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**DIGITAL DOCUMENTATION OF HERITAGE BUILDINGS
USING SCAN-TO-HBIM: CASE STUDY OF MUZIUM
SUNGAI LEMBING FOR SUSTAINABLE HERITAGE
MANAGEMENT**

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Abstract:

Heritage Building Information Modelling (HBIM) is increasingly adopted as a digital approach to heritage documentation; however, its implementation remains complex due to challenges integrating irregular geometries, multiple-source datasets, and fragmented historical information. This study develops and evaluates a Scan-to-HBIM workflow for heritage building documentation, aiming to improve data integration, modelling efficiency, and digital heritage management outcomes. The workflow integrates terrestrial laser scanning (TLS), UAV-based photogrammetry, and immersive visual documentation to support the creation of an information-rich HBIM model. A qualitative case study approach was employed to explore the implementation process and assess a route for systematically incorporating multiple digital datasets into a structured workflow. The workflow consists of four main stages: data acquisition, data processing, HBIM modelling, and workflow documentation and analysis. TLS generated dense geometric data for both interior and exterior spaces. UAV photogrammetry complemented the TLS dataset by capturing roof structures and upper façade elements. This integration ensures a complete and more continuous spatial dataset for HBIM development. This high-density dataset provides a reliable geometric reference for accurate HBIM modelling and spatial analysis. 3D volumetric visualisation facilitated spatial validation and model interpretation. The HBIM model was developed at Level of Detail (LOD) 300, identified as an appropriate level for balancing geometric accuracy with modelling efficiency in heritage documentation. This balance is particularly important in heritage projects, where time, cost, and data processing constraints must be carefully managed. The study further highlights the potential of digital heritage documentation to support sustainable heritage management and the development of heritage tourism. By providing a structured digital repository of heritage assets, Scan-to-HBIM workflows can facilitate conservation planning, digital interpretation, and long-term heritage management. This research offers tangible lessons learnt regarding workflow deployment, technical challenges, and considerations for the broader adoption of such an approach within a similar heritage context.

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Keyword:

Case Study, Heritage Building Documentation, Scan-To-HBIM, Terrestrial Laser Scanning, UAV Photogrammetry



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Introduction

Heritage buildings are important cultural resources that capture and embody a community's history, architectural heritage, and social memory. They are also among the most important tourist attractions in many countries, helping not only cultural tourism but also regional economic growth. However, the preservation and management of heritage buildings remain challenging due to aging structures, environmental exposure, and other compounded challenges arising from a lack of reliable architectural documentation (Mustafa, Ali, Hashim, et al., 2020; Sampaio et al., 2023). Often, existing historic structures lack available as-built or regulatory update records of their alterations (Liu et al., 2023), which poses major challenges for in-depth planning and the implementation of conservation actions aimed at heritage management.

Over the last few decades, new digital technologies have been implemented in heritage documentation to enhance the precision and speed of capturing historical building information. Among these technologies, Heritage Building Information Modelling (HBIM) has proven to be an effective digital process for documenting, analyzing, and managing heritage buildings (Dore et al., 2015; Liu et al., 2022). Building Information Modelling (BIM) represents a paradigm shift in the construction industry, materialised through the integration of three-dimensional digital models of building information within a structured environment where multiple users can access spatial and non-spatial data related to buildings. Simultaneously, Historical Building Information Modelling (HBIM) takes this concept a step further by broadening it to include historical data and architectural information. It can be applied to create information-rich virtual models of heritage buildings that support conservation planning, guide restoration activities, and provide sustainable management of sites where cultural heritage is located (Penjor et al., 2024).

Within the HBIM implementation, an important process is digitizing survey technologies into a Scan-to-HBIM workflow. Scan-to-HBIM is a general term for collecting spatial information of heritage buildings through terrestrial laser scanning (TLS) and photogrammetry, and then converting it into parametric BIM models (Liu et al., 2022; Rocha et al., 2020). Developed independently of traditional object-scanning procedures, this approach has been used for heritage documentation to acquire high-density point cloud data that can accurately model complex architectural geometries (Rocha et al., 2020). Terrestrial scanning alone will, however, not detect the adjustments and details of crystalline surfaces on rooftops or upper façade elements. These limitations are often addressed by combining TLS with UAV-based photogrammetry and immersive visual documentation, which produce richer digital datasets (Martínez-Carricondo et al., 2021).

Although the application of HBIM in heritage documentation research has been increasing, there are still various problems with its use. Due to their irregular geometries, hybrid construction techniques, and incomplete historical records, Heritage buildings pose several challenges for modelling and data integration (Penjor et al., 2024). In addition, most reported studies in the field of HBIM are based on European heritage buildings constructed of masonry. There is limited research on the use of Scan-to-HBIM in Southeast Asian heritage settings, particularly for timber-based heritage structures featuring colonial or vernacular architecture (Yusoff & Brahim, 2021).

Therefore, this study explores the implementation of a Scan-to-HBIM workflow for the digital documentation of a heritage building using Muzium Sungai Lembing in Pahang, Malaysia as a case study.

The study aims to:

- i. examine the applicability of selected digital documentation technologies for heritage data acquisition.
- ii. investigate the process of developing an information-rich HBIM model based on the collected datasets.

The empirical results from this study, which narrate a holistic process of combining TLs, UAV photogrammetry, and immersive visual documentation tools as integrated parts of a structured workflow, are based on experiences from actual use cases of contemporary digital recording technology in heritage conservation and sustainable management.

The study also suggests that digital heritage documentation could be a useful tool for developing heritage tourism. Digital heritage modelling powered by HBIM may help shape the interpretation of our cultural patrimony, enable virtual tourism experiences, and aid in the digital archiving of heritage assets (Penjor et al., 2024; Sampaio et al., 2023). As the world becomes increasingly dominated by heritage tourism, the growing use of digital documentation technologies, such as Scan-to-HBIM, may help create sustainable development in managing heritage destinations while making cultural heritage more accessible to the public.

