

Review

Static Terrestrial Laser Scanning (TLS) for Heritage Building Information Modeling (HBIM): A Systematic Review

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Abstract: Heritage Building Information Modeling (HBIM) is an essential technology for heritage documentation, conservation, and management. It enables people to understand, archive, advertise, and virtually reconstruct their built heritage. Creating highly accurate HBIM models requires the use of several reality capture tools, such as terrestrial laser scanning (TLS), photogrammetry, unmanned aerial vehicles (UAV), etc. However, the existing literature did not explicitly review the applications and impacts of TLS in implementing HBIM. This paper uses the PRISMA protocol to present a systematic review of TLS utilization in capturing reality data in order to recognize the status of applications of TLS for HBIM and identify the knowledge gaps on the topic. A thorough examination of the 58 selected articles revealed the state-of-the-art practices when utilizing static TLS technology for surveying and processing captured TLS data for developing HBIM models. Moreover, the absence of guidelines for using static TLS surveys for HBIM data acquisition, the lack of robust automated frameworks for producing/transferring 3D geometries and their attributes from TLS data to BIM entities, and the under-utilized application of TLS for long-term monitoring and change detection were identified as gaps in knowledge. The findings of this research provide stakeholders with a good grasp of static TLS for HBIM and therefore lay the foundation for further research, strategies, and scientific solutions for improving the utilization of TLS when documenting heritage structures and developing HBIM.

Keywords: BIM; HBIM; reality capture; systematic review; terrestrial laser scanning; TLS



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1. Introduction

Heritage Building Information Modeling (HBIM or H-BIM), utilizing 3D modeling and information management, is a process that produces intelligent BIM models documenting, containing, managing, and interpreting information about built heritage. HBIM has become an essential technology for cultural heritage presentation and conservation [1–6].

A typical HBIM implementation workflow includes a preliminary phase to identify the purpose and determine the Level of Development (LOD), a data acquisition phase to capture spatial and semantic data, a data processing phase, and a model development phase. Figure 1 illustrates a detailed HBIM workflow as well as the hardware and software utilized in each phase. During data acquisition for HBIM, both historical and existing data about the heritage structure are collected. The historical data includes the original design and construction documents, historical records and photographs, maintenance and renovation reports, bibliographic references, information about critical historical events relevant to the structure, etc. [7]. The existing (as-built) condition data of the built heritage, including its geometrical information, structural details, materials, defects, and decay, is acquired through field surveys using Reality Capture (RC) techniques. Next, all captured geometric and descriptive data of the structure is processed and used to develop a highly detailed and accurate as-built 3D digital model [5,8–10]. Finally, data about the structure, such as historical photographs, historical reports, maintenance and renovation records,

materials, and decay, are included as an add-on to the 3D model, making it an intelligent building information model [11].

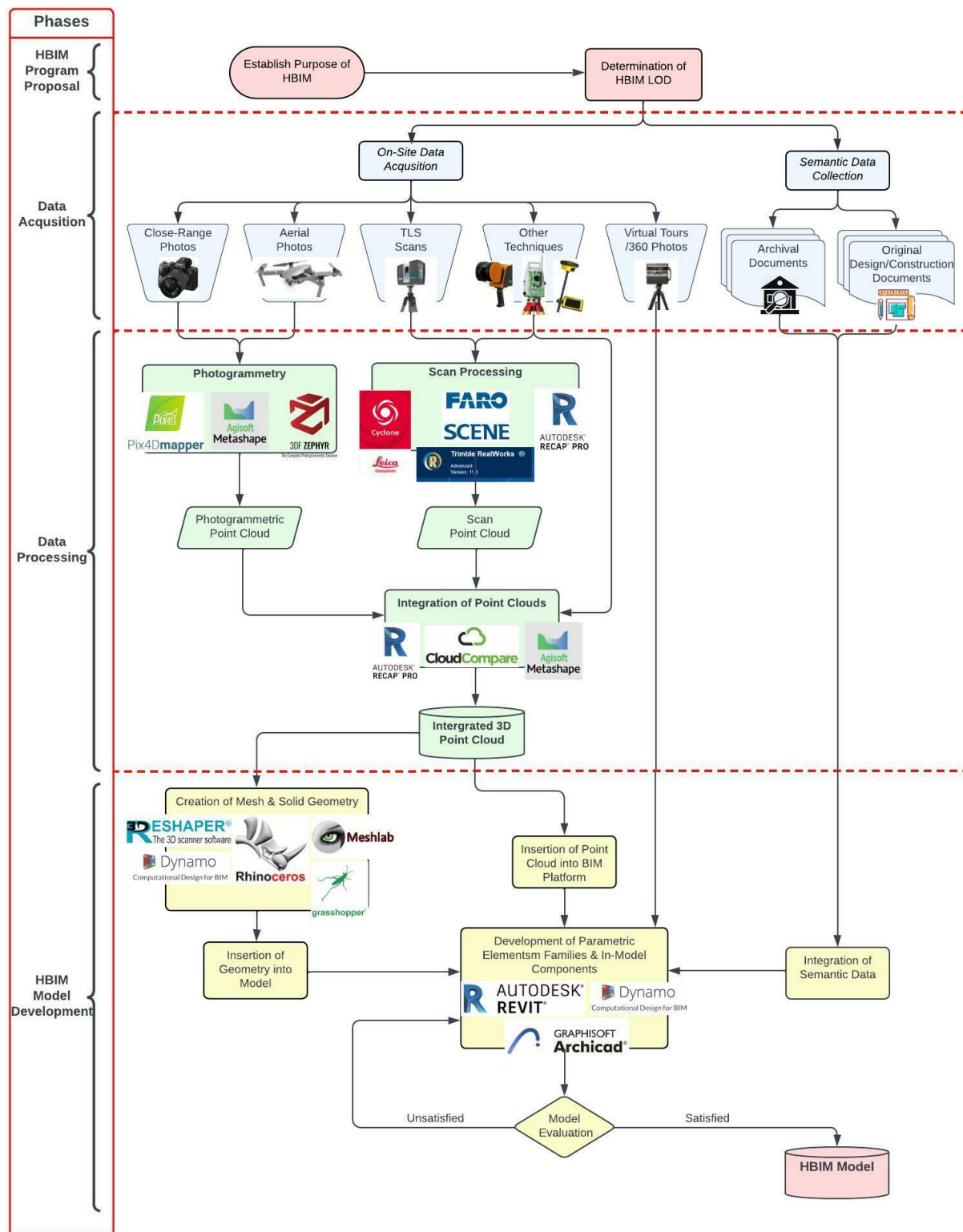


Figure 1. A representative diagram of the HBIM workflow and related software used in different stages.

The creation of HBIM models requires the acquisition of highly accurate RC data, which may be obtained with traditional analog tools (e.g., measuring tapes) and advanced instruments and techniques [9]. Each of the techniques and technologies has its own advan-

tages and limitations in the aspects of accessibility, comprehensiveness, level of accuracy, and feasibility. Multiple innovative RC technologies have been embraced by researchers and practitioners to capture geospatial data about heritage structures. These techniques include Terrestrial Laser Scanning (TLS) [12–15], photogrammetry [8,16], UAVs [17–20], and 360-degree photography [21,22] among others. RC technologies accelerate data collection and reduce errors and deficiencies relative to the conventional method [23]. TLS is a ground-based LiDAR (light detection and ranging) technology [24] that uses remote sensing measuring devices (a laser sensor) to collect dense point clouds of objects [25]. TLS can be divided into two categories: static TLS and mobile laser scanning (MLS). Static TLS involves setting up a tripod-mounted laser scanner in a fixed location and scanning the surrounding environment from different positions to capture high-resolution data. Static TLS is commonly used in construction, architecture, and engineering for precise measurements of building and site conditions [26–29]. MLS, on the other hand, involves a laser scanner mounted on a mobile platform such as a vehicle, drone, backpack, or being held by hand (a hand-held scanner). The MLS scanner can capture 3D data of the environment as the platform moves through the area, allowing for quick and efficient data capture. MLS is commonly used in applications such as surveying, mapping, and infrastructure management [26,30,31].

Both static TLS and MLS have their advantages and limitations. Static TLS offers higher resolution and accuracy, making it well-suited for capturing detailed data of smaller areas. MLS, on the other hand, offers the ability to capture data over a larger area in a shorter amount of time, making it ideal for scanning larger sites or environments [26–29]. Additionally, MLS can capture data from areas that are difficult or dangerous to access, such as high ledges or steep slopes [32,33]. However, MLS technology also has its limitations when compared to static TLS. For example, MLS data may be less detailed than TLS data due to the speed of the scanning process [26], and the accuracy of MLS data can be affected by factors such as the speed and trajectory of the mobile platform [30,31].

Figure 2 displays the principle of static TLS and its application in HBIM. Yang et al. [7] acknowledged in their review article that the utilization of static TLS to capture point clouds of heritage structures has become an important tool for HBIM researchers and practitioners. Although there are several publications that address the applications of MLS for HBIM development [34,35], the mass majority of the research that utilized TLS to capture data for HBIM chose static TLS. Therefore, this research study of TLS only focuses on the static type of the technology. The TLS mentioned in this article represents static TLS.

