The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage

Lovell, Lucy; Davies, Richard; Hunt, Dexter

DOI:
10.3390/heritage6100350

Citation for published version (Harvard):
Lovell, L, Davies, R & Hunt, D 2023, 'The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review', *Heritage*, vol. 6, no. 10, pp. 6691-6717. https://doi.org/10.3390/heritage6100350

heritage

MDPI

Review

The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review

Lucy J. Lovell *, Richard J. Davies and Dexter V. L. Hunt

School of Civil Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK; r.j.davies.1@bham.ac.uk (R.J.D.); d.hunt@bham.ac.uk (D.V.L.H.)
* Correspondence: ljl848@student.bham.ac.uk; Tel.: +44-7780720439

Abstract: Historic Building Information Modelling (HBIM) is the application of BIM, a digital modelling and information management technique, to assets of historical significance, otherwise known as Cultural Heritage (CH). The adoption of BIM for CH is justified by government mandates and acknowledgement by leading heritage institutions that there is a need to utilise digital tools for heritage management. This paper establishes the current state of HBIM implementation within CH as well as research trends to date via a review of the existing literature. Geometric modelling was found to be the topic of very early research into HBIM, with particular focus given to improving the accuracy and efficiency of modelling. Thus, methods for improving modelling were evaluated. HBIM as an information management tool is discussed including the issues encountered, such as data storage and insufficient existing tools, as well as key information requirements proposed in the literature. An evaluation of key HBIM case studies found limited evidence of the created models being used in practice and an overall lack of consideration of the information needs. It was determined that the implementation of HBIM is limited by a lack of defined information requirements, and standardisation regarding the method of implementation.

Keywords: HBIM; cultural heritage; BIM; built heritage

check for updates

Citation: Lovell, L.J.; Davies, R.J.; Hunt, D.V.L. The Application of Historic Building Information Modelling (HBIM) to Cultural Heritage: A Review. *Heritage* **2023**, *6*, 6691–6717. https://doi.org/10.3390/heritage6100350

Academic Editors: Mila Koeva, Mauro Lo Brutto and Marcello La Guardia

Received: 24 August 2023
Revised: 2 October 2023
Accepted: 7 October 2023
Published: 12 October 2023

1. Introduction

1.1. Historic Building Information Modelling

Building Information Modelling (BIM) is a standardised procedure (ISO 19650) [1] developed by the Architecture, Engineering and Construction (AEC) industry for the digital management of assets. BIM is the process of creating an intelligent 3D model of an asset which also contains extra information about 'objects' within the asset. This information includes geometric information (e.g., dimensions of a window) and non-geometric information (e.g., details of the materials that make up a structure, or manufacturers handbooks). Traditionally, BIM models are created for new build projects using construction drawings and are updated as the project progresses. Heritage or Historic BIM (HBIM) is an evolution of BIM, first suggested by [2], regarding assets of historical significance herein referred to as Cultural Heritage (CH). CH is defined by UNESCO as "artefacts, monuments, a group of buildings and sites, museums that have a diversity of values including symbolic, historic, artistic, aesthetic, ethnological or anthropological, scientific and social significance" [3]. Subsequently, this paper will use 'BIM' to refer to BIM for new assets only. Contrary to BIM, where the asset is built according to the model, an HBIM is retrospectively created from survey data and then enriched. By definition, CH is in the Operation and Maintenance (O&M) lifecycle phase, a phase already underrepresented by BIM standards [4] and further limited by ad hoc approaches to Facilities Management (FM) [5].

There is currently no standard for HBIM, nor comprehensive identification of the information requirements for HBIM. However, the justification for its adoption is two-fold. In 2016, the UK government mandated that BIM was required for all centrally funded projects and consequently many companies choose to implement BIM on all their projects regardless as it is increasingly becoming a client requirement. The UK BIM mandate does not distinguish between new build assets and assets of historical significance [5]. Furthermore, if correctly developed, HBIM could assist with the sustainable management of heritage for future generations. Ref. [6] suggests that effective management systems allow the coordination of activities from different stakeholders and also allow the allocation of resources, both of which are known functionalities of BIM. There is an argument that the subjective nature of heritage makes it unsuitable for BIM applications. However, the World Heritage List (WHL), an internationally respected convention managed by UNESCO, is a property-based convention [7], a format easily translatable to parametric BIM modelling. Ref. [8] successfully applied HBIM concepts to a UNESCO site in Marrakech, providing proof of concept. The barriers to HBIM include a lack of technical skills and existing culture for digitisation in the field of CH [9–11] as well as the associated costs of model creation [12]. A known benefit of HBIM is its ability to bring together multiple sources of disparate information [13]. However, the "current lack of appropriate information (regarding CH) provides both the need for HBIM and a barrier to it's adoption" [9].

The aim of this paper is to establish the current state of HBIM implementation within CH via a semi-structured scoping review. The objectives are:

- O1—Identify the literature regarding the current implementation of HBIM.
- O2—Review the identified literature and establish research trends and findings to date.
- O3—Evaluate the success of key modelling case studies.
- O4—Define the research gap and areas for future research.

1.2. Exisitng HBIM Reviews

There exists to date a number of literature reviews regarding HBIM; the majority of which identify and contain a considerable focus on the process of geometric data collection and modelling [14–17]. Thus, to avoid duplication of discussion, this paper will only provide an overview of geometric data collection and modelling techniques and will subsequently only discuss the most recent developments in this area. This will account for the changes in the available technology since the publication of existing reviews, which is particularly relevant for [15] who mention several emerging technologies which are now widely investigated (scan-to-BIM and augmented reality (AR)). Several reviews also discuss the capabilities of Geographic Information Systems (GISs) and their potential integration with BIM [14,18] as well as the use of a variety of open source software [19]. These are identified within the reviews as still emerging technologies which will be discussed in more detail in Section 4.2.2.

The requirements of the CH sector are only considered by a few reviews, with some disparity between them: Refs. [15,20] primarily focus on the use of HBIM for the dissemination of CH heritage to the public and the role of CH as a public resource whereas [16,21] consider conservation practice in regards to the analysis and interrogation of CH structures through historic documentation and condition data. Whilst differing, these approaches both reflect existing agreed international conventions regarding heritage management, with the latter reflecting the advice of the Venice Charter [22] and the former representing the cocreation principles championed by the Faro Convention [23]. Ref. [16] concluded that methods for storing the information required for the CH sector are lacking and, within reviews to date, the only notable consideration of this is [24] who reviewed ontology and external database methodologies for storing these data. Refs. [24,25] Given the apparent limited consideration of both information types and storage within the HBIM literature to date, concluded from published reviews, this paper will provide a detailed discussion in this area (Section 4).

Whilst limited in scope due to their exclusion of CH, the review of BIM for existing buildings conducted by [26] concludes that the application of BIM is limited by organisational, cultural and legal considerations. Existing guidance and advice regarding asset management suggests that these issues can be overcome by ensuring all future asset management approaches having consistent terminology and conceptual processes so even if a technology becomes obsolete, the information should be able to be maintained [27–29]. Ref. [29] claims it is a lack of standardised procedure which has most severely limited the field of asset management. Whilst it must be acknowledged that CH has unique complexities, the authors of this paper believe that CH should not ignore the recommendations of the asset management sector. As such, this review will consider the available HBIM standards.

2. Methodology

2.1. Literature Identification

The literature database 'Scopus' was used to search for the literature. The key word search was "HBIM" AND ("Cultural Heritage" OR "Built Heritage"). Papers written prior to 2015 were excluded from the initial search. This was for two key reasons. Primarily, it is evident that the majority of EU BIM mandates came into effect from 2015 onwards [30] and work before a national BIM mandate is typically undertaken by researchers, thus tends to be focused on theoretical uses as opposed to end user requirements. The second reason is that, due to the rate of BIM technology development, older works reviewed in the initial search experienced technological issues which are now obsolete. As an exception to the initial exclusion rule, papers considered key to the evolution of HBIM (prior to 2015), such as [2], which is the first to define HBIM as a concept, were included in the initial search and review. Following the initial review, additional key papers prior to 2015 [31–33] were then identified to remove any potential critical limitations to the work.