Literature Review

In recent decades, new methodologies have emerged from the use of digital technologies in heritage documentation, aiming to increase accuracy and efficiency in recording historic structures. Documentation of existing conditions by traditional means, such as manual measurement, photography, and 2D drawings, is limited in capturing complex architectural geometries and irregular building elements in heritage buildings (Mustafa, Ali, Hashim, et al., 2020). As a result, digital documentation technologies have increasingly been adopted to improve the accuracy, efficiency, and reliability of heritage documentation processes (Mustafa, Ali, Has Yun Hashim, et al., 2020).

The development of Heritage Building Information Modelling (HBIM) is among the most important events in digital heritage documentation. Traditional BIM systems do not document cultural information during the modelling process. In contrast, HBIM enhances existing repositories of data, which serve to deliver structural and cultural content through a structured digital environment that covers historical information. Successful HBIM implementations have shown that it is possible to integrate architectural knowledge with three-dimensional digital models of the heritage building to create systems that efficiently support conservation planning and heritage management (Dore et al., 2015; Liu et al., 2022). HBIM allows heritage buildings to be represented as enhanced, data-rich digital models that store both geometric and non-geometric properties regarding architectural features, materials, and historical references (Sampaio et al., 2023). They enable the digital documentation, analysis, and management of heritage assets.

A critical component of HBIM implementation is the use of digital survey technologies to capture accurate spatial data of heritage buildings. Among these technologies, terrestrial laser scanning (TLS) has become widely recognised as a reliable method for generating high-density point cloud data that accurately represents the geometry of complex architectural structures (Banfi, 2019; Rocha et al., 2020). TLS enables researchers to capture millions of spatial data points within a short period of time, allowing for detailed documentation of building components that would be difficult to measure using conventional surveying techniques (Liu et al., 2023).

Besides TLS, UAV-based photogrammetry has also gained popularity in heritage documentation, enabling the assessment of numerous and challenging building elements that cannot be surveyed with traditional ground-based survey techniques. Photogrammetry with UAVs would collect aerial images that capture roof structures, upper façade elements, and even other elevated architectural elements (Martínez-Carricondo et al., 2021) when combined in an integrated approach. Thus, the combination of TLS and UAV photogrammetry yields a more complex dataset that benefits both digital heritage preservation and HBIM model production.

To fuse these digital datasets into a unified modelling environment, researchers generally follow a Scan-to-HBIM pipeline. In recent years, the transformation from spatial datasets obtained by digital survey technologies into parametric BIM models representing existing built heritage values is referred to as scan-to-HBIM (Liu et al., 2022; Rocha et al., 2020). This workflow typically includes several steps, with sequential operations spanning data capture, point cloud processing, geometric modelling, and information fusion. A systematic implementation of digital documentation technologies can thus be performed to obtain accurate HBIM models from heritage documentation following this structured workflow (Cui & Wu, 2025).

As interest in HBIM-related research increases, many challenges remain in its application. Heritage buildings commonly exhibit irregular geometries and complex composition materials, along with incomplete documentation of the historical object (Penjor et al., 2024), making modelling/data integration a further challenge. Furthermore, converting dense point cloud datasets into structured BIM models often requires extensive manual modelling, particularly when dealing with heritage architectural elements that do not conform to standard BIM component libraries.

Another limitation in the current HBIM literature is the geographical focus of many studies. A large proportion of HBIM research has focused on European heritage buildings, particularly masonry structures such as churches, castles, and historic monuments (Sampaio et al., 2023). On the other hand, there has been less than a comparable amount of study on applying HBIM to heritage in the Southeast Asian context as buildings within this region tend to have different design aspects including timber structures, mixed colonial influences and vernacular approaches (Ahmad Jamal et al., 2022; Mustafa, Ali, Has Yun Hashim, et al., 2020; Yusoff & Brahim, 2021).

Therefore, further empirical research is required to explore how Scan-to-HBIM workflows can be applied to heritage buildings in Southeast Asian contexts. Such research can provide valuable insights into integrating digital documentation technologies to document heritage buildings with diverse architectural characteristics, while supporting sustainable heritage management and the development of heritage tourism.

Despite the growing body of research on Heritage Building Information Modelling (HBIM), several gaps remain in the current literature. First, many current HBIM researches mainly focus on technological development and modelling how-to, rather than on the full execution of Scan-to-HBIM workflows on-site in real heritage habitats (Penjor et al., 2024). Empirical studies that demonstrate the integration of multiple digital documentation technologies in practical heritage documentation projects remain relatively limited.

Secondly, the majority of HBIM studies focus on a European context and masonry-based heritage assets, including churches, castles, and historic monuments (Sampaio et al., 2023). Although the Scan-to-HBIM workflows have been widely adopted, there is limited literature on them in Southeast Asian heritage contexts, where buildings often exhibit architectural heterogeneity, including timber structures and hybrid-colonial/vernacular forms (Yusoff & Brahim, 2021). Such differences in their architecture pose specific challenges to digital documentation and HBIM modelling.

Moreover, most available HBIM studies have not focused on the potential implications of documenting cultural heritage in digital form for heritage management and tourism development. As heritage buildings are tourism resources, they can be incorporated into conservation planning when using digital documentation technologies, such as Scan-to-HBIM, as a future application for green and sustainable heritage tourism and for digital heritage interpretation.

Therefore, this study aims to address these research gaps by investigating the implementation of a Scan-to-HBIM workflow for the digital documentation of Muzium Sungai Lembing in Pahang, Malaysia. The study further provides empirical insights into where new technologies can be applied to digital documentation to support heritage conservation and sustain the development of able practices by adding a structured digital workflow, advancing terrestrial laser scanning, UAV photogrammetry, and immersive visual documentation.

Case Study Background: Muzium Sungai Lembing

In research on HBIM, case study-based approaches are typically adopted to test workflows in actual heritage sites, as they provide an understanding of practical constraints and site-specific limitations (Mustafa, Ali, Hashim, et al., 2020; Yusoff & Brahim, 2021). The Muzium Sungai Lembing was selected as the representative heritage building for testing a Scan-to-HBIM workflow.