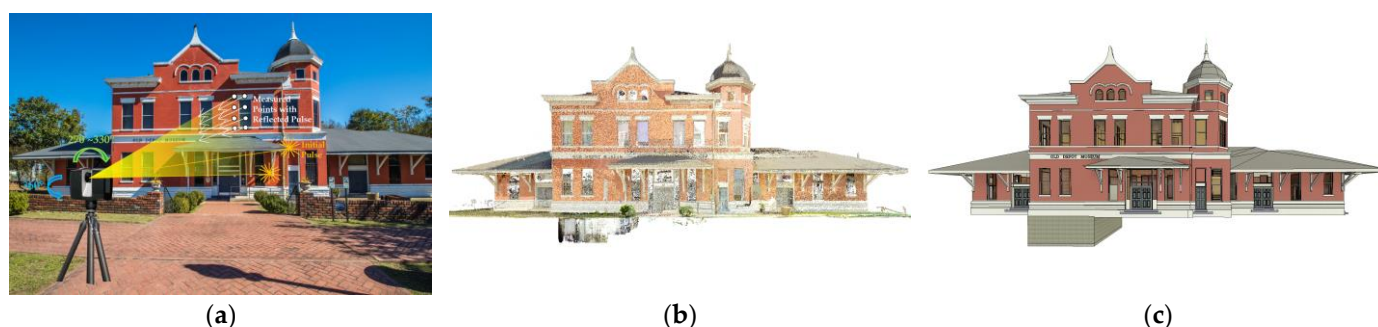


Figure 2. TLS technology and its application in HBIM: (a) the principle of TLS; (b) a resultant point cloud of the TLS survey; and (c) an HBIM model developed from the TLS point cloud.

The existing literature in the main scientific databases did not explicitly review the applications and impacts of TLS in the implementation of HBIM. Two research questions are raised for this study: (1) what is the state-of-the-art TLS used for HBIM development? (2) what are the knowledge gaps in this subject matter? This research aims to provide a comprehensive overview of the studies carried out on the utilization of TLS for HBIM. It focuses on the most commonly used devices, software, processes, and methods for quality

assessment and control of TLS for HBIM implementation. This research also presents the challenges of TLS for HBIM and proposes areas in which further studies are needed.

A systematic research review of this subject matter can provide researchers, practitioners, and other HBIM stakeholders with a good grasp of this topic and therefore lay the foundation for further research, strategies, and scientific solutions to improve the utilization of TLS for documenting heritage structures and developing HBIM. The findings of this research are also valuable for the development of as-built documentation and digital twins for new construction projects.

The structure of this article first includes the background of HBIM technology and introduction to RC. Next, it explains the research design and methodology, consisting of the selection of search databases and the deployment of the PRISMA approach for finding the relevant articles. Next, it shows the major metrics of the found articles, including (1) the chronological evolution of the papers' publication; (2) geographic distribution and collaboration; (3) the most active authors; (4) the keywords collaboration network; and (5) publications by the type of study. The main findings of this study are then presented and discussed to address the status of TLS technology and the techniques used to acquire data for HBIM development. Finally, a conclusion will be drawn, along with a discussion of the knowledge gaps and recommended areas for further research.

In this paper, abbreviations were used to refer to various terms and concepts. To avoid confusion and ensure clarity, below is a list of these abbreviations and their corresponding meanings:

- BIM: Building Information Modeling;
- CP: Control Point;
- DSLR: Digital Single Lens Reflex;
- GCP: Ground Control Point;
- GPS: Global Positioning System;
- HBIM: Heritage Building Information Modeling;
- LiDAR: Light Detection and Ranging;
- LOD: Level of Development;
- MLS: Mobile Laser Scanning;
- MMS: Mobile Mapping System;
- PRISMA: Preferred Reporting Items for Systematic Review and Meta-Analysis;
- RC: Reality Capture;
- SfM: Structure from Motion;
- TLS: Terrestrial Laser Scanning;
- TS: Total Station;
- UAV: Unmanned Aerial Vehicle;
- VR: Virtual Reality;
- WOS: Web of Science.

2. Research Design and Methodology

To answer the two research questions of this study, the researcher set up a systematic literature review process (see Figure 3) and elected to use the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) approach. The PRISMA approach was chosen over others because of its acceptance, comprehensiveness, and wide variety of applications in numerous academic disciplines [36].



Figure 3. Systematic literature review process. Inspired by [37].

2.1. Search Method and Information Sources

The study selection was searched within the significant domains of HBIM, architectural heritage, and reality capture (RC) technology. Two main citation databases were chosen as the primary sources to retrieve the relevant publications. They are Scopus and Web of Science (WOS). The generated keywords that were used for the search included terms that are closely associated with the primary domains of the study. Keywords that shared similar notions were grouped with “OR” to retrieve a broad view of articles and “AND” to include other concepts. Table 1 shows the keywords used in these two databases in their advanced or expert modes.

Table 1. Databases and keywords used for the search.

Database	Keywords (Code)
Scopus	(TITLE-ABS-KEY (“HBIM” OR “Historic*BIM” OR “Heritage*BIM” OR “Historical*BIM” OR “Historic*Building Information Model*” OR “Heritage*Building Information Model*” OR “Historical*Building Information Model*”)) AND TITLE-ABS-KEY (“LiDAR” OR “laser” OR “TLS” OR “scan”))
Web of Science (WOS)	ALL = (“HBIM” OR “Historic*BIM” OR “Heritage*BIM” OR “Historical*BIM” OR “Historic*Building Information Model*” OR “Heritage*Building Information Model*” OR “Historical*Building Information Model*”) AND ALL = ((“HBIM” OR “Historic*BIM” OR “Heritage*BIM” OR “Historical*BIM” OR “Historic*Building Information Model*” OR “Heritage*Building Information Model*” OR “Historical*Building Information Model*”)) AND ALL = ((“LiDAR” OR “laser” OR “TLS” OR “scan”))

* This symbol, or asterisk, is used as a wildcard in the search databases to represent any number of characters in a search term, allowing results containing various word forms or spellings with a single query.

2.2. Search Process

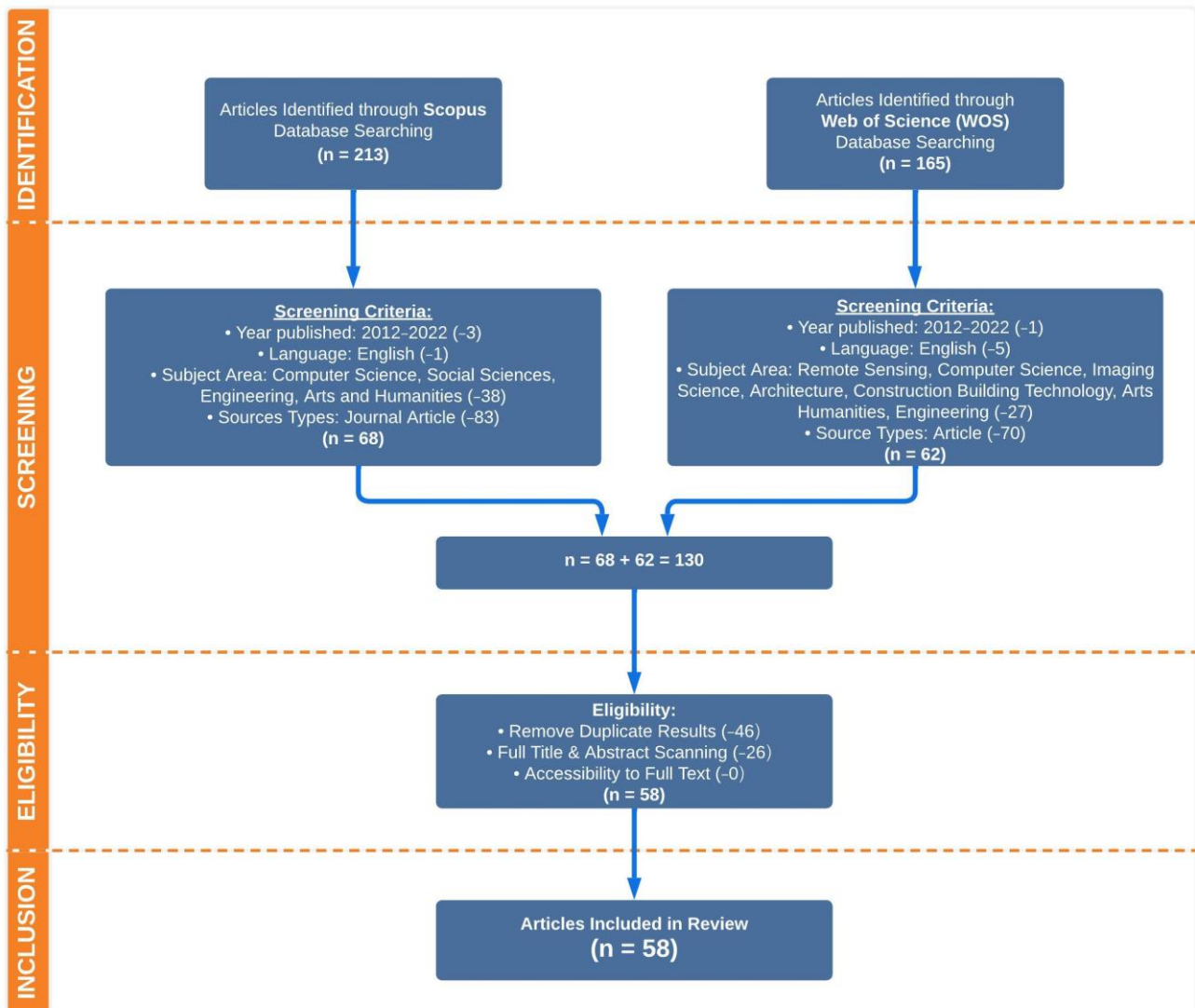
The researcher adopted a three-stage methodological approach to conduct the study: planning, searching, and screening (the PRISMA approach), and reporting [9].