Some have sought to distinguish HBIM, referring to more modern CH, and Archaeo-BIM, referring to ancient CH. There is justification for this since the same procedure applied to newer CH has been shown to encounter fewer issues than with ancient heritage [34]. However, Ref. [35] suggests that there is a tendency within heritage professionals to favour ancient history over modern history which implies that a site that encompasses both or that has experienced changes over time may be insufficiently modelled by separating these two disciplines. As such, this paper will refer to BIM for all CH as HBIM.

2.2. Literature Review and Research Trends

The literature review has been grouped into common research trends. The order corresponds with the commonality of the topic, starting with the most common.

- Geometric Data Collection and Modelling (Section 3);
- BIM for Information Management (Section 4);
- Augmented Reality (AR) vs. Virtual Reality (VR) (Section 5).

2.3. Evaluating the Success of Key Case Studies

From the reviewed literature, an assessment criteria for HBIM models was created and applied to key case studies (Section 3.2.1). The assessment criteria evaluated the resulting model based on geometric characteristics (including accuracy and granularity of model objects) and the amount of information stored in the models. The relative importance of each characteristic for two common use cases (FM and Conservation) was defined based on a consensus inferred from the literature reviewed. Sixteen case studies were evaluated in this way.

2.4. Defining the Research Gap and Areas for Future Research

Section 6 considers the papers reviewed and discusses the areas key to the implementation of HBIM, which appear as yet undeveloped, and which will be subsequently addressed in future work by the authors. Conclusions are drawn in Section 7 regarding the research trends to date and the current implementation of HBIM.

3. Geometric Data Collection and Modelling

Geometric modelling was the initial challenge associated with HBIM [2]. Its importance is summarised by [36] which says it is "the basis upon which all other attributes are defined and created" and [37] which claims "adequate graphic documentation can be one of the most effective means for the conservation of cultural heritage".

3.1. Data Collection

The most common geometric data collection methods tend to be photogrammetry and Terrestrial Laser Scanning (TLS). Typically, TLS is used for obtaining data from the ground and Unmanned Arial Vehicles (UAVs), often equipped with photogrammetry equipment, are used for unsafe structures [35] or inaccessible areas [38–42]. Ref. [36] compared common geometric data collection methods and concluded that both TLS and photogrammetry have a high degree of accuracy, but TLS is limited by cost and mobility considerations. In some cases, traditional surveying techniques or previous surveys are utilized for model creation [43] but survey specification guidance [44] typically advocates the use of mass data techniques such as TLS [35,38–42].

There is no formal standard for the scan resolution, however Ref. [36] compared different resolutions against a range of accuracy criteria and concluded that a resolution of 2 cm or less should be used. Ref. [44] also provided guidance on surveying CH for Historic England. The number of scans is determined by site characteristics, as demonstrated by [45] who had to undertake more scans at varying distances from their temple case study because the curved surfaces of the columns caused data voids. Notable outliers are [46], who used Optical Scanning (OS) for detailed elements, and [47], who utilised a handheld laser scanner to collect data for a decorative surface. OS was used because the resolution was much higher than TLS but was limited by unfeasibly large file sizes.

Ref. [48] discarded their UAV data due to measured inaccuracies and [38,49] noticed distortions in their UAV images which questions the validity of the UAV data. Ref. [42] claimed to be able to create an HBIM using only UAVs that was accurate to approximately 0.16 m. Their work relied on an extensive archive of architectural drawings, rarely available for CH. Their earlier work, undertaken without archival documents, was only accurate to 0.36 m of the real condition [37]. This number is arguably too high for certain use cases for an HBIM such as aiding in renovation works. In contrast to this, Refs. [50,51] suggest that with sufficient geometric validation points, UAVs can be used as an accurate means of data acquisition. Ref. [51] established the geometric validation points using a total station. The additional use of equipment may negate the benefit of UAVs being cheaper than TLS [36].

There seems to be little consideration given to survey data after model creation and no apparent consensus on whether the data should be kept in the HBIM or discarded. However, the value of survey data as an information source must not be underestimated [52]. Using just the point cloud, Ref. [53] was able to conduct a material quantification of a cathedral, to estimate its value, and [54] was able to successfully model the behaviour of a tower during an earthquake. Similarly, Ref. [55] suggests that UAVs could also be used to improve visual inspection techniques. Ref. [56] was able to automatically identify damage to a structure from the point cloud. As demonstrated, maintaining up-to-date survey information within a HBIM, as opposed to considering it as just a tool for model creation, could enable new analysis that appears to be, as yet, underutilised. Given the consequent importance of survey data, Refs. [11,57] suggest the necessity of additional meta data about how, and by whom, surveys were carried out. This meta data about the surveys enable their validity to be ensured as part of any future quality assurance activities.

3.2. Modelling

3.2.1. Adapting Standard BIM Procedures to HBIM

Previous case studies have attempted to adapt BIM procedures to HBIM [58], but these have generally been considered failures because BIM was primarily created for construction use [59]. The clearest example is demonstrated by the definition of the Level of Detail (LOD), which refers to the required level of graphical representation. The highest LOD for BIM refers to as-built, the current state of CH, but achieving that LOD in a heritage project is not yet feasible. It could be argued that the only standard definition applicable to HBIM is the recent definition of the Level of Information Need (LOIN), new to ISO 19650 [60], which is composed of the level of model detail and level of associated information, positing that in some instances a low level of model detail can be mitigated via a high level of associated information [1].

Thus, HBIM projects often define new LODs [61–63] or entirely new categories more appropriate to CH [43,64,65]; notable examples include the Level of Knowledge (LOK) [43], Level of History (LoH) [60,66] and Grades of Generation (GoG) [65]. The frequent creation of new terminology and definitions lead [48] to suggest that HBIM workflows are only applicable to the existing asset and cannot be applied to a new addition. Despite the numerous attempts to redefine LOD for heritage, ISO 19650 [1] does not reflect any of the new proposed definitions so they will not be adopted herein. However, the burgeoning shift in practice from LOD to the arguably more useful LOIN suggests future developments to ISO 19650 and associated BIM standards may be able to encompass some of the requirements of the CH.

The only international standard for BIM is ISO 19650, which has already been noted to not encompass CH, and parallel national standards exist. The extension of standardised procedures to include HBIM have been suggested by some [67], but [63] is one of the only works that has actually attempted standardisation in practice. Its procedure had eight phases describing the expected information and suitable LOD at each stage. The limitation of the work is that it is primarily designed for refurbishments so five of the eight phases are 'interventions' which are conceptually similar to standard construction. In practice, the achievable LOD for HBIM is limited by data collection and modelling methodologies [45].

3.2.2. Modelling Methodologies

There are three common modelling approaches: using conventional BIM authoring tools, using alternative technology and creating bespoke technologies. These approaches are summarised in Table 1 and their respective advantages and disadvantages discussed in the subsequent paragraphs.

Table 1. Modelling approaches for HBIM.

Approach		Details
A. BIM authoring tools, e.g., Revit	A.1. Parametric	Most conventional BIM technique. Objects are created within a BIM authoring tool with editable parameters associated with them. Most additional information will be attributed to these parameters.
	A.2. Manual	When an object is unique to an asset, it can be modelled manually within BIM authoring tools similar in principle to Computer Aided Design (CAD) modelling. An example of this method is included in [68].
B. Alternative technologies	B.1. NURBS- Non-Uniform Rational B-Splines	A mathematical modelling technique able to model complex shapes by creating curves from control points.
	B.2. Mesh-to-BIM	Software models the entire surface by creating polygons linking individual points in a point cloud. The greater the number of polygons, the more detailed the surface.
	B.3. CAD	3D model objects are made in generic CAD software and then imported to a BIM authoring tool for enrichment
C. Bespoke Systems		Development of a new software, often when a model needs to fulfil a particular use case. There are only a few instances where this is applied.