Figure 1: Exterior And Interior Views of Muzium Sungai Lembing, Pahang, Malaysia, Selected As The Case Study For The Implementation Of The Scan-To-HBIM Workflow

Source: (Authors' field documentation)

A museum in Sungai Lembing, shown in Figure 1 as a case study, was chosen based on its historical value, site challenges, concerning architectural complexity, and lack of proper as-built documentation. Muzium Sungai Lembing is situated in Sungai Lembing, Pahang, Malaysia. The site was the former home of PCCL, which operated one of the largest underground tin mines in the world during the 20th century. The building we see today has evolved over the years to become a museum that tells us about mining and the social culture of that period. The structure is, Architecturally, a mix of colonial and vernacular, with wood construction and raised floors, featuring irregular open plans. No complete as-built plans exist, and in conjunction with dialectic changes over the years, it is a challenge to use documentation techniques commonly. These features render Muzium Sungai Lembing a suitable pilot study for investigating the adoption of the Scan-to-HBIM workflow.

Methodology

This study utilises a case-based qualitative research approach to investigate the practice of HBIM for heritage documentation. Muzium Sungai Lembing was chosen as a test bed to assess the implementation of digital documentation technologies and to experiment with the detailed process flow of HBIM modelling. The methodology adopts an integrated digital workflow approach, where multiple data acquisition technologies are systematically combined to ensure comprehensive spatial documentation and accurate HBIM model development.

The methodology focuses on two primary objectives:

- (i) testing the applicability of selected technological tools for heritage data acquisition, and
- (ii) examining the process of developing an information-rich HBIM model based on the collected data.

The overall workflow follows a Scan-to-HBIM approach, encompassing data acquisition, data processing, HBIM modelling, and workflow analysis. This approach allows the study to document implementation challenges and identify lessons learned from a real-world heritage context.

Research Approach

The research study utilises a case-based qualitative approach to explore how HBIM has been implemented for the documentation of heritage buildings (Quattrini et al., 2015). This shift from theory development or performance testing to process implementation stories is an intentional focus (Argasiński & Tomczak, 2025). on the methodologies for applying information technologies and computational workflows to heritage problems in practice. The selected methodology would enable analysis of the scenario involving multiple data capture technologies and the knowledge-enhanced HBIM model that is subsequently created. By providing implementation processes, this research is anticipated to aid an empirical understanding of what is required to realise these Scan-to-HBIM workflows. The method is of particular interest in heritage documentation studies, since the complexity of buildings, with their unique site constraints, precludes rigorous, standardised experimentation.

This research utilises a rigorous research workflow to enable the digitisation of heritage building documentation. The workflow shows the key steps of the stage, starting with acquiring digital information, generating 3D point clouds, and finally creating the HBIM model. The research workflow, as shown in Figure 2, starts with the acquisition of digital data from the heritage building using terrestrial laser scanning and other digital documentation techniques that provide precise spatial information. The resultant datasets are then processed to create point cloud data, enabling the reconstruction, modelling, and design of the building's geometry in 3D.



Figure 2: Research Workflow Illustrating the Integration of Digital Documentation Technologies For The Development Of An HBIM Model And Sustainable Heritage Management Applications.

Source: (Developed by the authors)

The processed point cloud data serves as the primary reference for HBIM modelling, reconstructing the architectural features of the heritage building in a BIM environment. Using the Scan-to-HBIM workflow, the resulting HBIM is a combination of geometric and non-geometric information capable of generating documentation for digital heritage data.

The workflow also showcases how HBIM models contribute to sustainable heritage management and tourism use cases beyond technical documentation. These applications range from conservation planning and digital heritage archiving to virtual tours and educational platforms that enhance visitor engagement and heritage interpretation. Consequently, the research workflow serves as the basis for analysing the role of digital documentation technologies not only in facilitating heritage conservation but also in fostering sustainable tourism development centred on cultural heritage.

Case Study Selection

In this research, Muzium Sungai Lembing in Pahang, Malaysia, was chosen as the case study to fulfil the implementation-related items of the purpose. The structure is representative of architectural and historical features typically found in heritage buildings, such as irregular geometries, overlaid spatial arrangements, and a scarcity or absence of complete existing as-built record documents. These characteristics present practical challenges for conventional documentation techniques, making the site suitable for testing the applicability of a Scan-to-HBIM workflow. The selection of Muzium Sungai Lembing allows the study to examine how multiple digital documentation technologies can be integrated within a structured workflow to support accurate and systematic heritage building documentation. Furthermore, the case study provides an opportunity to evaluate the workflow in a regional heritage context, contributing empirical evidence to complement existing HBIM literature.

Overview of Scan-to-HBIM Workflow

To achieve a systematic and replicable HBIM integration, this research adopted an official Scan-to-HBIM workflow that has been widely popularised as an applicable guideline for the planning of complicated heritage documentation works, which can ensure coherence across 3D data acquisition, processing and formatting input for analysis (Khan et al., 2022; Liu et al., 2022). The workflow chosen in this study is based on these practices, but it has also been adapted to respond to local demand for heritage documentation.

As illustrated in Figure 3, the workflow begins with the integration of three primary technological tools for data acquisition: terrestrial laser scanning (TLS), UAV-based photogrammetry, and immersive visual documentation using a 360-degree virtual tour platform. TLS was utilized as the main source of geometric data for capturing interior and exterior architectural elements, while UAV photogrammetry complemented the dataset by documenting roof structures and upper façade components that were inaccessible from ground level. The 360-degree virtual tour provided supplementary visual information to support spatial understanding and model interpretation. The structured sequence of these stages ensures consistency, data reliability, and workflow reproducibility.