The research question, objectives, search databases, keywords, and a set of exclusion and inclusion criteria were included in Stage 1 (planning). The goal was to identify the status and applications of TLS for the development of HBIM for built heritage.

Stage 2 (searching and screening, the PRISMA approach) included a process for conducting the review. During this stage, relevant articles were searched for in October 2022. The use of TLS for HBIM has largely gained traction in the last decade. The initial search using the pre-identified keywords yielded 378 articles in total, including 213 from Scopus and 165 from WOS. To shortlist the articles for more accurate results, initial screening criteria were established: all English-only peer-reviewed journal articles in the subject areas of computer science, social sciences, engineering, and arts and humanities published between 2012 and 2022. See Table 2 for the screening criteria chosen for this research. After implementing the screening criteria, 130 articles were left for the next step of review. In this step, the titles of these 130 articles were manually scanned to identify duplicates from the two different databases, which resulted in the removal of 46 articles. Next, the researcher thoroughly studied the title and abstract of each remaining article with the intention to eliminate the irrelevant ones. Through this step, a total of 26 articles were removed from the result. After this step, the researcher was able to retrieve the full text of all the remaining 58 articles. Therefore, 58 articles were chosen for this systematic review. The workflow of the PRISMA approach is illustrated in Figure 4.

Table 2. Criteria applied for shortlisting articles.

Criteria	Details
Year of publication	From 2012 to 2022
Language	English
Subject areas	Computer science, social sciences, engineering, arts, and humanities
Source types	Only peer-reviewed journal papers

**Figure 4.** The PRISMA workflow to select the 58 articles for this research study.

In Stage 3 (reporting), all 58 articles chosen in Stage 2 were thoroughly studied and analyzed using content analysis methods to synthesize the themes. Each of the articles was carefully read, and all relevant information needed to address the main objectives of this paper was documented.

2.3. Search Results

2.3.1. Evolution of Publications per Year

The first definition of HBIM appeared in 2009, by Murphy et al. [38]. The number of publications saw a dramatic upward trend since 2018 (Figure 5). There was only one

article in a 5 year span from 2013 to 2017. In 2018 and 2019, there were seven and two publications, respectively. However, an average of 16 articles were released each year in the last three years.

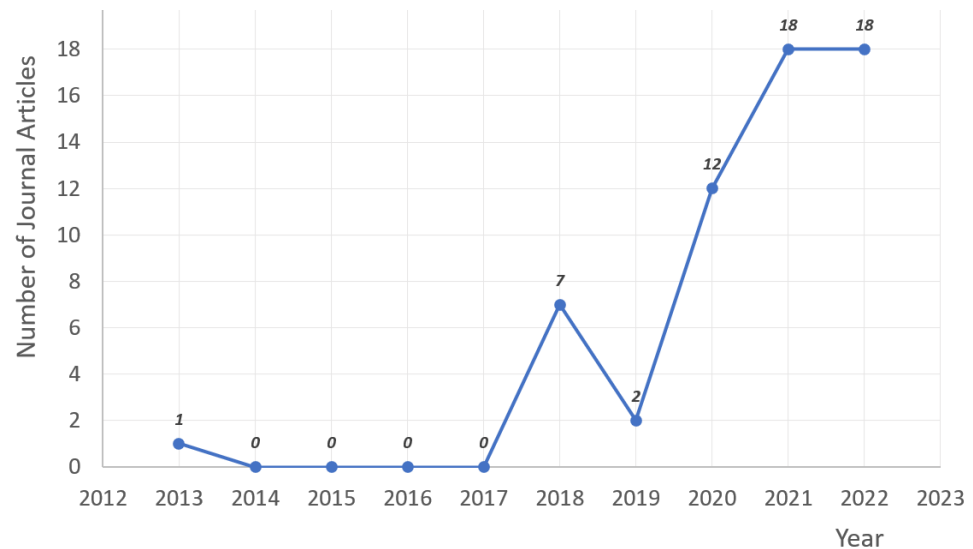


Figure 5. Year of publication of included articles.

2.3.2. Origin Countries of Authors

Figure 6 illustrates the countries of origin of the contributing authors of the selected publications. The three southern European countries, Italy (26, 35%), Spain (17, 23%), and Portugal (6, 8%) combined, are the homes of two thirds of the authors. Out of the seventy-five authors, sixty (80%) reside in Europe, eight (11% in Asia), four (6%) in the Americas, and the remaining three (4%) in Africa.

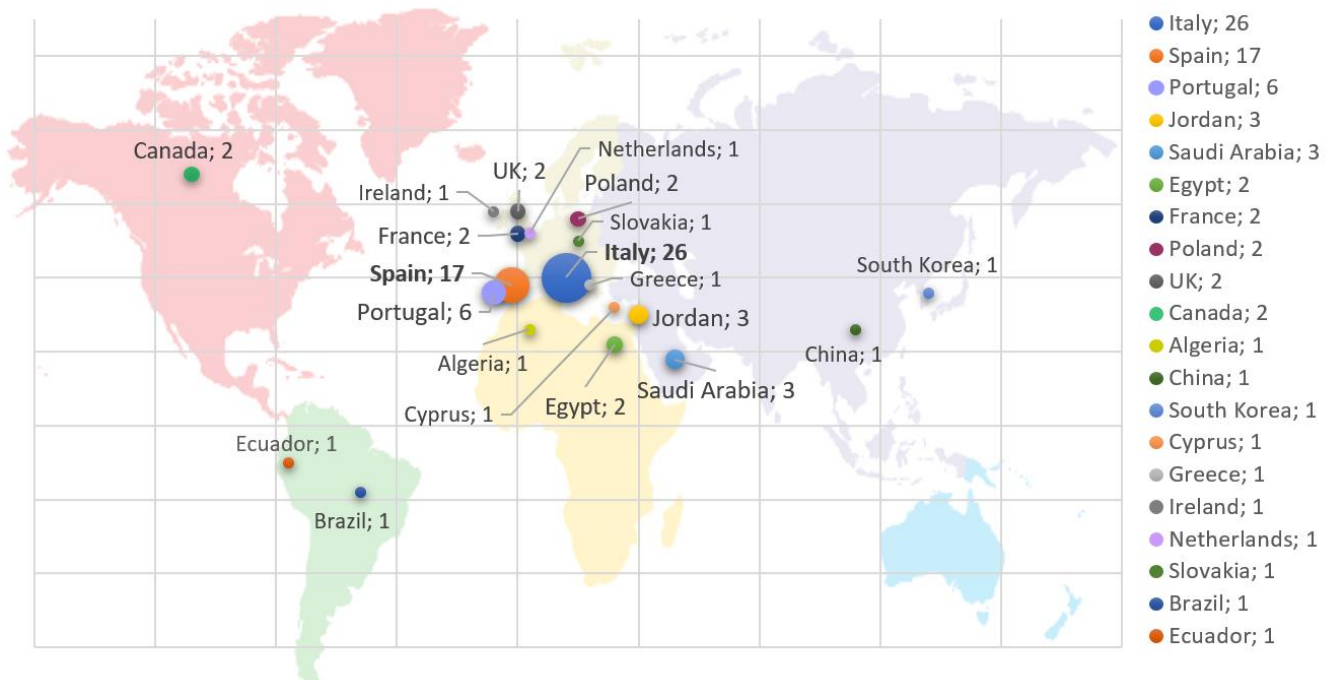


Figure 6. Origin of contributing authors.

2.3.3. Most Active Authors

Among the authors who have contributed to the selected journal articles, eleven appear in three or more papers (Figure 7). The top three authors are Moyano, J.; Nieto-Julián, J.E.; and Banfi, F., who have authored or co-authored seven, seven, and six articles, respectively. Banfi's articles have the most citations with a total of 166, followed by Mayona's with 124.