A.1. Parametric modelling—Parametric BIM objects can be used multiple times with slight edits available and the objects can be added to object libraries to enable their reuse on other projects. Creating new detailed parametric objects requires a large amount of modelling skill and time. There is an argument that the subjective nature of heritage makes it unsuitable for parametric modelling but the WHL is a property-based convention [7], a format easily translatable to parametric modelling. Ref. [8] also successfully applied HBIM concepts to a UNESCO site in Marrakech, providing proof of concept.

A.2. Manual modelling—Modelling within the BIM authoring tool makes it possible to make edits in the future and other information, such as materials, can be added in a standard format. BIM authoring tools do not have as many built-in modelling tools as software created specifically for CAD. Since heritage is often architecturally complex, modelling requires greater time and technical skill [69] and BIM tools are not yet accurate enough for complex modelling [70]. They were also designed for new-build construction so will not model irregularities which are inherent to CH [9]. Objects modelled 'in place' cannot be reused on other projects.

B.1. NURBS—NURBS models are easy and simple to create as they are a well-established modelling technique. They can model complex shapes to a high degree of accuracy but they lack depth of information, a secondary modelling software is required and they cannot be edited once imported into BIM authoring tools [71].

B.2. Mesh-to-BIM—Mesh models are good representations of the point cloud [72] and, correspondingly, the surface of the structure leading [73] to remark that depending on the defined LOD for the project it may not be necessary to model, for a specific object, anything other than a surface mesh. Furthermore, Refs. [48,74] suggest that mesh-to-BIM is the best modelling technique for modelling changes over time because it is the most dimensionally accurate. Having a high-resolution mesh surface can make files unfeasibly large and having too many mesh polygons causes issues with other software such as VR technologies [50]. Mesh models cannot be edited once exported to BIM authoring tools [74].

B.3. CAD—CAD typically provides increased modelling capabilities compared to BIM software meaning that CAD tools are often better equipped to model complex and irregular shapes and, since they are not designed specifically for the modelling of buildings, they do not impose building logic to models. However, there is rarely a bi-directional link between software (unless they are from the same manufacturer) so edits made in one model will not be applied to the other. Objects made in the CAD software cannot be added to an object library and, like NURBS, cannot be edited in BIM tools.

C. Bespoke Systems—Capabilities can be tailored to a specific project's needs. However, specific advantages are unique to each system and rarely have universal benefits so cannot be generalised herein. A lack of standardisation results in interoperability issues with other tools. Furthermore, the complete separation of HBIM and BIM via a bespoke system fails to acknowledge the interaction of new and old construction. This interaction is compounded by [75] which utilised lighting simulations, an existing capability of BIM tools, to design a new lighting system for a basilica in Florence. Similarly, Ref. [53] utilised 'take off' capabilities in Revit to conduct a monetary valuation of a Cathedral in Mexico.

3.2.3. Evaluating the Success of Modelling Case Studies

The choice of modelling technique is often dependent on the intended use and as such there are many disparate approaches. In generic terms, model uses can be split into two categories: FM, which includes everyday operation of the asset and normal maintenance tasks, and conservation, which includes restoration and work to upgrade or modify an asset to survive changing conditions. It is evident that the usefulness of the resulting model for its intended task is dependent on three parameters: (i) its Geometric Accuracy (GA) (used here instead of LOD due to the current lack of standard terminology), (ii) the number of unique Identifiable Objects (IO) (sometimes referred to as granularity) and (iii) the amount of Associated Information (AI).

From the papers reviewed, a new assessment criterion for determining the usefulness of an HBIM case study was developed. The criterion involves a series of parameters (see Table 2) applied to an appropriate newly proposed equation (see Table 3) for the intended use. These equations for the apparent usefulness level for conservation and FM were derived according to the perceived importance of each parameter inferred from the papers read in this review. For instance, it is generally agreed that for FM purposes, a lower level of GA is required but AI and IO are key [4,10,11,76,77].

Table 2. Assessment parameters for determining the usefulness of key HBIM case studies.

Geometric Accuracy (GA); No. Identifiable Objects (IO); Associated Information (AI).	Intended Use (IU)	Successful Implementation for Intended Use (SIIU)
1 = Low *	C = Conservation	1 = No evidence given or unspecified use.
2 = Low **		
3 = Medium *	FM = Facilities Management	1.5 = Strong argument for why implementation will be successful (either from author or other work) but no evidence given.
4 = Medium **		
5 = High *	U = Unspecified	2 = Proven successful implementation for specific use.
6 = High **		

* Assumed, ** Proven.

Table 3. Equations for calculating the usefulness of the HBIM.

Usefulness Level for Conservation (ULC)		Usefulness Level for Facilities Management (ULFM)	
If intended use is C, ULC = ((GA + AI) × SIIU) + (0.5 × IO).	(1)	If intended use is FM, ULFM = ((IO + AI) × SIIU) + (0.5 × GA).	(3)
If intended use is FM or U, ULC = (GA + AI) + (0.5 × IO).	(2)	If intended use is C or U, ULFM = (IO + AI) + (0.5 × GA).	(4)

Geometric accuracy was evaluated by visually comparing how accurate the model was to the real condition. Below is an example of how GA would be assessed for the modelling of an ancient stone wall.

- Wall represented as a regular shape (cuboid) with no deviations. Representation symbolic of actual object = Low GA.
- Wall depicted using an irregular shape, somewhat representative of actual object = Medium GA.
- Wall depicted using an irregular shape, representative of actual object. There may be additional details in the model representing areas of decay, weathering or aging = High GA.

Whether the GA was 'proven' or 'assumed' refers to whether the paper makes reference to an explicit, usually numerical comparison of the deviation of the model from the real condition.

The number of identifiable objects were evaluated by visual assessment of the model granularity. Below is an example of how IO would be assessed for the modelling of an interior wall of a residential structure.

- Wall represented as a single object. No individual features including artistic features, functional elements (e.g., light switches) or distinct building phases are distinguished = Low IO.
- Wall depicted as several distinct objects or as one object with sections. Typically, some individual features will be modelled = Medium IO.
- Wall depicted as several individual objects. This could include modelling each individual structural component of the wall (e.g., individual bricks or distinct structural layers) or including the majority of individual features as separate objects = High IO.

Whether the IO was 'proven' or 'assumed' refers to whether the paper makes an explicit reference to the granularity of modelling.

The amount of associated information was evaluated by assessing the number of individual types or sources of information stated to be included in addition to the geometric model. Below is an example of how AI was assessed.

- None/minimal discussion of any additional information besides the model itself = Low AI.
- Some discussion of a few other information types or sources to be included with the model. Generic types or information sources may be given = Medium AI.
- Detailed discussion of numerous additional information types or sources to be included with the model. Often an explicit list is provided = High AI.

Whether the AI was 'proven' or 'assumed' refers to whether the paper makes explicit reference to the actual inclusion of additional information to the finished model.

Notable modelling case studies are discussed in Table 4. To avoid duplication of the results and ensure the concise evaluation of individual methodologies, the case studies included herein were those deemed to be a good representation of a distinct methodology (see unique feature column of Table 4 for details). The assessment criterion was applied informally throughout the review process to all case studies so conclusions drawn from Table 4 can be considered representative of the whole. The case studies are ordered according to their assessed usefulness for their intended use where the maximum achievable score was 27 but the highest score was 16. The main limitation seems to be that whilst papers appear to briefly mention the AI to be attributed to the model, there is apparently very little evidence of its detailed inclusion.

Table 4. Key HBIM case studies including their unique feature and usefulness assessment.