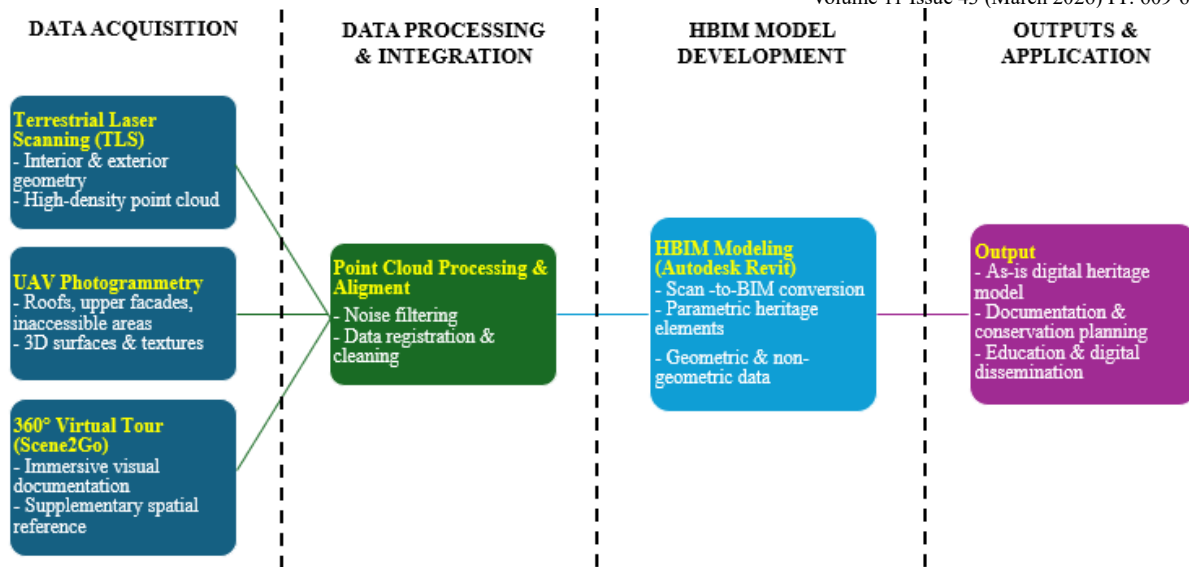


Figure 3: Overview Of the Scan-To-HBIM Workflow Adopted In This Study, Illustrating The Integration Of Digital Documentation Technologies From Data Acquisition To HBIM Model Development

Source: (Developed by the authors)

After this, the workflow advances to the second stage of data processing, in which the captured datasets are processed to develop an HBIM model. This stage includes point cloud registration, noise removal, and alignment to ensure geometric coherence and data reliability. Processed datasets are used as a comprehensive reference for the models quantifying the workflow.

The last part of the workflow process refers to HBIM modelling within a BIM (Autodesk Revit). Reconstructed point cloud data will serve as the primary reference for modelling architectural features, and the addition of non-geometric information will help better report the documentation value of the model. The process is completed by generating an intelligent HBIM model that serves as a digital repository for heritage documentation. In conclusion, the Scan-to-HBIM workflow described in Figure 3 provides a consistent framework that combines the tools and technological resources used, as well as the digital processes followed and documentation generated throughout all phases of data acquisition, processing, and modelling.

To further explain the relationship between the digital documentation process and heritage management outcomes, a conceptual framework was developed based on the Scan-to-HBIM workflow implemented in this study. The framework illustrates how multiple digital documentation technologies are integrated to generate an information-rich HBIM model that supports heritage conservation, digital archiving, and sustainable heritage tourism development.



Figure 4: Conceptual Framework of Digital Heritage Documentation Using The Scan-To-HBIM Workflow For Sustainable Heritage Management And Heritage Tourism Applications.

Source: (Developed by the authors)

As illustrated in Figure 4, the conceptual framework presents a structured process of digital heritage documentation beginning with data acquisition through terrestrial laser scanning, UAV photogrammetry, and immersive visual documentation. These technologies generate comprehensive spatial datasets that are processed and integrated to produce accurate point cloud information. The datasets are subsequently transformed into an HBIM model developed at LOD 300, which functions as a digital repository containing both geometric and non-geometric information related to the heritage building.

The HBIM model can then support various heritage management applications, including conservation planning, digital heritage archiving, and building monitoring. Furthermore, the digital model enables heritage tourism applications such as virtual tours, digital heritage interpretation, and educational platforms. This framework therefore highlights how Scan-to-HBIM can function not only as a documentation technique but also as a strategic digital platform supporting sustainable heritage management and heritage tourism development.

Findings and Results

The findings of this study are presented according to four main stages of the Scan-to-HBIM workflow implemented at Muzium Sungai Lembing.

Data Acquisition

Terrestrial laser scanning (TLS) and UAV-based photogrammetry integration are widely acknowledged as an efficient approach for achieving complete spatial documentation in level of detail studies of heritage buildings, particularly for complex or difficult-to-reach architectural elements (Martínez-Carricondo et al., 2021). The data acquisition approach chosen in this study follows these guidelines, utilising TLS, UAV photogrammetry, and immersive visualisation documentation.

Terrestrial Laser Scanning (TLS)

The TLS process generated high-density geometric data representing both interior and exterior architectural elements, forming a precise spatial reference for HBIM model development. The scanning tool used herein was a FARO Focus M70 laser scanner, which has a maximum scanning distance of 70 m, a minimum distance for short-range measurement of 0.6 m, and a maximum point cloud capture rate of 488,000 points per second. The scanner can acquire high-density point cloud data as well as panoramic images, which are indispensable for design documentation and visual references.



Figure 5: On-Site Discussion Among the Research Team During The Preliminary Site Survey To Determine Suitable TLS Scan Positions And Scanning Routes At Muzium Sungai Lembing

Source: (Authors' field documentation)

Before scanning, a thorough site survey was performed to gain an understanding of the overall building structure, spatial arrangement, and potential obstacles. This initial investigation facilitated the identification of appropriate scanning positions by the research team. Additionally, it provided a basis for discussing an efficient scanning strategy with the research team members on site, as shown in Figure 5. The early coordination made it possible to adjust

the flight path for optimal coverage within the short timeframe of the fieldwork schedule. TLS scanning was conducted to record the interior and exterior areas of the building on the first and second floors. Zig-zag scanning patterns were applied both inside and out to guarantee an adequate overlap between scanning stations and correlation of the scan positions during post-processing. Such scanning helped ensure superior registration and data continuity between separate building sections.