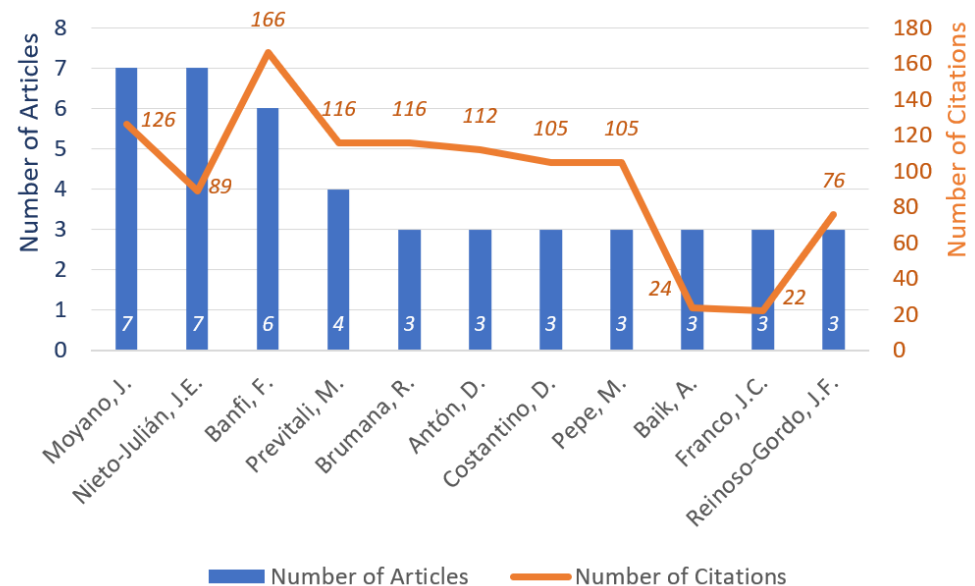


Figure 7. Most active authors.

2.3.4. Keywords Collaboration-Network

A total of 454 keywords were identified from the initial analysis. After further investigation, the author realized that some keywords share the same notions, e.g., 'Heritage BIM', 'Historic BIM', 'Historical BIM', 'H-BIM', etc., all of which can be interpreted as 'HBIM'. Therefore, all 454 keywords were manually scanned, and the ones that had the same implications were replaced and consolidated with a more common term. Table 3 shows a list of these common keywords and the keywords that they replaced. After this step, a total of 420 keywords remained for further analysis.

Table 3. A list of 12 "merged" keywords that share the same meaning.

Common Keyword	Alternatives
3D Modelling	3D Modeling; 3 Dimensional Modelling, 3 Dimensional Modeling; 3-Dimensional Modelling, 3-Dimensional Modeling
Architectural Heritage	Built Heritage
BIM	Building Information Modeling, Building Information Modelling, Building Information Model, HBIM (Historical Building Modelling), BIMs
HBIM	Heritage BIM, Historic BIM, Historical BIM, H-BIM, Heritage-BIM, hBIM
Heritage Building	Heritage Building, Heritage Buildings, Historic Building, Historical Building
Laser Scanning	Laser Scan, Laser Scanners, Laser Scanner, 3D Laser Scanning, LiDAR Scanning, Laser Scans
Modelling	Modeling
Point Cloud	Point Clouds, Point-Clouds, LiDAR Clouds, LiDAR Cloud, Cloud Point, Point Cloud Data
Scan-to-BIM	Scan-to-BIM, scan to BIM, Point Cloud-to-BIM
TLS	Terrestrial Laser Scanner, Terrestrial Laser Scanning, Terrestrial Laser Scanners
UAV	UAV, UAV (UAV), Drones, Drone, Unmanned Aerial Vehicles, Unmanned Aerial Vehicle
VR	Virtual Reality

There are 27 keywords identified in this study that occurred in at least five articles. These 27 keywords have an average total link strength of 74.8, an average occurrence of 11.5, and a maximum occurrence of 35 (i.e., HBIM). Figure 8 shows the mapped network of these 27 keywords and clusters of the five most occurring ones (i.e., 'HBIM', 'BIM', 'architectural design', 'point cloud', and 'laser scanning') with their occurrences. The average link strength is a metric reflecting the links between the nodes in the network. In bibliometric networks, links are typically co-citation or co-occurrence relationships between publications, authors, or keywords. The link strength represents the strength of the relationship between two nodes. The average total link strength of 74.8 indicates that, on average, the strength of the links between the nodes in the network is relatively high. Average occurrence and maximum occurrence reflect the frequency with which a node occurs in the publications included in the network. The occurrence of a node represents the number of publications in which the node appears. The average occurrence of 11.5 indicates that, on average, the nodes in the network appear in around 11 publications. The maximum occurrence of 35 indicates that there is at least one node, in this case 'HBIM', in the network that appears in 35 publications, which is relatively high. Figure 9 demonstrates that the average year of publication of the most cited keywords was between late 2019 and early 2021, which is in line with the findings shown in Figure 5 for the year of publication of the selected articles. The colors in this figure refer to the year in which the cited keywords were used in publications. It appears that some keywords were used more frequently in 2019, such as 'TLS' and 'Cultural Heritage', while others were mentioned more often since 2021, such as 'BIM' and 'HBIM'.

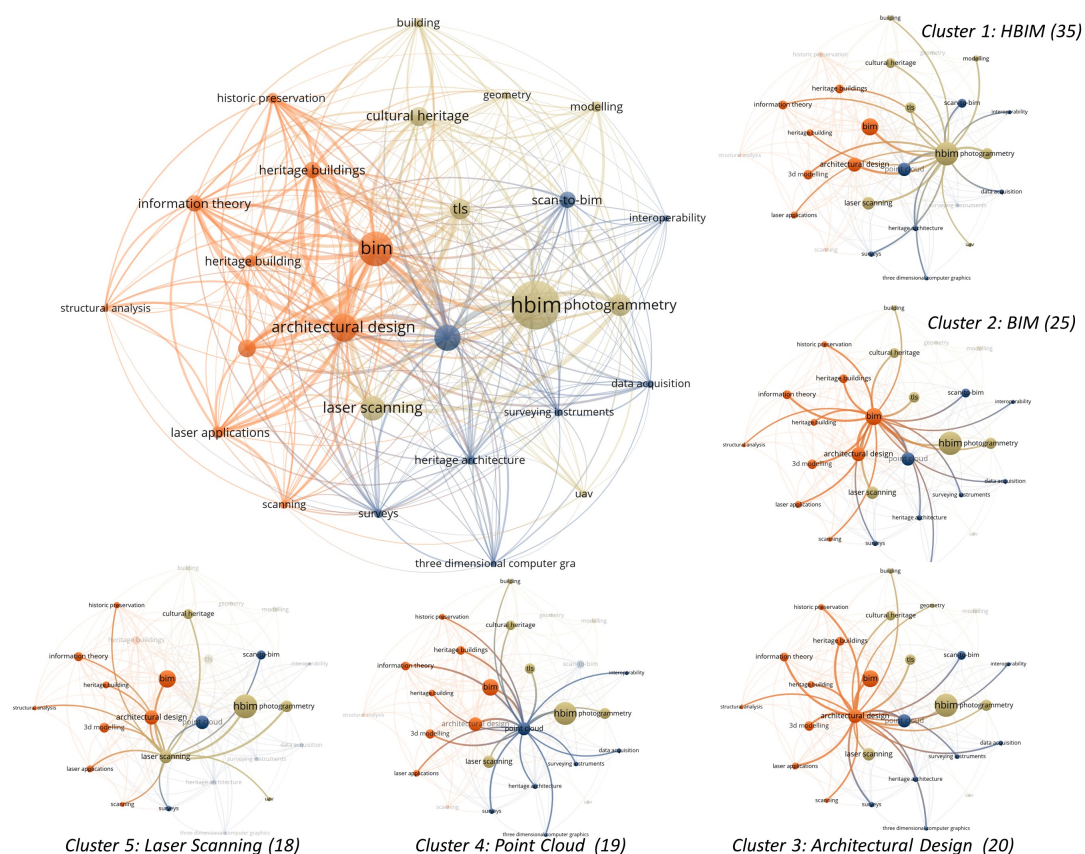


Figure 8. Network visualization of the most common keywords (five occurrences or more) and clusters of the five most cited keywords.

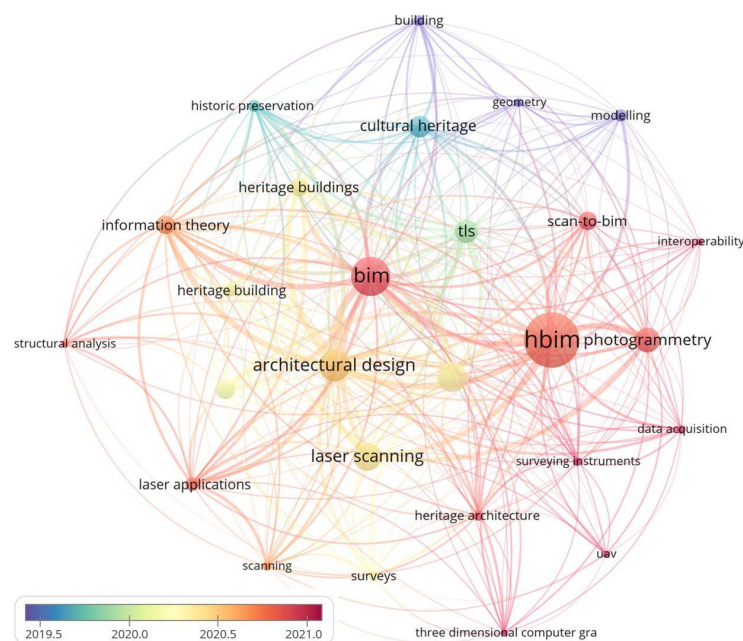


Figure 9. Distribution of the most frequently occurring keywords (five occurrences or more) over time.