Case Study	Unique Feature	Details	GA	IO	AI	IU	SIIU	ULC	ULFM
1 [11]	Hybrid approach using mesh and parametric modelling	Ref. [11] suggested that the ideal modelling technique would involve all elements being manually modelled parametrically, to achieve the accuracy of a mesh with the editability of a parametric object, but acknowledged that this had cost and time implications so instead opted for a hybrid approach. Simple surfaces were modelled parametrically and meshes were created for complex objects. The limited use of meshes reduced computer processing issues due to file sizes.	5	5	4	C	1.5	**16**	**11.5**
2 [78]	Developed a new modelling software with a focus on modelling decay.	Part of a 20-year project to model a Roman Fluvial Port. Ref. [78] was able to model the structure to a high degree of accuracy and include a segmentation tool for classifying decay mechanisms and the potential interventions required. Their methodology was validated by archaeological experts so was proven to be successful.	5	5	3	C	1.5	**14.5**	**10.5**
3 [13]	Modelling lost heritage for restoration	Ref. [13] modelled all the decorative elements of a Kurdish minaret. The decorative elements were modelled as they would have been (extrapolated from available data) as opposed to the as-is condition so that the model could be used for restoration purposes.	3	3	5	C	1.5	**13.5**	**9.5**
4 [10]	Modelling for structural condition analysis	Ref. [10] created an HBIM for structural condition analysis by removing all decorative elements from the model.	2	5	5	C	1.5	**13**	**11**
5 [79]	Simplifying model elements for structural analysis.	Ref. [79] created a model purely for structural analysis, so deconstructed components into a series of 3D line elements. This method worked as the elements modelled were standard steel components such as I-beams, so were of less complexity than most historical architecture.	2	5	3	C	2	**12.5**	**9**

Table 4. *Cont.*

Case Study	Unique Feature	Details	GA	IO	AI	IU	SIIU	ULC	ULFM
6 [80]	Modelling layers of a structure (decorative) as individual images.	Ref. [80] examined wall painting as a representative of decorative surfaces in BIM. They incorporated layers of the painting as a series of photos within the model. They suggest that the incorporation of all data within the model, as opposed to an external link, allows better informed management decisions.	5	5	1	C	1.5	**11.5**	**8.5**
7 [81]	Used placeholder objects for complex objects.	Ref. [81] determined that the accurate modelling of all objects was not possible due to time constraints (of manual modelling) and processing requirements (of mesh models). They used placeholder objects (geospatially accurate but otherwise arbitrary shapes) and then associated all other information as meta data, e.g., photos of the actual condition.	1	3	5	C	1.5	**10.5**	**8.5**
8 [82]	Creating a model for Finite Element Modelling (FEM) to determine seismic stability	Ref. [82] initially modelled complex architecture using NURBS surfaces but had to later convert the model to a mesh so that it could be exported to FEM software (Pro-Sap), a step that arguably could have been avoided if the shapes were modelled as a mesh initially.	5	1	1	C	1.5	**9.5**	**4.5**
9 [83]	Including model accuracy analysis to mitigate limitations regarding time and modeller skill	Ref. [83] conceded that a fully realistic model would require a highly specialised technician, so aimed to create a model using Revit without spending undue time on the modelling itself. They acknowledged limitations of Revit for modelling as-built deviations, but overcame this by using CloudCompare to compare the deviation between their model and the point cloud. The output of the process was a false colour map that was attached as a JPEG to the model. Whilst successful, they also suggested that a similar result could be achieved by storing the point cloud in Revit and visually assessing accuracy.	4	3	1	C	1	**6.5**	**6**
10 [84]	HBIM for Building Energy Model (BEM) analysis	Ref. [84] created an HBIM to be exported to BEM software (Cypetherm C.E.) to allow for analysis of the potential renovation options. They parametrically modelled objects but found that the inaccuracies at the modelling stage caused errors in the outputted result when they imported the model parameters to BEM software. They suggested this could be overcome by BEM calibration from existing data or by integrating digital twin technology.	1	3	1	C	1	**3.5**	**4.5**
11 [85]	Creating a model from orthophotos and photogrammetry	Ref. [85] had to create a model using photogrammetry and NURBS models because the building primarily consisted of marble and mosaic surfaces. It is rare that a model is made without TLS due to its increased accuracy; however, the marble surfaces partially absorb lasers and the mosaic surfaces caused huge amounts of reflection. Orthophotos were also included within the model which were of high enough resolution that individual mosaic tiles could be distinguished. As such, they were able to use the images for restoration purposes. Orthophotos are not typically included as they are unfeasibly large files.	5	3	1	C	1	**7.5**	**6.5**

Table 4. *Cont.*

Case Study	Unique Feature	Details	GA	IO	AI	IU	SIIU	ULC	ULFM
12 [86]	Modelling only from the surface mesh	Ref. [86] modelled an underground heritage site and used the resulting model to design a non-invasive ventilation system using Computational Fluid Dynamics (CFD). It was clear from the complexity of the shapes and available data that Mesh-to-BIM was the only suitable method. They experimented with different mesh sizes and found that reducing the complexity of the mesh had minimal effect on the CFD output.	5	1	1	FM	2	**6.5**	**6.5**
13 [87]	Adding additional parameters to Revit to describe structural irregularities.	Ref. [87] found from the point cloud that the walls of their case study were not straight and had large amounts of tilt. Using Revit, they were not able to easily model this. They overcame this by adding additional parameters to the model to describe wall tilt.	1	3	3	FM	1	**5.5**	**6.5**
14 [88]	Manually creating a 3D model of a cathedral portico in a single CAD software (AutoCAD) and then exporting to BIM authoring tools.	Whilst the model of [88] was made to a high level of accuracy, they found the process time-consuming and complex. It seems unclear what the benefits of their completely accurate model were as no future intended use was specified.	5	5	2	U	1	**9.5**	**9.5**
15 [89]	Using multiple CAD software to create the 3D model.	Ref. [89] created a 3D model entirely in CAD software without any associated extra information or parametric capabilities; i.e., it was not a BIM model. The CAD was then imported into Revit to add extra information and elevate it to a BIM model. This bypassed certain modelling limitations of BIM tools with regards to the number of modelling tools available (Table 1).	3	3	3	U	1	**7.5**	**7.5**
16 [90]	Applied orthophotography to a model created in Revit to accurately model the as-is texture of the structures.	Ref. [90] created a model of a village in Saudi Arabia. The aim was to include texture information so that it could provide information regarding structure condition, decay of material, decorative variety and phases of buildings as well as being useful for creating virtual environments	5	3	1	U	1	**7.5**	**6.5**

Whilst non-exhaustive of all case studies reviewed, it can be seen from Table 4 that models made using BIM authoring tools generally achieve a lower level of GA. Case studies that implemented alternative technologies generally achieved a high GA but the use of additional software further increases the cost of model creation, a pre-existing barrier to the implementation of HBIM [12]. Whilst its assessed usefulness was limited by a lack of AI, the approach of [83] (case study 9) may provide the simplest, lowest-cost solution to modelling limitations. GA is less important when the model is used for numerical analysis as the analysis software often requires a simplified model (see case study 5). Several papers used digital twins [84,86] or sensor integration [91] to overcome modelling simplifications. However, Ref. [49] suggests that an accurate model increases confidence in high-risk developments which could potentially cause damage to an asset, which may be why many of the models intended for conservation work in Table 4 had a high level of GA. Ref. [64] states that advanced techniques are rendered obsolete by heritage professionals not using them; it is notable in Table 4 that of the 16 case studies, 3 were created without a clearly specified use and only 2 demonstrated a model being successfully used for its intended purpose.

3.2.4. Increasing Modelling Speed and Quality

As evident in Section 3.2.2, there is no single modelling approach for HBIM which is without limitations, and the existing methodologies are either time-consuming or produce inaccurate models. It is worth noting that creating BIM models for new build construction still requires significant investments in terms of cost and time so it is arguably inappropriate to assume that the creation of an HBIM will ever be instant. That being said, a few methodologies for increasing modelling speed and quality have been attempted, summarised in Table 5. Details of each approach are discussed below.

Table 5. Methodologies for increasing modelling speed and quality.