Figure 6: Terrestrial Laser Scanning Activities Using the FARO Focus M70 During Field Data Acquisition At Muzium Sungai Lembing

Source: (Authors' field documentation)

In total, 62 scan stations were set up and completed in approximately 6 hours. All scans were performed using a pre-defined medium resolution scanning profile (which offers a trade-off between geometric accuracy and scanning efficiency). The scans took on average five to seven minutes, comprising scan station preparation, laser scanning, and panoramic image acquisition. As with the earlier phones, non-HDR panoramas were captured at each station to aid in post-processing for data colourisation. During the scanning process, spherical and checkerboard targets were used to aid in the registration of scans. We put the targets less than 10 m, which is an essential criterion for a good re-scanning alignment, in correspondence with the optimal gravity centre of reconstruction point clouds. The TLS data acquisition during fieldwork with the FARO Focus M70 scanner is shown in Figure 6.

360-Degree Virtual Tour

In addition to geometry recording, the TLS process provided a 360-degree virtual tour created from panoramic images captured by the FARO Focus M70 scanner, recorded in the scene. These panoramic images were used to develop full 360° tours of the property, providing an immersive visual representation of on-site facilities. We utilised all 62 panoramic image locations that correspond to the TLS scan stations to create the virtual environment. Although the 360-degree visual data were not directly used in geometric modelling, these immersive views supplied supplementary, geographically sensitive information for spatial identification, interpretation of architectural elements, and validation of the HBIM model during modelling.

UAV-Based Photogrammetry

UAV photogrammetry complemented the TLS data by capturing roof structures and upper façade elements that were inaccessible from ground level. This approach enhances the completeness of the dataset and ensures continuous spatial coverage for HBIM modelling. An

aerial image (i.e., no photography from an aircraft) of the site, captured with a DJI Phantom 4 drone, is provided. For roof mapping, the flight height was carefully chosen to achieve good image overlap and spatial resolution for photogrammetric processing. For safety's sake, the minimum height for a planned flight was set at 15 m above the highest obstruction on site. This method guaranteed safe drone flight and provided sufficient coverage for 3D reconstruction. The workflow for aerial image acquisition, achieved with the help of a DJI Phantom 4 drone, is illustrated in Figure 7.



Figure 7: UAV Aerial Image Acquisition Using A DJI Phantom 4 Drone for Documenting The Roof Structure And Upper Façade Elements Of Muzium Sungai Lembing

Source: (Authors' field documentation)

Data Processing

Reliable scan registration and data processing are crucial in Scan-to-HBIM workflows, as it is necessary to maintain the geometric consistency and usability of the point cloud data in order to model it for further applications (Ahmad Jamal et al., 2022; Liu et al., 2022). The use of the utilisation of FARO SCENE and Pix4D in the present case study provides insight into processing pathways frequently presented in recent HBIM literature.

TLS Data Processing Using FARO SCENE

The raw terrestrial scanning data collected during fieldwork were first processed using FARO SCENE 2023, the core software for filtering, registration, and management of point cloud datasets obtained from FARO laser scanners. All raw scan data files were loaded into FARO SCENE, and the first check of the unregistered data and project settings was completed here. In FARO SCENE, the raw scan data were filtered for noise and then registered and aligned, so that disparate individual scan stations were seamlessly merged into a single project point cloud.

We processed and registered 62 scan stations in this work, resulting in a super-dense 3D point cloud dataset with approximately 1,298,844,704 points. This highly detailed 3D dataset offers a precise geometric representation of the building's internal and external layout. Figure 8 shows the main interface of FARO SCENE 2023, employed for the Muzium Sungai Lembing project, which includes the project structure and scan management environment. Figure 9 shows the registered and processed point cloud dataset, illustrating the three-dimensional data as complete (filled) and continuous in the TLS data processing pipeline. The employment of

FARO SCENE enabled the rapid registration of scans through target-based alignment using spherical and checkerboard targets, as well as cloud-to-cloud registration methods. The processed point cloud was the main geometric base on which further HBIM modelling processing was based.

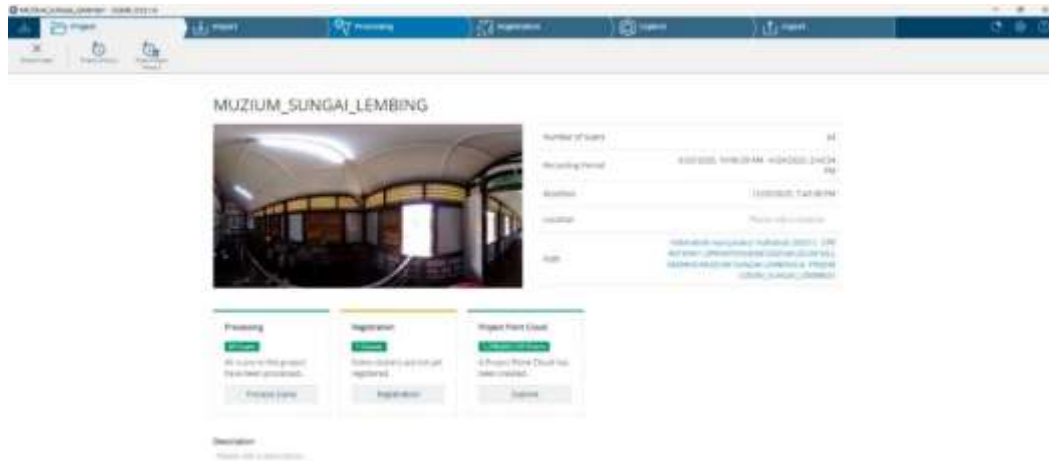


Figure 8: FARO SCENE 2023 Interface Used for Point Cloud Processing, Scan Registration, And Project Management In The Muzium Sungai Lembing Documentation Project

Source: (Authors' documentation)



Figure 9: Registered TLS Point Cloud Dataset Of Muzium Sungai Lembing Generated Through FARO SCENE, Illustrating The Complete Three-Dimensional Spatial Representation Of The Heritage Building

Source: (Authors' processing results)

Processing of 360-Degree Virtual Tour Using Scene2Go

Apart from point cloud processing, 360-degree virtual tours and immersive visual documentation were created using FARO SCENE. The virtual tour was exported from FARO SCENE to Scene2Go using the built-in 'Scene2Go App' in the software environment. The procedure consisted of selecting the "Create Scene2Go Data" option, setting up export options for gap-filling 3D data to achieve higher-quality visualisation (if required), and choosing between colour or grayscale presentations. Once all options were set, the Scene2Go data was

exported and transferred using the Transfer Scene2Go Data feature. This process produced a standalone viewer package that includes an executable file and project data, accessible offline on Windows or macOS desktops, without the need to install FARO SCENE. Figure 10 shows the virtual tour interface developed on Scene2Go with (a) a floor plan of Muzium Sungai Lembing, (b) an immersive panoramic and 3D views within space. The visual tour offered an important aesthetic as well as spatial reference point for validating spatial and interpretative solutions, supplementing the HBIM modelling process by facilitating continued crossover between geometric information and firsthand views.