2.3.5. Publications by Study Type

The researcher also categorized the final selection of the 58 articles into four types of study: literature review, case study, design and development, and evaluation and assessment papers [39]. Most of the articles are case studies, with a total of 38 (66%); the second-largest category, design and development, has seventeen (29%); literature reviews and evaluation and assessment only have two (3%) and one (2%), respectively.

3. TLS Survey for HBIM

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

The literature points out that TLS is one of the most important techniques for the research of heritage assets and has become the mandatory technique for HBIM development [40]. The biggest advantages of TLS for HBIM over other techniques include its high accuracy [41,42], fast speed for the amount of data captured over the time spent [43], and thoroughness of non-invasive object capture [44,45] that does not require a returned field survey [46]. As mentioned in Al-Bayari and Shatnawi's study [47], 25–30% of the time for field surveys could be reduced using TLS to capture and document heritage.

3.2. Challenges and Limitations of TLS for HBIM

On the other hand, TLS has several drawbacks when being used for data acquisition for HBIM. It is expensive. A new laser scanner can easily cost USD tens of thousands [46]. It requires specialty software, substantial hardware, and highly trained professionals to process and handle the scan data [41,48]. A TLS survey can also be time-consuming [49], especially when it is used to capture large and complex heritage sites and is sensitive to the environment such as lighting conditions, dust, fog, rain, etc. [46]. The time required for a TLS survey varies depending on the complexity of the area of interest, the accuracy required, and the processing software used. Factors such as data acquisition time, environmental conditions, and data processing time can all contribute to the overall time required for the survey:

- **Data acquisition time:** TLS involves capturing a large number of high-density point clouds from various viewpoints to cover the entire area of interest. This process can take a considerable amount of time, especially for large or complex areas where multiple scanning setups are needed;

- Environmental conditions: Environmental conditions can also impact the survey time. Factors such as weather conditions, sunlight, and shadowing can affect the quality of the data collected, which may require additional scanning time to compensate;
- Data processing time: Once the data is acquired, it needs to be processed to generate a usable point cloud. Large datasets with high point densities can take a long time to process, which can contribute to the overall time required for the survey.

Shiny/reflective, black, and transparent surfaces can also be troublesome. TLS is unable to capture objects that are hidden or not in line-of-sight [50]. Capturing accurate color is another challenge for the majority of the LiDAR scanners that are used for studying heritage [12].

Some of the articles selected for this study revealed specific limitations of using TLS for data acquisition and challenges of processing the TLS scan data for HBIM development, as shown in Table 4.

Table 4. Limitations and challenges of TLS mentioned in the selected articles for this study.

Category	Limitations or Challenges of TLS	Articles
Data Acquisition	Limited range of TLS: most roofs and upper building facades were out of range of TLS. Other RC technologies, such as UAVs, had to be used to compensate.	[12,44,51–57]
	Poor results of capturing colors with the camera mounted on the scanner in varying lighting conditions are due to time gaps between the successive scans.	[12,58]
	The distance from the scanner to the scanned object greatly influences the quality of the captured point cloud.	[58]
	Scanners were used in dangerous areas.	[59]
	Maintain the stability of the scaffolding that was set up for scanning.	[59]
	It is impossible to perform a static laser scanning acquisition in some areas due to safety issues. Therefore, a handheld Mobile Mapping System (MMS) was used to capture those areas.	[59]
	Lack of capability to capture images using the scanner.	[60]
	Had to dismantle the building to scan the bracket set with hidden geometry.	[61]
Data Processing	Combine multiple point cloud datasets created from different approaches (e.g., TLS and aerial photogrammetry) into one single point cloud.	[12,44,46,48,52–54,57]
	Number of software applications required to process the scan data	[22,50,57,62–64]
	Processing TLS scans is time-consuming.	[22,65]
	Incorporation of TLS scans from two separate campaigns that were 10 years apart.	[66]

To overcome these limitations, HBIM practitioners usually utilize other RC techniques to supplement TLS and acquire data for HBIM development. These techniques include analog survey, manual measurement, mobile scanners, and Structure from Motion (SfM) or photogrammetry [12]. More details about combining multiple data acquisition techniques for HBIM are addressed in Section 3.6.

3.3. Planning for the TLS Survey

A successful TLS survey begins with a good plan to guarantee the maximum coverage of the relevant surfaces, reduce self-occlusions, and ensure a sufficient density of the point

cloud with the least amount of scans [51]. The quality of the data obtained from laser scanning might be influenced by several different factors, including:

- The expectation of the data to be collected, e.g., accuracy and density of the point cloud, coverage of the structure [67];
- The characteristics of the heritage to be captured, e.g., location, size, accessibility, complexity, occlusions and inaccessible areas; and the time constraints of the survey [68];
- The atmosphere during the TLS survey, e.g., weather conditions such as humidity, temperature, and visibility [69];
- The specification and limitation of the TLS equipment, i.e., scanning range, speed, scan-station setting up requirements, and the requirements for scanning targets [51].

One of the common mistakes for TLS data acquisition is “over scanning”, which can lead to long hours in the field and unnecessary extension of the registration process of scans in the postprocessing phase [46]. A scan position layout plan developed during site visits prior to scanning is a very efficient way to optimize the number of scan positions for saving time and obtaining good coverage [47,63,70]. Another important factor for determining scan positions is to ensure proper connections between each of the rooms, spaces, floors, outdoor, and indoor environments. These precautions are vital to guarantee that when the raw scan files are processed, the scan processing software can recognize corresponding features as well as properly align and connect each of the scans [68]. Project documentation, such as a floor plan [46] or Google Maps [63], can be used to draw the scan layout plan. To obtain data with higher accuracy, ground control points (GCPs) or scan targets (e.g., spheres or checkboards) are often used for TLS surveys, so they need to be included in the scan plans as well [42,54,71]. Figure 10 shows a proposed scan position plan for a project to capture a historic museum in Alabama, USA, using a Leica ScanStation C10 scanner.

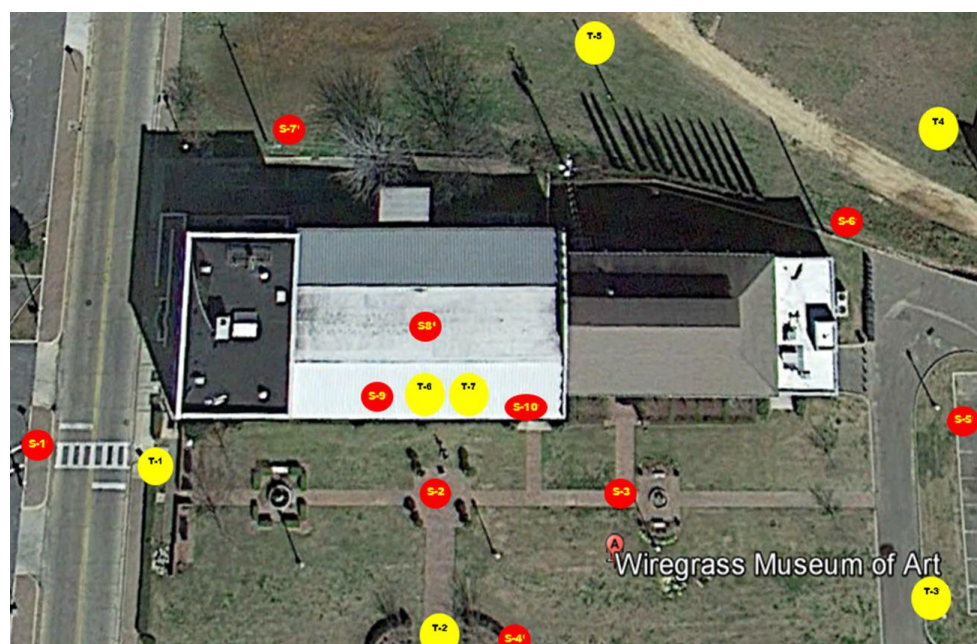


Figure 10. A sample “Scan Position Layout Plan”. Red circles represent proposed scan locations, and yellow circles represent scan target locations.

Other aspects to be considered during TLS survey planning include the expected coverage of the survey (i.e., interior, exterior, or both), other data acquisition technologies and techniques that may be involved [52,72], the capture of color [40], and safety [59]. Column (b) in Table 5 shows the coverage (e.g., exterior façade only, interior façade only, or both exterior and interior) of the TLS scans for the studies included in the 58 selected publications.

Table 5. Information on data acquisition techniques and scan data processing of the HBIM projects in the included publications.

