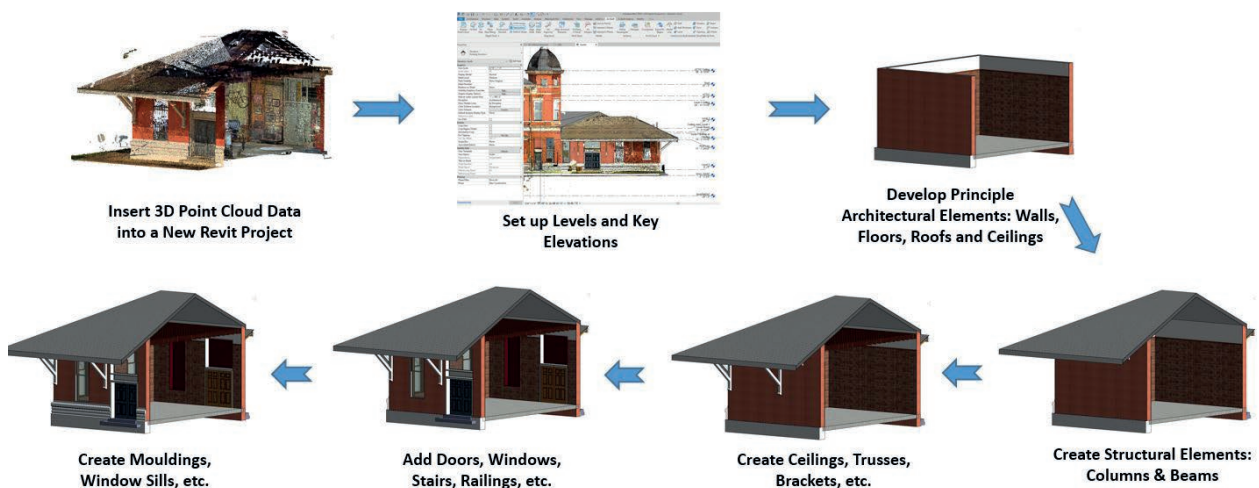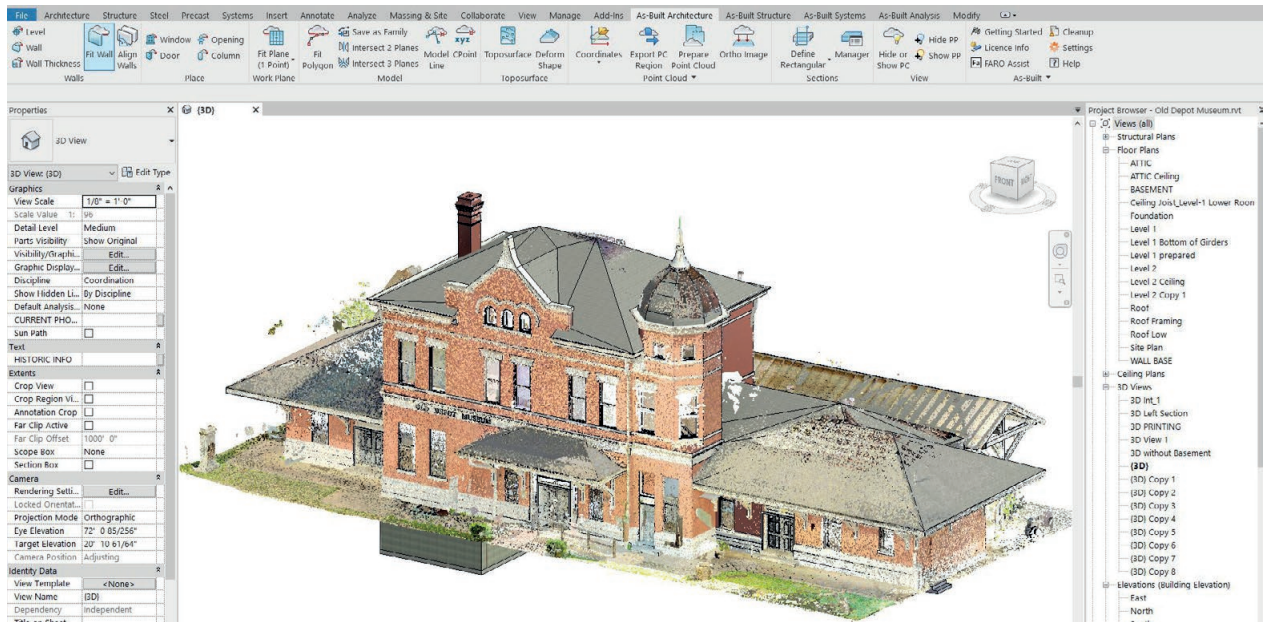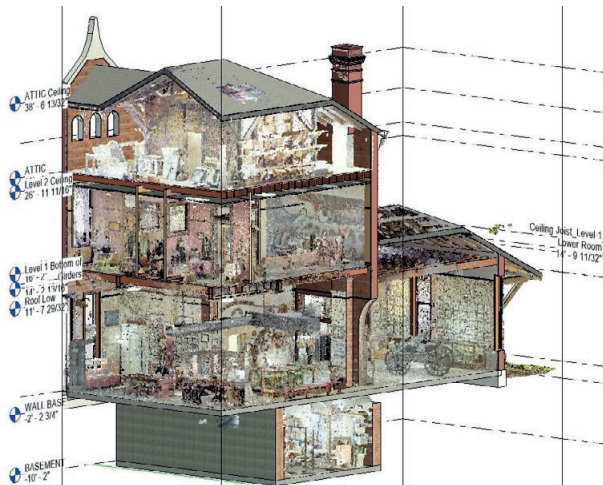