Approach		**Success Level**
A. Automatic/Semi-Automatic Processes	A.1. Point cloud and mesh segmentation	Developing
	A.2. Model creation	Limited to simple surfaces
B. Creating a Model from Existing Documents or traditional surveys		Poor
C. HBIM Libraries	C.1. Creating new parametric models as per BIM methodologies	Poor
	C.2. Adapting existing objects	Limited accuracy
	C.3. Creating theoretical objects	Limited accuracy
	C.4. Increasing the granularity of BIM objects	Currently limited to simple shapes

A.1. Point cloud and mesh segmentation—Whilst point clouds will model an entire surface, they can be segmented into more usable units to reduce processing requirements, enable meshes of individual objects or more easily model individual elements [64,74,92,93]. Automatic techniques are being developed that can detect which points in a cloud or sections of a surface mesh correspond with a single object. This is known as semantic segmentation. Tests of semantic segmentation techniques have had limited success and it is mostly still a manual process as technology is not advanced enough [64]. Ref. [94] tested a segmentation algorithm but found that it was only successful for large areas as opposed to detailed shapes and even in large areas it included many false positives. Ref. [95] was able to segment a point cloud by first defining an extensive ontology of the elements and rules relating to castles and applying machine learning but the necessity of defining the ontology mitigates the modelling efficiency.

A.2. Model creation—Arguably the next evolution of point cloud segmentation is where a modelling algorithm detects areas of the point cloud belonging to a single object, separates the point and then creates a 3D object in that place. This method has been investigated and applied with some success to individual work [96], but there is yet to be a fully automated process [97]. Other works have repeatedly concluded that modelling algorithms are not yet developed enough to model complex architecture or differences due to aging [73,74,98–100]. Ref. [45] suggests that modelling requires a degree of technical insight regarding constructive techniques which cannot be automatically determined. The most successful automatic modelling techniques model geometric primitives [97,101]. Of these, the accuracy is potentially insufficient for certain use cases, with [97] only achieving a distance accuracy for columns of approximately 64 mm.

B. Creating a model from existing documents or traditional surveys—The least used modelling efficiency, suggested by [62,74], involves creating a model from existing documentation and then validating that model with scan data. An alternative approach to this method is using traditional cartography as a data source for model creation [43]. In practice, it seems to only be used for instances of lost heritage [102–104] or for when the model is being used for visualisation purposes only [105]. Refs. [10,41,106] all compared their resulting models to the point cloud and found significant differences in the measured geometries, arguably invalidating the method.

C.1. Creating new parametric models as per BIM methodologies—Manually creating new parametric objects to be added to a library specifically for HBIM. Objects should be true to the as-is condition. Ref. [107] attempted to implement an HBIM library, envisioning minimal issues, due to the nature of their case study for which there was already an extensive index of building component information. They encountered difficulties at the modelling stage due the geometrical complexity of the objects and were unable to implement the HBIM library they proposed. Ref. [108] also attempted to create a library of objects and encountered issues regarding transferring point clouds to object modelling platforms and adding additional data. Their method was effort-intensive but successful.

C.2. Adapting existing objects—A common simplification which involves the adaption of existing object libraries by altering the pre-existing parameters of similar objects. The main assumption is that certain features are regular [100]. Ref. [70] states that the regular objects of HBIM libraries lead to the normalisation of the complexity of heritage and a loss of understanding of the real value.

C.3. Creating theoretical object—Rather than modelling from the point cloud, objects are created from historical documents such as architectural drawings, manuals, treatises and building guidance. This creates a library of uniform theoretical objects. This alternative method was trialled by [109,110], who created a series of ideal vault elements, as well as [111] who created a library of classic architectural elements. Whilst successful, this process is incredibly time-consuming and relied upon large amounts of existing data and architectural rules. Its validity is questioned by the work of [100] who created a component library for a church but noted that the objects did not reflect the real condition as per the point cloud. Similar issues to creating models from existing drawings are encountered.

C.4. Increasing the granularity of BIM objects—Involves splitting objects into smaller components that are more likely to be reused. The most common example is splitting columns into shafts and bases, a method previously utilised by [112] who attempted to create a library of algorithmically modelled columns by splitting them into functional components. They found that the shaft element of certain columns could be reused for other, similar columns. Similar methodologies were employed by [73,113] but their work was manual as opposed to algorithmic. Ref. [114] also split elements into components but states that, to be able to generate a model sufficient for structural analysis, the components must be developed with an understanding of their structural interactions.

Object libraries were arguably the first [115], and now one of the most commonly investigated, approaches because they already contribute to the procedural efficiency of BIM. However, they have yet to encompass CH [110]; the generation of new BIM objects requires a significant time investment which is further complicated by the complexity of CH objects and modelling tools and formats do not account for CH features such as irregular and tilted walls [87]. As such, there have been many varying attempts to develop an HBIM library as they are the only proven mechanism for improving modelling efficiency. However, the application tends to be limited to newer heritage [77,84,116], and to architectural styles where there are known to be common repeating elements across different assets [40,69,90,107,113,117,118]. It has been suggested that, due to the uniqueness of CH, each asset requires its own non-transferable library of elements [73]. However, Ref. [119] created a component library for traditional Taiwanese woodwork and distinguished 4 families with parameters (same shape but varying size) and 23 families without parameters (same shape and size), exhibiting the effectiveness of an HBIM library. Ref. [120] is one of very few that suggested that all the objects modelled should be added to a shareable HBIM library regardless of perceived object commonality.

4. BIM for Information Management

4.1. Overview of the Issue

As seen in Table 4, HBIM models are often developed without a known use and there appears to be very limited evidence of them being used in practice. Ref. [121] suggests that, despite the emerging prevalence of HBIM models, they risk being abandoned post any restoration work due to a lack of useful information, illustrated by the lack of AI in Table 4. Whilst arguably true, the issue is exacerbated by the lack of integration between BIM and FM tools resulting in a large amount of data loss between stages [122] and a lack of engagement with CH stakeholders both in terms of their awareness and understanding of BIM [25], and the understanding of their organisational information requirements (OIRs). Refs. [15,21] conclude that future works need to enable the continuous use of the HBIM for FM but [4] suggest that BIM and FM are not yet fully integrated because there is insufficient legislation mandating the use of BIM in FM and, since ISO 19650 [1] was designed for construction, it does not encompass the breadth required for CH. As previously discussed, the uses of an HBIM are typically split into conservation and FM and different models are developed depending on the end use. Without evidence of the models being used for their intended it purpose, it is consequently unclear whether this is due to the actual differences in need for FM and conservation or just the limited scope of the specific project. It can therefore be concluded that without knowing the OIRs for HBIM, it is impossible to define a storage approach. Ref. [6] suggested some requirements for heritage management systems based on common factors across a diverse range of world heritage sites and some papers have made attempts to define the information requirements for HBIM ([8,58,73,99], but their attempts often seem oversimplified. Ref. [122] established a more comprehensive list of requirements but since this work focused on a renovation project, similar to [63], it primarily included construction activities. Other papers appear to simply identify one requirement with little regard for other information types, contributing to the numerous disparate methodologies for implementing HBIM.

The following sections thus present the generic methods commonly employed for information storage and then discuss more specific requirements frequently covered: heritage significance, moveable assets, building condition and changes over time.

4.2. Storing Information

4.2.1. Modifying Existing Workflows

Extra data are added to BIM models as object parameters. As evident in Table 4, it is not yet possible to create a fully accurate model using a single software [123] so models must be in a standard format so they can be exported between programmes with no loss of data [93]. The Industry Foundation Class (IFC), a vendor neutral tool, is the most widely used BIM export format [124] and is conceptually beneficial for HBIM as it enables stakeholder collaboration [13]. However, since the IFC was developed for BIM, it does not cater for the requirements of heritage [125]. The existing schema do not encompass common cultural heritage elements such as vaults [71,126,127] and some works have experienced interoperability issues with FM systems [82,84]. Only [124,125] seem to suggest the adaption of the existing IFC standard to meet heritage requirements. This has precedence as the IFC is regularly updated to include new schema. The latest update at the time of writing, IFC 4.3, was an expansion to include road, rail, ports and waterways and bridges which were not included previously [128]. This is the issue currently facing CH; thus, it can concluded that the logical approach is to further develop the IFC for CH. Ref. [125] tested their suggestion of updating the IFC schema and achieved good results but did contend that the exact definitions of the IFC are not suitable for the complete classification of CH. This sentiment is echoed by [71], which suggests that the hierarchal relationships of the IFC (e.g., window objects are related to wall objects), which relay structural relationships, may not be true for CH. A key document for looking after heritage is a conservation plan based on the recommendations of the Burra Charter. Typically, these are stored separately but there have been attempts at the IFC conversion. Ref. [124] found that it was possible to convert a conservation plan to the IFC but the actual implementation of this format would require a concerted effort.