Article	Country of Heritage Site	Year of Survey	(a) TLS Scanner Brands				(b) TLS Coverage	(c) # of Scans	(d) Control Reference		(e) Other RC Technologies Used for Data Acquisition					(f) Scan Processing Software				(g) # of Points Captured (million)
			FARO	Leica	Trimble	Other			GCP	Target	SfM	UAV	T.S.	GPS	Other	FARO SCENE	Leica Cyclone	Autodesk ReCap	Other	
[44]	Italy	2012 and 2017	✓				Ext. and Int.	58			✓	✓	✓						3DReshaper	
[47]	Jordan				✓			11	✓	✓			✓							
[48] a	Saudi Arabia			✓				123	✓		✓	✓	✓	✓						10,600
[12] b	Saudi Arabia			✓					✓	✓	✓	✓	✓	✓						
[73]	Spain	2019		✓			Ext. and Int.	7										✓		
[74]	Spain	2016		✓														✓		
[58]	Spain	2021		✓									✓					✓		
[75]	Saudi Arabia			✓			Ext. and Int.	100+	✓	✓			✓					✓		
[56]	Italy		✓																✓	
[62]	Italy		✓													✓			✓	
[59]	Italy	2020	✓				Ext. and Int.	65	✓				✓		Handheld scanner					
[51]	Italy		✓					213			✓	✓	✓						✓	
[22]	Italy	2021	✓				Ext. and Int.		✓		✓	✓	✓			✓			✓	
[65]	Italy	2019	✓													✓				
[76] a	Italy		✓																	
[77] b	Italy		✓					182			✓		✓							
[78]																				
[52]	Italy	2021					Ext. and Int.	47	✓	✓	✓	✓	✓							
[64]	Italy	2018	✓				Ext.	3			✓	✓							3D Zephyr	
[79]	Italy	2020		✓							✓	✓							✓	
[72]	Brazil	2016		✓							✓							✓		
[53]	Spain	2019	✓				Ext.	107		✓	✓	✓	✓	✓		✓		✓		182
[45]	Spain	2019	✓				Ext. and Int.	108		✓		✓		✓		✓		✓		214
[69]	Poland	2017		✓			Ext. and Int.	7		✓										
[66]	Portugal	2021	✓					3			✓				Three-dimensional photo, Ground Penetrating Radar (GPR); X-ray and SEM + EDX tests					1345
[80]	Italy	2018	✓				Ext.			✓	✓		✓							
[81]	China	2019			✓		Ext.	35		✓	✓	✓						✓	Trimble Realwoks	
[41]	Spain	2020		✓			Ext.				✓	✓			Thermal images		✓		PolyWorks	
[14]	Egypt	2019				Z + F IMAGER		160					✓					✓		
[54]	Portugal	2019	✓				Ext. and Int.	95		✓			✓	✓		✓				

Table 5. Cont.

Article	Country of Heritage Site	Year of Survey	(a) TLS Scanner Brands				(b) TLS Coverage	(c) # of Scans	(d) Control Reference		(e) Other RC Technologies Used for Data Acquisition					(f) Scan Processing Software				(g) # of Points Captured (million)
			FARO	Leica	Trimble	Other			GCP	Target	SfM	UAV	T.S.	GPS	Other	FARO SCENE	Leica Cyclone	Autodesk ReCap	Other	
[49]	Italy	2019		✓			Ext. and Int.	69			✓						✓	✓		1200
[50]	Italy	2019	✓				Ext. and Int.	64								✓				1014
[71]	Portugal	2019	✓				Ext. and Int.	8		✓									CloudCompare	
[42] a	Spain																			
[35] b	Spain			✓			Ext. and Int.	15	✓				✓	✓			✓			103
[82]	Spain	2018		✓													✓			
[40] c																				
[5]																				
[83]	Italy	2018		✓			Ext. and Int.	256			✓				3D photo, wearable laser scanner					
[63]	Vietnam	2021			✓		Ext. and Int.	162										✓	Trimble Realwoks	
[84]	Spain	2018		✓			Ext. and Int.													
[85]	Spain										✓									
[46]	Slovakia		✓				Ext. and Int.	141		✓	✓	✓				✓				
[57]	Italy		✓				Ext.	3										✓	3DF Zephyr	
[70]	Italy	2020		✓				3	✓								✓			
[6]	Spain	2018		✓			Ext. and Int.	99			✓		✓					✓		
[43]																				
[68]	Portugal	2019	✓				Ext. and Int.	144	✓		✓	✓		✓	GPS	✓		✓		
[86]	Spain	2016		✓			Ext. and Int.	27		✓			✓	✓	GPS		✓		3DReshaper	
[55]	France	2015	✓				Ext. and Int.	40		✓						✓			3DReshaper	839
[87]	Italy	2017	✓				Ext. and Int.	14												
[60]	Cyprus					Surphased	Ext. and Int.	73			✓							✓	JRC Reconstructor	2080
[88]	Portugal							10											CloudCompare	
[89]	Poland	2016				Z + F IMAGER	Ext. and Int.	36		✓							✓			
[90]	China	2021	✓				Ext. and Int.	25			✓	✓	✓					✓		
[91]	Italy	2020					Ext and Int	24	✓							✓		✓		
[61]	S. Korea														Handheld scanner			✓		
[92]	Algeria	2020	✓				Ext. and Int.	188		✓						✓		✓		

3.4. Static TLS Devices

A total of 50 static TLS scanners from five different brands are explicitly mentioned in the selected publications, as shown in Figure 11. FARO® and Leica® dominate the list, supplying 24 and 20 of the scanners, respectively. Leica ScanStation C10 was one of the most widely adopted TLS scanners between 2015 and 2018 due to its high accuracy and long range. However, FARO Focus 3D series scanners started taking over in the late 2010s because of their high mobility and affordability. The FARO Focus Premium [93], Leica BLK360 [94], and Trimble X7 [95], as shown in Figure 12, are all considered to be the current state-of-the-art TLS scanners. All are lightweight, extremely fast, and have the capability of on-site registration. The brands of the TLS scanners used for HBIM projects in the included articles are shown in column (a) in Table 5.

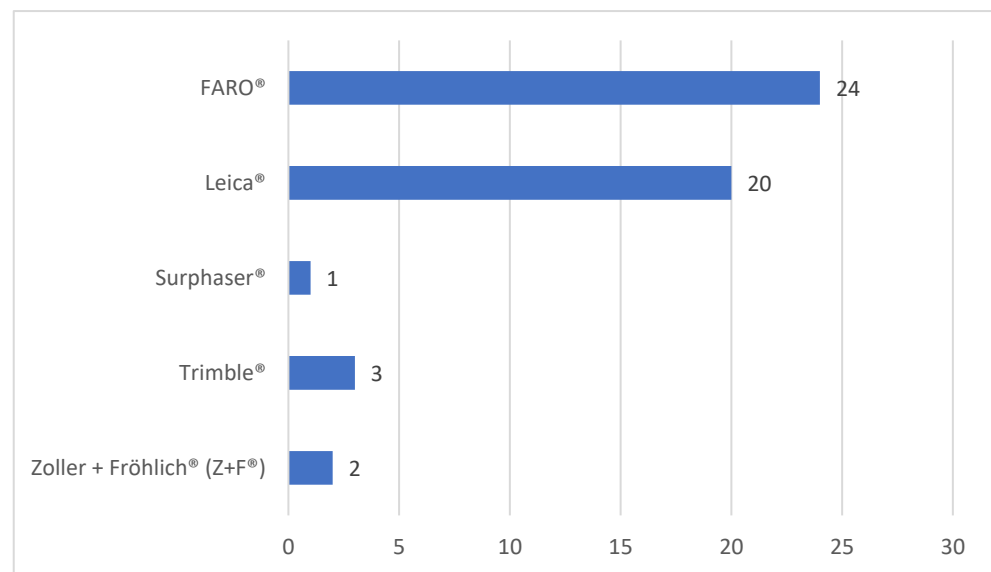


Figure 11. Occurrences of TLS scanner brand names listed in the included publications.

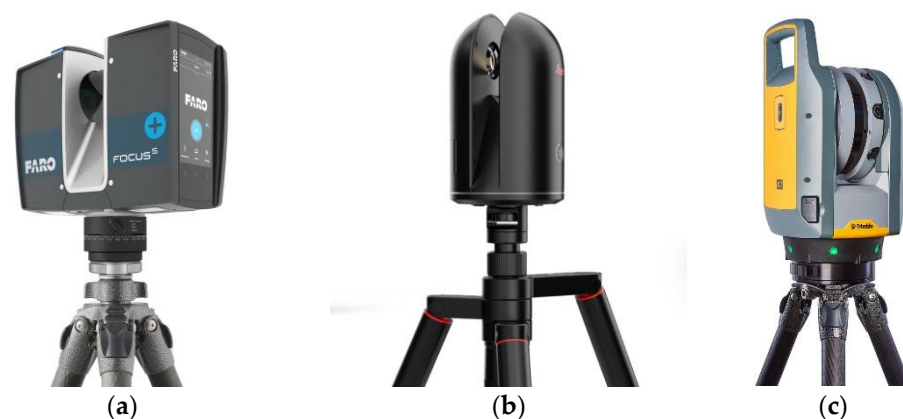
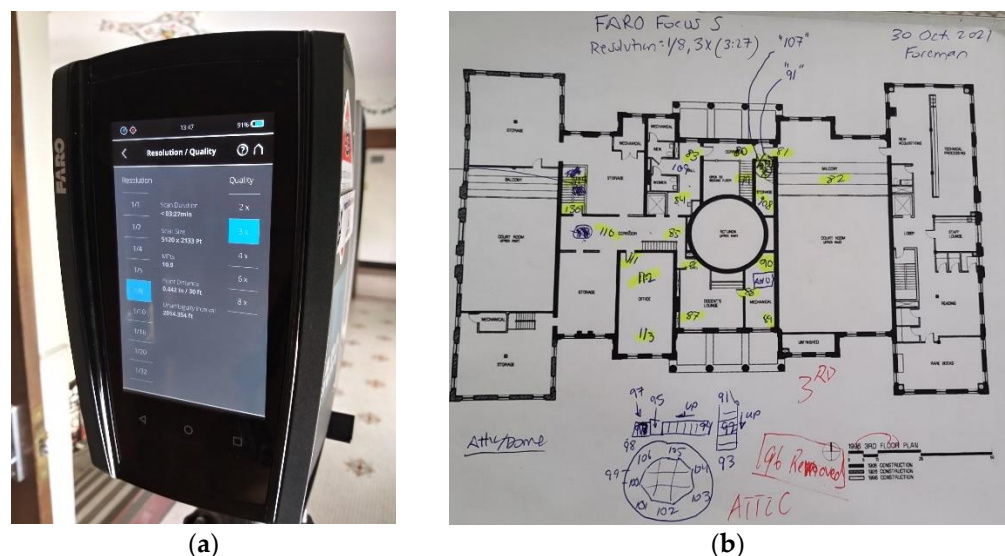