Fig. 17. Process of developing the ODM HBIM model in Autodesk Revit. (Source: authors).

(a) The HBIM model in Revit with the inserted 3D TLS point cloud.

(b) A 3D view showing interior details with TLS point cloud displaying.

(c) A 3D view showing interior details with TLS point cloud turned off.

Fig. 18. Photos illustrating the HBIM model of ODM. (Source: authors).

software programs' biggest disadvantages for heritage building modelling. This is due to: 1) the unique (and irregular) geometries of the building elements that need to be represented in their existing condition, and 2) the lack of parametric libraries for historic buildings.

The researchers recognized this challenge during the early stage of model development. They tried to solve the issue by adopting an artificial intelligence (AI) aided modelling plug-in application, FARO As-Built for Autodesk Revit (As-Built), to improve modeling productivity and accuracy. As-Built was designed for modelling 3D building models from 3D point cloud data (As-

Built™ for Autodesk Revit® 2018). The three As-Built's point cloud modelling functions that the researchers utilized on this project included:

- Providing flexibility of displaying the inserted 3D point cloud in Revit, allowing to show a custom section of the point cloud.

- Creating walls quickly and precisely using the 3D point cloud. The As-Built can automatically select the most appropriate wall type based on the determined wall thickness from analyzing the point cloud data, which would have been done by a manual method without the plug-in.
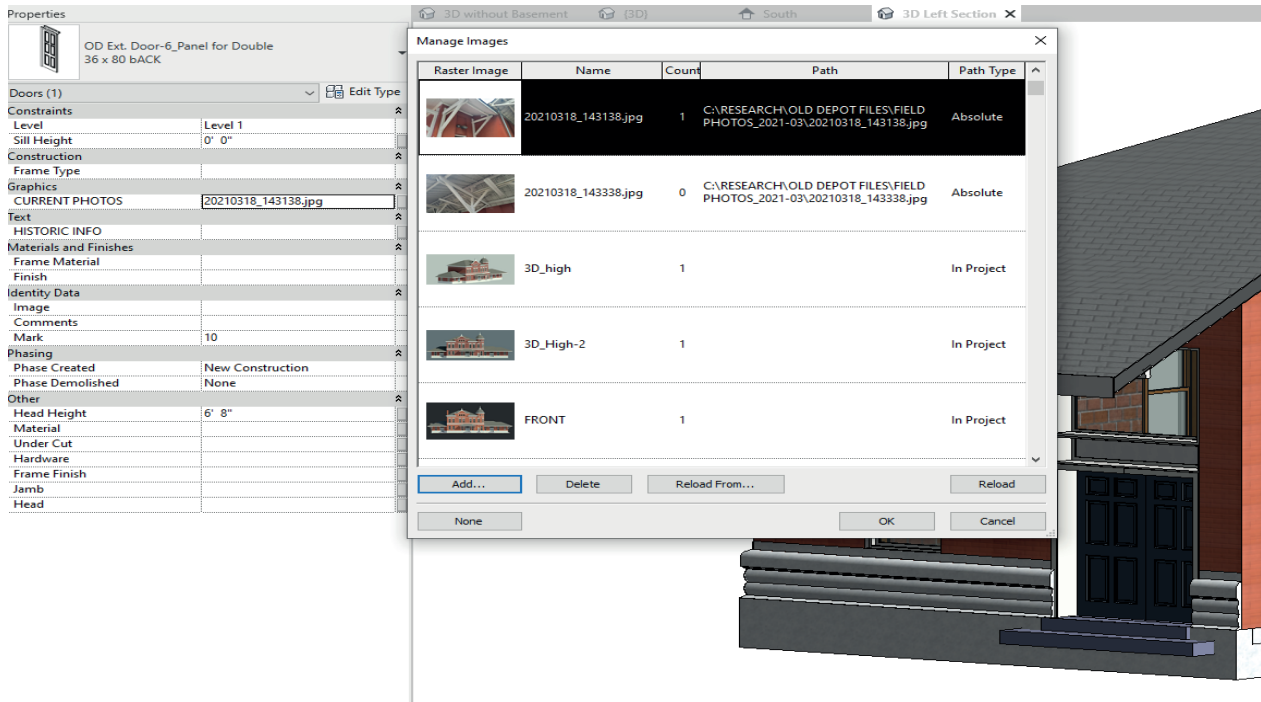
Fig. 19. Photos of a particular type of window were attached to the relevant elements in the HBIM model. (Source: authors).