Consequently, many people choose approaches that modify traditional BIM workflows. Ref. [39] chose to assign all their information, including oral history and informative websites, to the Revit materials as opposed to the objects themselves. This essentially created an HBIM material library. Other works chose to assign information to different layers or segments [68] of the model as opposed to the whole objects, with [99] splitting the model into three layers: global, macro (groups of architectural elements structurally linked) and individual elements. A similar concept was applied by [81] who chose to attach information to building zones; however, they encountered issues when an object existed on the peripherals of a zone. Ref. [129] suggests the inclusion of flaggable parameters to indicate the existence of specific themes such as historical information and conservation information which would then be stored externally.

A perhaps simpler solution to the limitations of the IFC is to store data in an external repository, often a database. The use of external repositories is discussed in numerous works [11,43,121,122,130–133] but the exact details of how external databases should be linked to, and interact with, the HBIM is as yet undefined. Ref. [24] compared the use of ontologies, such as the IFC, with the use of databases and argues that ontologies allow leaner storage and more complex queries but lack the structure of databases. There remains no clear consensus on the best approach but it is worth noting that, for FM, most information will be stored in an external database [25] and there is an existing BIM exchange format (COBie) to achieve this.

There is a tendency to assume that a single model can meet the needs of all stakeholders, perhaps because most studies have a single use case. Ref. [134] is an outlier in this respect, given that they suggest the segregation of a geometric survey, and conceptual information (attributed to simplified geometries) into sub-models which then become a part of the whole federated model. This suggestion has precedence because BIM already segregates models (e.g., for Mechanical, Electrical and Plumbing (MEP) and structural information) due to the different expertise required. This is known as the federation strategy [1]. Whilst conservation guidance, such as the Venice Charter [22], states that records regarding heritage should be publicly stored and available to researchers, [20,64,101] suggest that there should be a capability within the HBIM to limit what information is shared with who for security purposes. This is part of the purpose of a federation strategy.

4.2.2. Alternative Technologies

The proprietary nature of BIM software is another barrier to interoperability [135]. Visual Programming Language (VPL), a user-friendly programming technique, has been suggested to overcome this [61,113,136–138]. Ref. [139] was able to successfully integrate Grasshopper (a VPL) to create a bi-directional link between Rhinoceros (modelling software) and Revit, a BIM authoring tool. Similarly, Ref. [140] created a Revit add-in that aggregated several modelling steps from external software but the add-in was tailored to terminology and modelling definitions specific to their work so may be inapplicable to others. Another theorised solution is Free Open-Source Software (FOSS), a low-cost or free platform where the user is able to manually edit the source code [141,142]. Ref. [19] concluded, from 6 years of research into FOSS, that it was able to be utilised at every stage of HBIM and cited advantages relating to customisability. Alternatively, many suggested systems are web-based [55,81,143]. Ref. [144] claimed that a web-based platform is the best approach to find “common ground” for users with varying skills and expertise as they enable semantic queries and do not require knowledge of BIM [145]. However, the creation of the web platforms and use of a VPL still requires some programming knowledge [99], which fails to acknowledge the existing skills gap for heritage professionals.

The integration of BIM and GISs, a tool for modelling at environmental scale, has been suggested by several works [48,74,146,147]. Ref. [6] states that effective management systems for heritage must include information regarding the wider setting. It is also worth considering that many historical places encompass whole cities such as in the work carried out by [50,118]. Functionally, Ref. [18] suggested some information requirements for HBIM and compared the capabilities of the BIM and GIS software. They found that BIM authoring tools are better for modelling and GISs are better for semantic interpretation but neither software can adequately accomplish all requirements, a reality that may suggest the necessity of BIM-GIS integration. Other theoretical benefits include a shared knowledge base for maintenance enquiries across sites [61] and the opportunity to create a global HBIM library by establishing similar features between multiple buildings [84,92]. However, this fails to acknowledge that, in an urban area, much of the surrounding area is likely to be privately owned so it may not be possible to garner any meaningful information. Most papers try to integrate BIM and GISs using a VPL [148,149] but [150] found that it was possible to integrate HBIM with a GIS without the loss of any parameters using a combination of multiple pre-existing software. Refs. [59,150] appear to be the only papers that suggest creating bespoke software for BIM-GIS. Ref. [59] created Chimera which was subsequently applied to a case study by [151]. Chimera was shown to have good capabilities for information storage and demonstrating changes over time. On a smaller scale, Ref. [152] utilised the spatial capabilities of GISs to create thematic maps to accurately model decay on a façade.

Given the diverse needs of CH, it is arguable that to properly meet all the needs of CH, you must combine the capabilities of BIM, GISs and game engines to encompass all the potential information requirements. Only [150] suggests a theoretical framework to facilitate this.

4.3. Common Information Requirements

4.3.1. Historical Significance

The inclusion of heritage specific information is unique to HBIM. Heritage consists of both tangible and intangible attributes and "respect for cultural and heritage diversity requires conscious efforts to avoid imposing mechanistic formulae or standardized procedures" [153]. A lack of formulaic descripting regarding heritage information makes it difficult to include in BIM, a parameter-based modelling tool. Whilst [154] were able to include intangible information as descriptions and images associated with objects (e.g., paint colours indicating a link to France), this was the exception to the norm. Thus, finding intangible information can require semantic querying, a functionality not native to BIM. A common solution is to link the data to the model in an external database [121] or by creating a bespoke ID system for heritage objects [12]. Ref. [155] created an entirely new system that, by attributing inference rules to objects based on end-user needs, was able to query heterogeneous information. Whilst their system was bespoke and novel, it arguably could have been implemented using rule-based filtering already present in BIM authoring tools such as Revit.

The lack of a standard vocabulary herein causes issues when trying to integrate different software because all VPLs become case specific [147]. A vast amount of standardised vocabulary could engender the automatic extraction of elements [156]. Hence, it is not surprising that a number of papers mention the inclusion of ontologies such as CIDOC-CRM (now ISO 21127 [157]), which is the standard for the cataloguing of data for museum collections [14,81,124,135,146,158]. The most successful implementation of ontologies for the structuring of semantic data seems to occur when multiple ontologies are used, as presented in the work by [95], who combined the Getty Art and Architecture Thesaurus (AAT), CIDOC-CRM, IFC, CityGML in addition to a castle nomenclature dictionary. Ontology inclusion usually occurs on web-based software as exampled in the work by [143], who incorporated the Getty AAT schema, and [158], who converted CIDOC-CRM using ifcOWL, also known as the IFC web ontology.

4.3.2. Moveable Assets

Modelling moveable assets is a consideration rarely included in BIM. Ref. [35], whilst modelling an Italian paper mill, suggested that the exclusion of moveable assets, in their case industrial machines, risked the exclusion of fundamental parts of the asset's significance. Likewise, Ref. [64] modelled moveable and artistic assets so that the model could also be used for the sustainable management of those assets as opposed to the building fabric itself. Similarly, Ref. [138] applied HBIM procedures to the modelling of museum artefacts in order to plan exhibit layouts and enable the condition monitoring of artefacts. Ref. [20] suggests that CH is made for public use or else the value and appreciation of heritage will be lost, so HBIMs able to assist with this are crucial.