Figure 12. Three of the latest state-of-the-art TLS scanners: (a) FARO Focus Premium [93]; (b) Leica BLK360 [94]; and (c) Trimble X7 [95].

3.5. TLS Survey

The scanners used for TLS surveys offer different options for scan resolution (Figure 13a). Scan resolution indicates the number of points captured per unit on a flat surface [58]. Scan resolution refers to the level of detail captured by the laser scanner during the scanning process and is an important consideration when selecting the appropriate settings for a particular scanning application. The scan resolution setting determines the density of points that the scanner will capture and create a point cloud from [69]. Several factors

can impact the scan resolution, including the specification of the scanner, distance to the object, scan speed, reflectivity of the object, and environmental factors [69]. Choosing a scan resolution setting for TLS surveys depends on the specific application and the level of detail required. Depending on the site condition, the characteristics of the heritage, and time constraints, many HBIM practitioners choose to stay with the same scan resolution setting, normally an “intermedium level”, throughout the entire TLS survey for convenience and to save time. On the other hand, it is not unusual to use a combination of several resolution options to capture important facades at a high resolution and other areas at a medium or low resolution [6]. Maintaining field notes of the scan route to corroborate scan locations is essential for successful scan data postprocessing, as a project will rarely go as planned. Adjustments will be made, and more scans may be added to overcome occlusions or improve coverage and scan overlapping. All these changes to the original scan plan should be documented in the file notes. To improve the scan accuracy and help scan registration during postprocessing, reference points, such as GCPs or scan targets (e.g., spheres or checkboards) [46,52], are sometimes used, as shown in Table 5, Column (d). It is important to keep a record of the locations of these reference points in the field notes (Figure 13b).



3.6.1. SfM/Photogrammetry

TLS and photogrammetry can be integrated by exploiting the advantages of one over the other [64]. TLS is a more expensive technology in comparison with photogrammetric surveys, and higher knowledge is required to perform laser scans than to take photographs for 3D photoreconstructions [68]. On the other hand, photogrammetry is more cost-effective, more flexible, faster, and capable of collecting accurate and quality data for complex objects [48]. The benefit of integrating these two technologies is to take advantage of the TLS's capability to acquire an accurate and dense point cloud and the flexibility of photogrammetry to operate even in exceptional conditions.

Combining TLS and photogrammetric techniques has proven to be the most effective way to record large and complex heritage sites in applications for documentation, structure assessment, texture mapping, feature extraction, etc. [12]. Twenty-three out of the fifty-eight articles included the capture of photogrammetric point clouds and combining them with TLS point clouds to fulfill the data acquisition task. In their research, de la Plata et al. [53] used a DSLR (digital single lens reflex) camera to generate high-density terrestrial photogrammetric point clouds of the interior surfaces of the buildings and TLS to capture exterior facades. Costantino, Pepe, and Restuccia [64] deployed a similar approach, using TLS to survey the external façade, a DSLR camera for inside, and a camera mounted on an unmanned aerial vehicle (UAV) for the upper part of the building. The integrated UAV with photogrammetric technology, as seen in Figure 14, offers practitioners the capacity to capture built heritage at higher elevations [96].

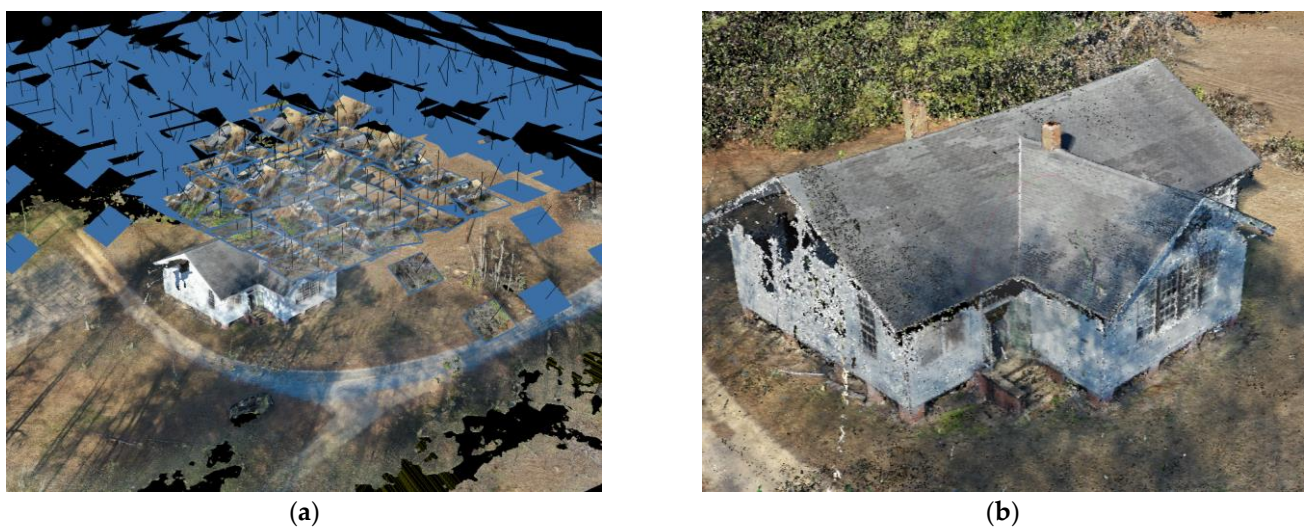


Figure 14. UAV photogrammetry: (a) UAV photogrammetry schematic and (b) UAV photogrammetric point cloud.

3.6.2. Mobile Handheld Scanners

Two reviewed articles indicated the utilization of hand-held MLS scanners to supplement static TLS surveys. A mobile handheld scanner supported by photogrammetry or LiDAR technology can be used to capture some hard-to-reach small spaces or to record fine details. To scan the unsafe areas that were inaccessible by using their tripod-based FARO Focus 3D scanner, Banfi et al. [59] used a handheld Mobile Mapping System (MMS), a GeoSLAM ZEB-HORIZON, to perform the work. Nieto-Julian et al. [84] used a Leica ScanStation C10 scanner to capture walls, columns, ceilings, beams, and roofs alongside a handheld Artec MHT 3D optical scanner (OS) to record the complex column capitals of a historic building.

3.6.3. TS and GPS

TS and GPS are used to establish control points (CPs). CPs can be used to integrate point clouds acquired through different technologies (e.g., TLS and photogrammetry) or to check the quality and accuracy of the TLS scan data. Banfi et al. [59] used a Leica TPS1200 total station to setup eight CPs (four inside and four outside), and then used them to successfully combine the two point clouds captured with a TLS scanner and a handheld scanner.

4. TLS Scan Data Processing

4.1. Scan Processing Software

Most TLS surveys capture multiple scans, as shown in Column (c) in Table 5. It is a common practice for HBIM practitioners to use the LiDAR scanner manufacturer's own software to process the captured raw scan data, as shown in Column (f) in Table 5. For instance, FARO SCENE [97] is mentioned in 12 articles as the software chosen for processing, colorizing, registering, cleaning, and exporting the original scans captured by a FARO® Focus 3D scanner. Leica Cyclone [98] is also listed in 12 articles for handling scans taken by a Leica scanner. However, as a powerful third-party RC data processing and manipulation software, Autodesk ReCap Pro® [99] was used in 15 of the included articles. The other scan data software programs mentioned are 3D Zephyr® software (two articles), CloudCompare® (two articles), JRC Reconstructor® (one article), and Trimble Realworks® (two articles). In each of the case studies examined in the selected publications, the researchers had to come up with their own choice of software programs for TLS data processing. This study has determined that the lack of a software suite that is compatible and capable of all the tasks required to process and manipulate TLS datasets for the development of HBIM is one of the main challenges for using TLS for HBIM [57].