- Fitting beams and columns. As-Built can place standard structural elements in the point cloud. Common beam and column profiles can be automatically identified and selected.

However, the researchers quickly recognized the limitations of As-Built – it did not apply to the majority of the elements in the BIM model. Therefore those elements had to be customized via a very time-consuming manual process. During HBIM process, although it is ideal to automate as many manual operations as possible, it was not possible to mechanize all the processes. Hopefully with the rapidly advancing of artificial intelligence and machine learning tools, it is possible to streamline most of the procedures and standardize the method (Massafra et al. 2020).

5. CONCLUSION AND DISCUSSION

As one of the fast-developing fields within heritage studies, for both research and practice, Heritage Building Information Modelling or HBIM is a multi-disciplinary process that requires the contribution and collaboration of professionals with very different skillsets. HBIM represents a promising tool for the management and documentation of heritage structures, both for daily operations as well as preservation planning.

HBIM can be used to track the aging process of the built asset, such as structural deflection, renovations, and rehabilitations. It can also record the significant historic events that have taken place in the built environment. However, the digital replication procedures associated with historic buildings are not straightforward. Through a review of existing research and investigation of two projects, this article introduces the basic concept, implementation process and challenges of HBIM. It's proven that unlike conventional BIM workflows for new constructions, the tried and tested tools and methods must be adapted, and even reinvented, for HBIM applications.

HBIM has yet to be widely adopted due to its complicate implementation process and high cost. However, with the rapid advancement of innovated technological tools that can significantly improve productivity and affordability of HBIM, such as artificial intelligence (AI), the authors believe that HBIM will become a more common practice for heritage documentation and management in the future.

REFERENCES

Antonopoulou, S., Bryan, P. 2017. 'BIM for Heritage: Developing a Historic Building Information Model'. Historic England. Available at: https://historicengland.org.uk/images-books/publications/bim-for-heritage/heag-154-bim-for-heritage/.

Apollonio, F., Gaiani, M. and Sun, Z. 2013. '3D Modeling And Data Enrichment In Digital Reconstruction Of Architectural Heritage'. https://doi.org/10.5194/isprsarchives-XL-5-W2-43-2013

As-Built™ *for Autodesk Revit®.* 2018. *FARO® Knowledge Base.* Available at: https://knowledge.faro.com/Software/As-Built/As-Built_for_Autodesk_Revit (Accessed: 15 December 2021).