(a)



(B)

Figure 10: Scene2Go Virtual Tour Interface Showing (A) Floor Plan Overview Of Muzium Sungai Lembing And (B) Immersive Panoramic View Used For Spatial Interpretation And Documentation

Source: (Authors' digital documentation)

UAV Photogrammetry Data Processing

Although it offers features for point cloud filtering, editing, as well as analysis and evaluation processes, FARO SCENE is primarily intended to process and register point clouds from terrestrial laser scanners, but not as a means for creating them from UAV imagery. Hence, the imagery taken from the DJI Phantom 4 drone is processed separately using Pix4D photogrammetry software. All images taken by the UAV are initially aligned in the Pix4D environment to orient them spatially and ensure overlap. Following this, the registered images were post-processed to create a 3D point cloud and surface mesh model that describes the outer

geometry of the building, with an emphasis on the roof lines. The focus of this dataset is to aid HBIM modelling for the above-ground parts of buildings, which are not appropriately captured by terrestrial scanning alone. Combining the photogrammetric results from UAV with TLS data could fill in all the gaps and be used to complement the documentation for HBIM modelling.

The processing steps for TLS, UAV photogrammetry, and immersive visual documentation are provided in Table 1. The table summarises the software platforms, processing steps, and output datasets supporting our Scan-to-HBIM workflow, as deployed in this work.

Table 1: Summary Of Data Processing Procedures For Terrestrial Laser Scanning (TLS), UAV-Based Photogrammetry, And Immersive Visual Documentation Using Scene2Go Within The Scan-To-HBIM Workflow

Data Type	Input Data	Processing Software	Processing Steps	Output Data	Purpose in HBIM Workflow
TLS	Raw laser scan data from FARO Focus M70	FARO SCENE 2023	Noise filtering, scan registration, target-based and cloud-to-cloud alignment	Registered 3D point cloud (~1.29 billion points)	Primary geometric reference for HBIM model development
TLS Panoramic Images	Panoramic images captured at scan stations	FARO SCENE 2023	Image linking, panorama processing, colorization support	Colorized point cloud and panoramic views	Visual reference and spatial verification
360-Degree Virtual Tour	Panoramic images from TLS scans	Scene2Go (via FARO SCENE)	Scene2Go data creation, gap filling, export and transfer	Offline virtual tour (executable + project data)	Immersive visualization and model interpretation
UAV Photogrammetry	Aerial photographs captured by DJI Phantom 4	Pix4D	Image alignment, dense point cloud generation, mesh creation	3D point cloud and surface mesh	Roof and upper façade modeling support

Source: (Developed by the authors)

HBIM Model Development

According to previous research, LOD 300 is necessary to provide geometric accuracy that enables the visualisation and integration of information without the need for fabrication-level detailing (Alshawabkeh et al., 2024; Kandemir & Akboğa Kale, 2025). The HBIM model produced in this paper complies with such a recommendation, focusing on spatial precision and documentation quality. The HBIM model was produced using Autodesk Revit and relied on point cloud data reduction as the primary geometric reference. The architectural elements,

such as walls, floors, roofs and openings, have been modelled to denote the building's existing condition. Customised modelling approaches were devised, as heritage buildings feature irregular geometry and are not readily available with off-the-shelf elements. Non-geometric data, such as material and architectural information, were added to enrich the documentation of the HBIM model.

Workflow Documentation and Analysis

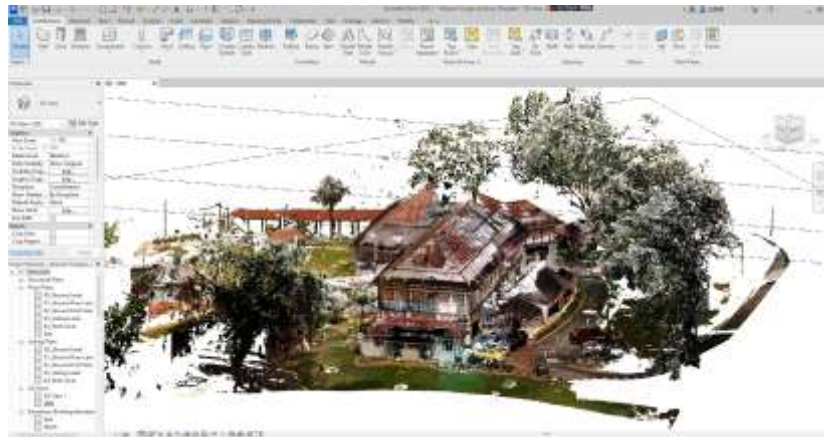


Figure 11: Autodesk Revit Interface Showing the Imported TLS Point Cloud Dataset Used as The Primary Reference For HBIM Model Development

Source: (Authors' modelling process)

The construction of the HBIM model was created in Autodesk Revit, as it is a standard BIM software with accurate 3D modelling, point cloud integration, and an information storage and retrieval system. Since Autodesk Revit allows both geometric and non-geometric information to be included simultaneously, it can be used for heritage documentation. The registered 3D point cloud from TLS served as the basis for HBIM modelling. The point cloud data was imported into the Revit environment, informing the precise modelling of architectural components. As shown in Figure 11, when a TLS point cloud is input within the Revit interface, survey data can be aligned with the modelling workspace.