4.2. TLS Scan Processing Workflow

Administering raw TLS survey scans for HBIM development includes three main steps: (1) scan registration, (2) point cloud data cleaning and optimization, and (3) point cloud dataset downsizing [69]. Scan data processing begins with scan registration. This step involves the alignment of scans into a single reference system to produce a unified point cloud of the entire heritage site. Scan registration is typically performed manually or automatically in pairs using pre-established targets (target-based registration) or homologous features (targetless registration).

After registration of the original scans, it is necessary to clean the point cloud to ensure that the resulting model is accurate and useful for further analysis and documentation. Point clouds are essentially a collection of data points in 3D space that represent the geometry of a scanned object or environment. However, these data points can be affected by a number of factors, such as sensor noise, reflective surfaces, and occlusions, resulting in inaccuracies and inconsistencies in the point cloud data. Cleaning the point cloud involves removing any noise or unwanted data points that may have been captured during the scanning process, as well as correcting any errors or inaccuracies that may have occurred. This process typically involves a combination of automated and manual techniques, such as filtering, segmentation, and classification, to identify and remove unwanted points [68].

As shown in Column (g) in Table 5, TLS point clouds contain millions or sometimes billions of points and are massive in file size. However, more points would not always mean a better dataset for HBIM development. The number of points should be reduced, but only to the extent that no important information about geometry is lost. The ability to model building elements for HBIM with the use of a 3D point cloud depends on the cloud resolution, which is defined by the distance between the points or the density of points that the scanner will capture and create a point cloud from [69]. An approach deployed in the literature to reduce the number of points and subsequently decrease the scan data file size is subsampling [66]. This process can be done using software programs such as Autodesk ReCap Pro [74], CloudCompare [71], FARO SCENE [22], and Leica Cyclone [41],

which allow the users to subsample a point cloud by increasing the distance between the points. This technique can dramatically reduce the point cloud file size and increase its manageability with computer systems for model development [74]. Figure 15 demonstrates the steps of processing TLS scans.



Figure 15. TLS scan processing: (a) the “raw” TLS point cloud captured with 341 scans shown in Autodesk ReCap Pro before cleaning (5600 million points; an 80 GB.rcp file in size) and (b) the cleaned, subsampled at 10 mm point distance, and unified point cloud (104 million points; a 2.2 GB.rcp file in size).

4.3. Integration of Multiple RC Point Clouds

As discussed in Section 3.6, the data acquisition of a heritage site for HBIM development often utilizes multiple technologies and techniques; therefore, the survey may end up with more than one-point clouds of the same structure. The studies in the 23 articles included in this research captured at least one TLS point cloud and one photogrammetric point cloud. It is necessary to integrate (or fuse) these separate point clouds into one that could provide the final conclusions and the overall vision for modeling [45]. The fusion of two individual point clouds can be conducted using Iterative Closest Point (ICP), an algorithm that minimizes the difference between two point clouds, transforms the source points, and reassociates them [81]. One of the most challenging aspects of point cloud integration is aligning all point clouds and converting them into the same coordinate system [48]. A common approach that was identified in the literature to overcome this hurdle was using the established GCPs as a shared reference in all point cloud data for alignment and scaling [22]. Several software platforms were used to perform point cloud fusion, including CloudCompare [46], Autodesk ReCap Pro [65], and Agisoft Metashape [60].

4.4. Evaluation of Point Cloud Data

Resolution (or accuracy) and quality are the two most important parameters for the 3D point cloud data [46], because they are decisive factors for the level of detail and accuracy of the HBIM models developed from them [5]. The assessment and verification of the point clouds are urgent tasks for many researchers. In a study conducted by Ariza-López et al. [58], a method was created and tested for using the ISO 19157 framework to establish quality specifications for a TLS point cloud that was captured for developing the HBIM of a historic bridge. In another article, Barrile and Fotia [65] presented a procedure that allowed them to verify the quality of the TLS surveys in order to achieve a better integration of different point clouds.

5. Discussion

Static Terrestrial Laser Scanning (TLS) has become a mandatory tool for data acquisition for HBIM development. The benefits of using TLS for HBIM include high accuracy

and comprehensive coverage. However, there are also some drawbacks to using TLS, such as the substantial amount of initial investment required for equipment and software, the time-consuming process when capturing a large or complex project, and the sensitivity of TLS to the environment. To overcome these limitations, practitioners can implement a well-developed TLS survey plan and adopt other RC (Reality Capture) technologies to assist the data acquisition process.

A well-thought-out TLS survey plan can ensure maximum coverage of aqueduct surfaces with sufficient point density, reduce the occurrence of self-occlusions, and minimize the time spent on-site. TLS is normally used with other RC technologies, especially SfM (Structure-from-Motion) or photogrammetry. Integration of TLS and photogrammetry allows practitioners to take advantage of TLS's high accuracy and photogrammetry's flexibility. In terms of the choice of TLS scanners, FARO and Leica are the two dominant brands, with each holding almost half of the scanner market share.

A typical workflow to process the TLS scan data includes three steps: scan registration, point cloud data cleaning and optimization, and dataset downsizing. While reviewing the selected literature on TLS data processing and registration software, it was revealed that FARO SCENE and Leica Cyclone are among the most popular choices. Autodesk ReCap Pro is also a common choice, but it is mostly used for point cloud cleaning, filtering, and downsizing.

In order to ensure that the point cloud datasets can be effectively used for modeling in BIM platforms (such as Revit or ArchiCAD), the enormous point cloud files have to be downsized by reducing the point density and increasing the distance between the points while still maintaining the information and integrity of the important geometry in the point clouds. Most of the studied HBIM cases in the literature also used other RC technologies for data acquisition, especially photogrammetry; the data processing in these cases involved the fusion of multiple point clouds into one. To achieve this, the two separate point clouds are aligned and merged into the same coordinate system using the ICP (Iterative Closest Point) algorithm or with the assistance of pre-established reference points (i.e., GCPs). Autodesk ReCap Pro and an open-source software named CloudCompare are the leading software platforms for this task. The final step of TLS scan data processing is evaluating the accuracy and quality of the point cloud data.

6. Conclusions, Knowledge Gaps, and Research Limitations

Heritage Building Information Modeling (HBIM) plays a vital role in heritage documentation, conservation, and management, with Terrestrial Laser Scanning (TLS) emerging as an indispensable tool for data acquisition in this area. This research, based on a systematic review of 58 peer-reviewed journal articles published in English between 2012 and 2022, offers a comprehensive overview of the current state-of-the-art in the application of static TLS for HBIM development and has identified the existing knowledge gaps in this domain.

State-of-the-art static TLS is used for HBIM development. The review highlights that the integration of TLS into HBIM workflows significantly improves the accuracy, efficiency, and reliability of data collection and 3D modeling for cultural heritage sites [67,69]. The incorporation of high-resolution point cloud data derived from TLS has allowed researchers and practitioners to capture complex geometries and structural details, leading to more accurate and detailed HBIM models [57,63]. Furthermore, the combination of TLS with other technologies, such as photogrammetry, has resulted in more robust and comprehensive datasets for the development of HBIM models [56,78].

Knowledge gaps in the subject matter. Despite the advancements in TLS for HBIM development, several knowledge gaps have been identified in this study. These gaps offer opportunities for future research and innovation:

- The lack of guidelines for data acquisition for HBIM programs is a significant challenge that must be addressed. The lack of standardized methodologies and protocols for the integration of TLS data into HBIM models hinders the adoption and implementation

of these technologies in the cultural heritage domain [86]. Practitioners often have to create their own methods to capture the existing condition of the built heritage based on the project's characteristics, available resources, and their own experiences and knowledge. A clear guideline covering the planning, implementation, and data processing and transferring can help simplify the process and lower the cost, and it can also help practitioners establish their data acquisition methodology in line with the Level of Development (LOD) of the proposed HBIM model;

- The development of HBIM from TLS point cloud data mainly remains a manual process that requires significant effort. Efficient and accurate processing and integration of large and complex datasets derived from TLS and other sources remain a challenge [85]. Developing automated and semi-automated techniques for data processing, segmentation, and feature extraction can significantly reduce the time and resources required for capturing data on the existing condition of built heritage and creating the models, and contribute to streamlining the overall HBIM development process;
- The under-utilized capacity of TLS for long-term monitoring and change detection: While TLS has been widely used for the initial documentation and 3D modeling of heritage sites, its potential for long-term monitoring, change detection, and condition assessment remains underexplored [60,82]. Future research can focus on developing methodologies and tools for the systematic use of TLS data in monitoring and assessing the conservation status of heritage structures over time.

By addressing these knowledge gaps, future research can further improve the applicability of TLS in HBIM development, ultimately contributing to the preservation and management of our shared cultural heritage. In summary, this study not only provides a comprehensive overview of the state-of-the-art of TLS for HBIM development but also highlights the critical areas for future research and innovation in the field.

This research has some limitations. The included publications were extracted from two databases based on specific keywords and restricted to journal articles written in English, which does not cover all published data related to the discussed topic. It has been discovered by the author that the vast majority of these publications originate in Italy (twenty-nine), Spain (seventeen), or Portugal (six). Therefore, it is reasonable to assume that there are many studies related to the discussed topic published in those countries' native languages that were excluded from this study.

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