Baik, A., Alitany, A., Boehm, J., Robson, S. 2014. "Jeddah Historical Building Information Modelling 'JHBIM' – Object Library", *In: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences.* (pp. 41 - 47). Riva del Garda, Italy. https://doi.org/10.5194/isprsannals-II-5-41-2014

Baik, A. 2017. 'From point cloud to Jeddah Heritage BIM Nasif Historical House – case study', *Digital Applications in Archaeology and Cultural Heritage*, no. 4, pp. 1–18. https://doi.org/10.1016/j.daach.2017.02.001

Barazzetti, L., Banfi, F., Brumana, R., Gusmeroli, G., Previtali, M., Schiantarelli, G. 2015. 'Cloud-to-BIM-to-FEM: Structural simulation with accurate historic BIM from laser scans', *Simulation Modelling Practice and Theory*, no. 57, pp. 71–87. https://doi.org/10.1016/j.simpat.2015.06.004

Bryan, P., Blake, B., Bedford, J., Barber, D., Mills, J. 2013. *Metric Survey Specifications for Cultural Heritage.* English Heritage. https://doi.org/10.2307/j.ctvxbphrz

Castellano-Román, M. Pinto-Puerto, F. 2019. 'HBIM oriented towards the master plan of the Charterhouse of Jerez (Cádiz, Spain)', *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W15, pp. 285–290. https://doi.org/10.5194/isprs-archives-XLII-2-W15-285-2019

Chevrier, C., Maillard, Y., Perrin, J.-P. 2009. 'A Method for the 3D Modelling of Historic Monuments: The Case of a Gothic Abbey'. Available at: https://halshs.archives-ouvertes.fr/halshs-00440184 (Accessed: 12 December 2021).

Dore, C., Murphy, M. 2017. 'Current State Of The Art Historic Building Information Modelling', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W5, pp. 185–192. https://doi.org/10.5194/isprs-archives-XLII-2-W5-185-2017

Fadli, F., AlSaeed, M. 2019. 'Digitizing Vanishing Architectural Heritage; The Design and Development of Qatar Historic Buildings Information Modeling [Q-HBIM] Platform', *Sustainability*, *11*(9), p. 2501. https://doi.org/10.3390/su11092501

Fai, S., Graham, K., Duckworth, T., Wood, N., Attar, R. 2011. *Building Information Modeling and Heritage Documentation.*

Gogo, M.E. 2011. 'Digital Documentation For Historic Resources, A Thesis Submitted to the Graduate Faculty of the University of Georgia'.

Green, A. and Dixon, J. 2016. 'Standing buildings and built heritage', *Post-Medieval Archaeology*, vol. 50, no. 1, pp. 121–133. https://doi.org/10.1080/00794236.2016.1169492

Gromova, Y. 2019. 'BIM for Heritage: How to Develop a Historic Building Information Model'. Available at: https://strelkamag.com/en/article/bim-to-the-rescue-of-heritage-sites (Accessed: 26 April 2021).

Ham, N., Bae, B.-I., Yuh, O.-K. 2020. 'Phased Reverse Engineering Framework for Sustainable Cultural Heritage Archives Using Laser Scanning and BIM: The Case of the Hwanggungwoo (Seoul, Korea)', *Sustainability*, vol. 12, no. 19, p. 8108. https://doi.org/10.3390/su12198108

Historic American Buildings Survey/Historic American Engineering Record/Historic American Landscapes Survey - Digitizing the Collections. 1930. Available at: https://www.loc.gov/pictures/collection/hh/digitizing.html (Accessed: 27 April 2021).

How 360° Images Take Construction Documentation to the Next Level (no date) *Construction Junkie*. Available at: https://www.constructionjunkie.com/blog/2017/8/8/how-360-images-take-construction-documentation-to-the-next-level (Accessed: 13 December 2021).

Janisio-Pawłowska, D. 2021. "Analysis of the Possibilities of Using HBIM Technology in the Protection of Cultural Heritage, Based on a Review of the Latest Research Carried out in Poland" *ISPRS International Journal of Geo-Information,* no. 10, 633. https://doi.org/10.3390/ijgi10100633

Jordan-Palomar, I., Tzortzopoulos, P., García-Valldecabres, J., Pellicer, E. 2018. 'Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM)', *Sustainability*, vol. 10, no. 4, p. 908. https://doi.org/10.3390/su10040908

Kalyan, T.S., Zadeh, P.A., Staub-French, S., Froese, T.M. 2016. 'Construction Quality Assessment Using 3D as-built Models Generated with Project Tango', *Procedia Engineering*, no. 145, pp. 1416–1423. https://doi.org/10.1016/j.proeng.2016.04.178

Liu, J., Jennesse, M., Holley, P. 2016. 'Utilizing Light Unmanned Aerial Vehicles for the Inspection of Curtain Walls: A Case Study', In *Construction Research Congress 2016*. pp. 2651–2659. https://doi.org/10.1061/9780784479827.264