We used additional reference materials to aid in model interpretation and verification, in addition to the TLS point cloud. These were the 360-degree virtual tours created with Scene2Go, UAV photos, and on-site photographic documentation. The addition of multiple reference sources was especially valuable in interpreting architectural details and building elements that were partially obscured or less well-defined in the point cloud data. The HBIM model was built to characterise the current state of the building, and includes architectural elements such as walls, slabs, roofs, columns, beams, doors and windows. Due to the irregularly shaped geometry and non-standard building construction common in heritage buildings, parametric families were developed where standard Revit libraries fell short. This method facilitated more realistic modelling of heritage-specific elements while navigating parametric control.

Used the LOD 300 LOD for heritage documentation in the HBIM model. At this level, building elements are modelled with the correct geometry (length and width), location, and orientation with respect to point clouds, spatially enabling them for analysis, visualisation, and information integration without extending to fabrication details. This level of detail is credible

for modelling effort and geometrical accuracy in a Scan-to-HBIM implementation study. Non-geometric data is embedded in the HBIM model using an information schema that includes properties such as material specification, building element category, and descriptive notes on architectural features. This organised data will make the HBIM model more valuable as a digital collection by combining physical geometry with background information related to heritage documentation. Selected three-dimensional views from the HBIM model generated in Autodesk Revit are shown in Figure 12, including (a) a 3D interior view with the display using TLS point cloud to illustrate geometric registration, and (b) a corresponding 3D interior view of pointing off for the HBIM model accomplishment. These viewpoints demonstrate how point cloud data supported the modelling activities and how the finalised HBIM model represents an understandable or interpretable digital replica of the heritage building.



Figure 12: Three-Dimensional Visualisation of The HBIM Model Developed in Autodesk Revit: (A) Interior View With TLS Point Cloud Displayed For Geometric Reference, And (B) Completed HBIM Model With The Point Cloud Hidden

Source: (Authors' modelling results)

Discussion

This study illustrates the Scan-to-HBIM workflow for heritage building documentation by presenting a case study of Muzium Sungai Lembing. The discussion also summarises the results and addresses the strengths of the currently implemented workflow, areas for

improvement, insights gained from application to practice, and its positioning with respect to other HBIM studies.

These findings also underscore the increasing significance of digital documentation technologies within heritage conservation practices. Since the full set of archival drawings or accurate as-built documentation is rarely available for heritage buildings, digital survey technologies such as TLS and UAV photogrammetry provide reliable methods for recording existing building conditions. These proposed technologies, if combined through a defined pathway, aka the Scan-to-HBIM workflow, enable heritage researchers and conservation practitioners to produce detailed digital records for subsequent conservation, restoration, and heritage management actions.

Strengths of the Scan-to-HBIM Implementation

One of the strengths of this workflow is that it brings together several digital documentation technologies to handle the complexity demanded by heritage building management. The use of terrestrial laser scanning (TLS) as the central methodology for geometric data ensured the precise acquisition of indoor/outdoor spaces. At the same time, UAV-based photogrammetry complemented it by capturing roof elements and the upper parts of facades that are not accessible by walking. The addition of immersive visual recording to enhance understanding and interpretation was found to enrich the HBIM modelling process.

Moreover, the Scan-to-HBIM process is structured and organised, which greatly helped in systematising data management from capture to processing and model generation. The distinct division of workflow stages enhanced data scalability and decreased incoherence between datasets. Such a methodical and systematic approach to documentation is beneficial in heritage documentation projects, where there may be an incomplete or fragmented record of the site, and challenges associated with limited on-site time typically make digital documentation difficult. A further methodological strength is the use of LOD 300 for implementing the HBIM model. At this stage, the model delivers good shape fidelity combined with rich information for documentation and visualisation, while not being carried through to fabrication-level detailing. Fast and accurate interactive 3D modelling methods are therefore crucial for heritage projects because such endeavours are often time-, budget-, and resource-limited.

In addition, the integration of immersive visual documentation through panoramic images and virtual tours further enhances the interpretative value of the digital dataset. These visual records assist researchers in understanding spatial relationships and architectural details that may not be immediately visible in point cloud data alone. Consequently, the use of multiple digital documentation techniques not only improves modelling accuracy but also strengthens the overall quality of heritage documentation.

Limitations of the Workflow

The introduced Scan-to-HBIM approach in this work presents promising advantages as well as some limitations. One of the most significant problems is the slow data processing and generation of HBIM models, particularly in cases involving dense point cloud data containing billions of points. Although TLS provides excellent geometric fidelity, manipulating and interpreting large datasets in this form are both computer resource and skill-intensive activities.

Another drawback concerns the manual workload required to model complex heritage parts. They had to be modelled as custom parametric families to realistically portray non-standard building elements, which led to additional modelling time and depended significantly on the modelling team's ability. This reflects a more general challenge in HBIM, where the automation of heritage-specific elements is currently incomplete. Moreover, although UAV photogrammetry could assist in modelling the roof structure, processing a multi-source dataset was more practical than using automatic methods. It is noted that this limitation echoes the reported difficulties in the HBIM literature, suggesting the use of more interoperable and automated data fusion methods for future research.

Furthermore, the integration of multi-source datasets also presents interoperability challenges. Data generated from different platforms, such as TLS point clouds and photogrammetric models, often require additional processing to ensure compatibility within BIM environments. This highlights the importance of developing more automated and interoperable digital documentation workflows in future heritage documentation research.

Lessons Learned and Practical Implications

There are several notable takeaways from the deployment of the Scan-to-HBIM methodology at Muzium Sungai Lembing. First, the early site inspection and workflow pre-planning are crucial for successful high-speed data acquisition, especially in heritage buildings with complicated space layouts. Transparent communication between team members during the planning process significantly contributed to efficient scanning and the completeness of data. Second, the study emphasises that it is crucial to set a documentation goal before developing a model. LOD 300 was chosen because the research team could concentrate on spatial correctness and information integration without excessive modelling. This is an essential lesson for heritage documentation projects that prioritise long-term digital archiving over construction-derived outputs.