4.3.3. Building Condition

Building Condition Assessments (BCAs) are of crucial importance for CH both for renovations, restoration and FM. Ref. [137] suggests that integrating manual inspection methods into BIM could improve cost and efficiency whilst reducing the accumulation of human errors. In parallel, [159], whilst only modelling an isolated wall mural removed from its architectural setting, found that integrating Non-Destructive Testing (NDT) data in its corresponding location in a 3D space enabled a multi-disciplinary evaluation of its condition. Ref. [56] undertook extensive work investigating the different types of damage that had impacted a Portuguese CH site; notably, material loss, moisture and biological damage. They carried out a number of NDT tests with the aim of visually integrating the data into the model. However, Ref. [133] suggests that there is a lack of native capabilities within BIM tools to store NDT data. Visual BCAs from the point cloud are likewise discussed by [160].

To counter this, Ref. [57] made a specific effort to define how to store BCA data by storing graphical outputs of the analysis as images that were then overlayed as building façades in Revit. The methodology was necessary as the analysis software was not IFC-compatible, but the façades were. This technique was hindered, similarly to the work by [73], by Revit's conformity to building logic, where a wall can only have one façade. Multiple 'virtual' walls were required to model the outputs of different tests. Ref. [129] made a similar attempt to model building condition as a façade and created an algorithm to model decay as a CAD overlay but the algorithm itself was prone to error. Ref. [132] also discussed additional external object layers but instead proposed the use of 'Surface Information Points', individual point objects, densely distributed across the surface of the object containing condition information, which could be filtered according to associated parameters. Whilst arguably more successful than the use of external object layers, the process for applying the surface points required a considerable degree of coding ability. Ref. [161] modelled decay on a bridge as photo panels and created two bespoke parameters to define decay. Ref. [162] created bespoke element IDs and then modelled decay using individual editable objects. The necessity of the IDs could have been mitigated by expanding IFC to enable the storage of BCAs.

Even contemporary CH was primarily built before the advent of rigorous building standards [136] so it may be necessary to undertake analysis to check the stability of the existing structure or the asset's energy performance [84,91,116,133]. Refs. [93,136] suggest that HBIM lends itself to structural analysis since it requires extensive knowledge of the building (contained in historic information) and most analysis software rely on parametric input. This statement is refuted by the work of [55] which included diagnostic data as parameters in Revit but were unable to export the data to other software because they were not in a recognisable format. A lack of pre-existing diagnostic and restoration IFC categories was also cited as a problem by [159,163]. Refs. [79,82] created work in an IFC format but had to simplify their model to a dxf format because of compatibility issues with the IFC and the Finite Element Modelling (FEM) software. Ref. [82] also experienced issues due to Revit being unable to understand that the vaulted ceilings existed as both an architectural feature and a structural component. There is not yet exhaustive integration of numerical simulation software and BIM but [91] were able to develop a custom integration using a VPL and created a real-time link between the software.

4.3.4. Changes over Time

Effective conservation relies on understanding the changes that have occurred over time [69]. This is referred to as 4D in BIM and is typically utilised for modelling construction or demolition planning. For HBIM, several works have suggested repurposing 4D functionalities for modelling large-scale changes over time [31,34,35,68,89,99,102,132], or for modelling the progress of decay [39]. Ref. [127] categorised model elements based on their constructive phase claiming that it would allow the identification of previous interventions and thus the evaluation of future risks and vulnerabilities. This claim was validated by [152], which used construction phases to determine the likely causes of cracks in the masonry, and by [56] which determined that previous restoration activities were the cause of subsequent damage. A unique approach was employed by [164] which created a model of a bridge in an area prone to ground movements. The authors created a model from new survey data and from data collected in 1860 and then compared the two models to assess the deformation of the bridge. Ref. [165] differs slightly from the papers previously mentioned by suggesting the separation of 4D into macro 4D, modelling large-scale changes, and micro 4D, modelling small changes such as maintenance works. The need for the latter is also discussed by [132] and the distinction of the two is justified because much guidance on conservation work begins with an interrogation of the major changes that have occurred over time [166] but then relies on the continual monitoring and management of change [167]. A visual representation of changes at both a small and large scale would assist with this.

Additionally, 4D could be used for educational purposes. Refs. [20,39] suggest that by working out the chronological stages of the building's construction and attributing this information to the model, it could be used to teach people about historical construction techniques. This sentiment is echoed by [119] which, whilst not explicitly referring to 4D BIM, discusses surveys teaching people about techniques now obsolete. The exact timing of interventions is often estimated from existing documentation [102] so some works have suggested adding a reliability statement regarding whether the date is known or estimated [10].

4.4. Data Reliability

Data voids are common in HBIM, due to inaccessibility during data collection [39,82] and a lack of or incompleteness of existing documentation [66,120]. It is also worth noting that point clouds only provide surface data and the age and restrictions regarding the structure may prevent invasive tests from occurring. Ref. [168] overcame this issue by utilising expert interpretation from historical advisors who helped corroborate their assumptions of the likely construction methods. Ref. [120] mitigated documentation-related data voids by using any historical source exploring themes related to the construction period of that asset. Similarly, Ref. [116] suggested using building standards and legislation, as well as patents, advertisements of products and other information from architectural journals to supplement surveyed data. This could have implications for the modelling accuracy, especially since there is minimal knowledge about how actual building practice complied with manuals [58] and there will have inevitably been degradation to the building with time [73]. Ref. [104] employed historical surveys and records to supplement a point cloud of a now-damaged historical asset. Ref. [82] chose to use current building standards to estimate the minimum structural performance of a material so they could combine their HBIM with FEM tools as they were unable to undertake invasive tests to determine the real values. There is a risk that inaccurate judgements will be made if this information is assumed [116].

Ref. [49] suggests that a geometrically accurate model increases confidence in a high-risk intervention but, whilst undeniably important, the actual geometric reliability of the models is given minimal consideration, with the exception of a few works that compare the resulting model to the point cloud or mesh [51,72,83,132,160]. However, there is a tendency to assume that point cloud surveys and photogrammetry are entirely accurate and only some works appear to employ additional validation surveys [51,164] or investigations to ensure this [36,160].

There is a general consensus that the reliability status of data—i.e., whether it is assumed or known (fact); should be recorded [66,71,145,169]. Ref. [39] decided to extrapolate existing data, assuming that future investigations would eventually fill the voids, and colour code it according to whether the data were surveyed or hypothesised. All of these suggestions arguably contradict the advice of The Venice Charter which states restoration "must stop at the point where conjecture begins" [22]. Refs. [66,169,170] all explicitly distinguish the need to define reliability both for the source of geometric data and any information stored within the model [170], suggesting that these should be two independently recorded factors.

5. AR and VR

AR and VR have been frequently explored as visualisation tools for HBIM to enable increased collaboration and more inclusive access to heritage [35,40,49,93,105,171]. These works normally involve the user being able to 'walk' around the model and interact with objects [172] to reveal additional information, often regarding intangible heritage [173]. Ref. [174] created a virtual model for tourists to show the changes over time to a basilica in Milan. Refs. [55,175] suggest data in a BIM model could be shared via VR to reduce intervention errors on construction sites and aid future maintenance works. Ref. [176] utilised game engines to create a holographic HBIM; although, it is unclear what the benefits of this were as the model was small, non-portable and lacked meaningful information.

Another stream of research has suggested the use of VR to enable the population of the geometric model with additional data remotely, a development partially instigated by the COVID-19 pandemic [70,175]. This technique has been successful, with [177] demonstrating that a VR tour allowed students on their 'survey education' course to make meaningful observations on the condition of a temple in China. Additional data can include heritage significance, a value notoriously hard to define and entirely dependent on the assessor. The benefit of VR/AR for populating these data is that all stakeholders can input their significance assessments, a key factor of effective CH management [7]. This utilisation of VR was successfully employed by [175], who created a model of a church in Belgium and allowed VR visitors to place colour-coded markers about what they deemed significant and the type of significance. The system recorded geospatial data relating to where visitors were standing in the virtual environment when they placed the markers. The authors of [175] suggest using the geospatial data to plan future visitor routes, a sentiment echoed by [20], and go on to suggest the information regarding who attributed value to what could be used more generally to improve the process for historical significance assessments.