Liu, J., Willkens, D. 2021. 'Reexamining the Old Depot Museum in Selma, Alabama, USA', in *BIM 2021*, Santiago de Compostela, Spain, pp. 171–186. https://doi.org/10.2495/BIM210141

Logothetis, S., Delinasiou, A., Stylianidis, E. 2015. 'Building Information Modelling for Cultural Heritage: A Review', in *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. 25th International CIPA Symposium 2015*, Taipei, Taiwan, pp. 177–183. https://doi.org/10.5194/isprsannals-II-5-W3-177-2015

López, F.J., Lerones, P.M., Llamas, J., Gómez-García-Bermejo, J., Zalama, E. 2018. 'A Review of Heritage Building Information Modeling (H-BIM)', *Multimodal Technologies and Interaction*, vol. 2, no. 2, p. 21. https://doi.org/10.3390/mti2020021

Massafra, A., Prati, D., Predari, G., Gulli, R. 2020. 'Wooden Truss Analysis, Preservation Strategies, and Digital Documentation through Parametric 3D Modeling and HBIM Workflow', *Sustainability*, vol. 12, no. 12, p. 4975. https://doi.org/10.3390/su12124975

Megahed, N. 2015. 'Towards a Theoretical Framework for HBIM Approach in Historic Preservation and Management', *International Journal of Architectural Research: ArchNet-IJAR*, vol. 9, no. 3, p. 130. https://doi.org/10.26687/archnet-ijar.v9i3.737

Moyano, J., León, J., Nieto-Julián, J.E., & Bruno, S. 2021. 'Semantic interpretation of architectural and archaeological geometries: Point cloud segmentation for HBIM parameterisation', *Automation in Construction*, no. 130, p. 103856. https://doi.org/10.1016/j.autcon.2021.103856

Murphy, M. 2012. 'Historic Building Information Modelling PhD'.

Oreni, D., Brumana, R., Georgopoulos, A., Cuca, B. 2013. 'HBIM For Conservation And Management Of Built Heritage: Towards A Library Of Vaults And Wooden Bean Floors'. In *ISPRS annals of photogrammetry, remote sensing and spatial information sciences*, 5, W1. https://doi.org/10.5194/isprsannals-II-5-W1-215-2013

Pocobelli, D.P., Boehm, J., Bryan, P., Still, J., Grau-Bové, J. 2018. 'BIM for heritage science: a review', *Heritage Science*, vol. 6, no. 1, p. 30. https://doi.org/10.1186/s40494-018-0191-4

Quattrini, R., Malinverni, E.S., Clini, P., Nespeca, R., Orlietti, E. 2015. 'From TLS to HBIM. high quality semantically-aware 3d modeling of complex architecture', in *6th International Workshop on 3D Virtual Reconstruction and Visualization of Complex Architectures, 3D-ARCH 2015, February 25, 2015*. Avila, Spain. pp. 367–374. https://doi.org/10.5194/isprsarchives-XL-5-W4-367-2015

Rodríguez-Moreno, C., Reinoso-Gordo, J.F., Rivas-López, E., Gómez-Blanco, A., Ariza-López, F.J., Ariza-López, I. 2018. 'From point cloud to BIM: an integrated workflow for documentation, research and modelling of architectural heritage', *Survey Review*, vol. 50, no. 360, pp. 212–231. https://doi.org/10.1080/00396265.2016.1259719

Saygi, G., Remondino, F. 2013. 'Management of Architectural Heritage Information in BIM and GIS: State-of-the-Art and Future Perspectives', *International Journal of Heritage in the Digital Era*, vol. 2, no. 4, pp. 695–713. https://doi.org/10.1260/2047-4970.2.4.695

Thomson, C., Boehm, J. 2015. 'Automatic Geometry Generation from Point Clouds for BIM', *Remote Sensing*, vol. 7, no. 9, pp. 11753–11775. https://doi.org/10.3390/rs70911753

Willkens, D.S., Haley, H.M., Liu, J. 2020. 'Race, Space, and Digital Interpretation at Selma's Old Depot Museum.', *Arris: The Journal of the Southeast Chapter of Architectural Historians*, no. 31, pp. 108–119. https://doi.org/10.1353/arr.2020.0009