Lastly, but not least, the results indicate that implementing HBIM should not be considered solely as a matter of technical modelling, but above all as a digital strategy based on processes. The presented structured workflow for heritage documentation enables environmentally friendly data reuse, interdisciplinary cooperation, and further model extension.

Comparison with Existing HBIM Studies

Compared to current HBIM studies, the approach proposed in this paper not only aligns with established practice but also incorporates its own unique contextual contributions. In a previous study by Dore et al., (2015), terrestrial laser scanning has been endorsed as the primary means for data collection in HBIM generation, as it effectively represents complex historic geometries. This is because high-density point clouds provide detailed information related to datasets from which generic and specific architectural components can be produced. This is also the method adopted in the present study: TLS as a primary geometric database, yet one extended with UAV-borne photogrammetry and immersive visual documentation, which helps overcome issues of access while allowing for deeper spatial interpretation.

Additionally, a majority of HBIM research studies centre around European stone and masonry heritage buildings, while the Muzium Sungai Lembing case study presents an opportunity to demonstrate how Scan-to-HBIM workflows are applicable in Southeast Asian heritage settings

that feature timber components, hybrid construction methods, and various additions. Unlike those who emphasise great detail in modelling strategies, the work has demonstrated that an LOD 300 HBIM model can deliver trustworthy documentation results and is more feasible for heritage projects with time and technology constraints. These results provide empirical evidence to complement the current HBIM literature, indicating that workflow flexibility and context-based modelling can underpin satisfactory heritage documentation.

The findings of this study therefore contribute additional empirical evidence for the application of HBIM in Southeast Asian heritage contexts. Many heritage buildings in the region are characterised by timber construction, hybrid colonial architectural influences, and incremental modifications over time. These characteristics present unique documentation challenges that differ from masonry-based heritage structures commonly studied in previous HBIM research.

Implications for Tourism, Hospitality and Heritage Management

Scan-to-HBIM as a digital documentation technology affects the development of impermanent tourism management and conservation culture. Whose makers, as this is a primary ingredient of a destination's historical narrative and cultural accounts, are often pivotal on the tourism map. Thus, accurate documentation is vital to conservation planning, heritage interpretation, and long-term heritage management.

Integrating multiple digital documentation technologies into the Scan-to-HBIM enhances technical documentation and augments broader heritage management and tourism applications. Within the framework of digital tourism, these technologies can be used to create digital datasets as a basis for conservation planning, heritage interpretation, and immersive experiences. Table 2 summarises the core digital documentation technologies used in this study and their connection with heritage management and tourism development.

Table 2: Digital Documentation Technologies and Their Contributions to Heritage Management

Digital Technology	Function in Documentation	Contribution to Heritage Management	Tourism and Educational Value
Terrestrial Laser Scanning (TLS)	Captures highly accurate spatial geometry of buildings through dense point cloud data	Provides precise digital records for conservation planning, restoration analysis, and long-term monitoring	Enables detailed 3D visualisation of heritage buildings for interpretation and educational purposes
UAV Photogrammetry	Captures aerial images of roofs and upper façade elements that are difficult to access	Complements terrestrial scanning data and improves completeness of building documentation	Enhances visual understanding of architectural forms for heritage interpretation
360° Virtual Tour	Produces immersive panoramic	Supports spatial verification and digital documentation	Enables virtual heritage exploration

	visualisation of interior spaces	of architectural features	and remote visitor engagement
HBIM Modelling	Integrates geometric and non-geometric data into an information-rich digital model	Serves as a digital repository for heritage documentation, conservation planning, and heritage management	Supports digital exhibitions, educational platforms, and virtual tourism experiences

Source: (Developed by the authors)

The role of each type of digital documentation technology in heritage documentation and management is shown in Table 2. Due to these characteristics, terrestrial laser scanning is widely used to acquire high-precision geometric information of the heritage works, forming a solid virtual foundation for digital modelling and conservation data analysis. While terrestrial scanning remains a valuable tool for documenting building components at street level, UAV photogrammetry enables capturing building elements above ground/road level, such as roof structures and higher-level façade fragments.

Immersive visual documentation of digital heritage datasets in the form of 360-degree virtual tours, however, enhances their interpretation. These immersive visual environments enable researchers, conservation professionals, and visitors to understand the spatial characteristics of heritage buildings better.

Most importantly, integrating these datasets into an HBIM model enables the development of an information-rich digital repository for heritage buildings. Digital repositories of this kind promote conservation planning, heritage interpretation, and long-term heritage management. In addition, the development of digital heritage models can also play an important role in tourism development, enabling virtual heritage experiences, digital exhibitions, and educational platforms, raising public awareness of cultural heritage.

Conclusion

This study developed and evaluated a structured Scan-to-HBIM workflow for the digital documentation of Muzium Sungai Lembing, Malaysia. The integration of terrestrial laser scanning, UAV-based photogrammetry, and immersive visual documentation enabled the generation of a comprehensive and reliable spatial dataset for HBIM model development. The findings demonstrate that combining multiple digital documentation technologies significantly improves the accuracy, completeness, and efficiency of building documentation.

The HBIM model developed at Level of Detail (LOD) 300 was identified as an appropriate level for balancing geometric accuracy with modelling efficiency. This level allows effective representation of architectural elements while maintaining practical modelling effort, making it suitable for documentation, conservation planning, and digital archiving.

Beyond technical modelling, this study highlights the role of digital documentation as an enabling platform for sustainable practices and tourism applications. The integration of digital datasets into an information-rich HBIM model supports conservation decision-making, long-term monitoring, and the creation of interactive digital environments such as virtual tours and

educational platforms. These applications enhance public accessibility and engagement while reducing physical impact on sensitive sites.

This research contributes empirical evidence on the implementation of Scan-to-HBIM in a Southeast Asian context, particularly for timber-based and hybrid architectural structures that present unique modelling challenges. The proposed workflow provides a practical reference for researchers, practitioners, and stakeholders seeking to adopt digital documentation strategies in similar contexts.

Future research may focus on automating HBIM modelling processes, improving interoperability between digital documentation platforms, and integrating advanced virtual tourism technologies to further enhance digital heritage applications and user engagement.

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