Whilst theoretically beneficial, the process for converting HBIM to VR and AR is not yet sufficiently advanced. Ref. [76] implemented current methodologies to convert the HBIM of two case studies into both AR and VR. They found that the results lacked interactivity and that the process required a large number of steps. Ref. [178] achieved a good visual correlation between the real and VR environment but the process reduced the parametric BIM model to a mesh reducing the associated level of information.

6. Future Work

From the reviewed papers, it can be seen that the implementation of HBIM is currently limited by a lack of standard methodology and lack of developed OIRs. Previous research has investigated different modelling approaches and to a lesser extent information requirements for specific use cases; however, it is clear that a standardised approach is remiss. As such, there is a need to define the common OIRs for CH and their relative importance: whether they are critical requirements, non-essential yet value adding or aspirational requirements. Once the OIRs are known, a viable standardised approach should be defined to include all the critical requirements with additional scope for the non-essential yet value-adding requirements. The strategy should account for the practical technology level achievable by CH managers to avoid obsolescence of the model. Ultimately, the question can be posed—to what extent can HBIM be aligned with the existing and future developments of ISO 19650?

In order to fill this gap in knowledge, future work by the authors of this paper will include the comprehensive identification of existing OIRs for heritage according to the guidance and standards published by heritage experts and facilities managers. The OIRs will then be validated by consulting experts within the field of heritage management and maintenance. Once the OIRs are validated, they will be compared to existing BIM practices for the purposes of identifying which, if any, BIM practices can be applied to HBIM. This should (and will) look at both BIM tools and exchange formats including IFC. A comprehensive identification of OIRs for HBIM can be used as the foundation for the standard methodology for the application of HBIM within CH.

7. Conclusions

This paper carried out a semi-structured literature review to determine the current implementation of HBIM. It established that existing research areas could be grouped into three key areas: Geometric Data Collection and Modelling, BIM for Information Management and AR and VR. Geometric Data Collection and Modelling was determined to be the primary focus of early HBIM research. An assessment criterion for evaluating the usefulness level of HBIM models was created and applied to 16 case studies. It was observed that the HBIM case studies had given minimal consideration or discussion to what associated information should be included with models and there was minimal evidence of the models being used in practice for an intended purpose. This was determined to be a limitation when evaluating the usefulness of models. It was concluded that HBIM implementation is currently limited by a lack of standard methodology and defined OIRs. It is suggested that future work should address this limitation by collating and validating existing OIRs for the management and maintenance of heritage which can then be applied to defining a future standard HBIM methodology.

Author Contributions: Conceptualisation, L.J.L. and R.J.D.; methodology, L.J.L.; validation, L.J.L.; formal analysis, L.J.L.; writing—original draft preparation, L.J.L.; writing—review and editing, R.J.D. and D.V.L.H.; visualisation, L.J.L.; supervision, R.J.D. and D.V.L.H. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support of the UK Engineering and Physical Sciences Research Council (EPSRC) under grant number EP/W524396/1. The APC was funded by University of Birmingham.

Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to thank the School of Engineering at the University of Birmingham for providing access to its scanning equipment and BIM cave; and the University of Birmingham Estates for providing access to various assets around campus that helped shape the formulation of the HBIM problem statement.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

AEC	Architecture, Engineering and Construction
AI	Associated Information
AR	Augmented Reality
BCA	Building Condition Assessment
BEM	Building Energy Model
BIM	Building Information Modelling
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CH	Cultural Heritage
FEM	Finite Element Modelling
FM	Facilities Management
FOSS	Free Open-Source Software

GA	Geometric Accuracy
GIS	Geographic Information System
GoG	Grade of Generation
HBIM	Historic Building Information Modelling
IFC	Industry Foundation Class
IO	Identifiable Objects
IU	Intended Use
LOD	Level of Detail
LOH	Level of History
LOIN	Level of Information Need
LOK	Level of Knowledge
MEP	Mechanical, Electrical and Plumbing
NDT	Non-Destructive Testing
NURBS	Non-Uniform Rational B-Splines
O&M	Operation and Maintenance
OIR	Organisation Information Requirements
OS	Optical Scanning
SIIU	Successful Implementation for Intended Use
TLS	Terrestrial Laser Scanning
UAV	Unmanned Arial Vehicles
ULC	Usefulness Level for Conservation
ULFM	Usefulness Level for Facilities Management
VPL	Visual Programming Language
VR	Virtual Reality
WHL	World Heritage List

References

1. *ISO 19650-2:2018*; Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management using Building Information Modelling—Part 2: Delivery Phase of the Assets. The British Standards Institute: London, UK, 2018.
2. Murphy, M.; McGovern, E.; Pavia, S. Historic Building Information Modelling (HBIM). *Struct. Surv.* **2009**, *27*, 311–327. [CrossRef]
3. UNESCO Institute for Statistics Cultural Heritage. Available online: https://uis.unesco.org/en/glossary-term/cultural-heritage (accessed on 18 April 2023).
4. Dlesk, A.; Vach, K.; Shults, R.; Doubrava, P. Generalization of BIM Model for Purposes of Facility Management. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *XLIII-B4-2022*, 309–314. [CrossRef]
5. Durdyev, S.; Ashour, M.; Connelly, S.; Mahdiyar, A. Barriers to the Implementation of Building Information Modelling (BIM) for Facility Management. *J. Build. Eng.* **2022**, *46*, 103736. [CrossRef]
6. UNESCO. *Operational Guidelines for the Implementation of the World Heritage Convention*; UNESCO: Paris, France, 2021.
7. UNESCO. *Preparing World Heritage Nominations*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2011; ISBN 978-92-3-001029-4.
8. Gomih, S.; Leporelli, E.; Martino, M.; Santi, G. Sustainable Strategies for the Development of UNESCO Sites: The Medina of Marrakech. *Sustain. Mediterr. Constr.* **2021**, *13*, 153–159.
9. Charlton, J.; Kelly, K.; Greenwood, D.; Moreton, L. The Complexities of Managing Historic Buildings with BIM. *Eng. Constr. Archit. Manag.* **2021**, *28*, 570–583. [CrossRef]
10. Barontini, A.; Alarcon, C.; Sousa, H.S.; Oliveira, D.V.; Masciotta, M.G.; Azenha, M. Development and Demonstration of an HBIM Framework for the Preventive Conservation of Cultural Heritage. *Int. J. Archit. Herit.* **2022**, *16*, 1451–1473. [CrossRef]
11. Bruno, N.; Roncella, R. A Restoration Oriented HBIM System for Cultural Heritage Documentation: The Case Study of Parma Cathedral. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *XLII–2*, 171–178. [CrossRef]
12. di Stefano, F.; Malinverni, E.S.; Pierdicca, R.; Fangi, G.; Ejupi, S. HBIM implementation for an ottoman mosque. Case of study: Sultan mehmet fatih II mosque in Kosovo. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
13. Wafaei Baneh, K.; Wafaei Baneh, B.; Osman, A.; Mostafapour, O.; Bradosty, Z.R. Regeneration and Documentation of Historic Geometric Islamic Patterns via HBIM: A Case Study of Choli Minaret, Kurdistan Region. *Int. J. Build. Pathol. Adapt.* **2021**, *41*, 347–363. [CrossRef]
14. Yang, X.; Grussenmeyer, P.; Koehl, M.; Macher, H.; Murtiyoso, A.; Landes, T. Review of Built Heritage Modelling: Integration of HBIM and Other Information Techniques. *J. Cult. Herit.* **2020**, *46*, 350–360. [CrossRef]

15. García-Valldecabres, J.; Pellicer, E.; Jordan-Palomar, I. BIM Scientific Literature Review for Existing Buildings and a Theoretical Method: Proposal for Heritage Data Management Using HBIM. In Proceedings of the Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan—Proceedings of the 2016 Construction Research Congress, San Juan, Puerto Rico, 31 May–2 June 2016.
16. Pocobelli, D.P.; Boehm, J.; Bryan, P.; Still, J.; Grau-Bové, J. BIM for Heritage Science: A Review. *Heritage Sci.* **2018**, *6*, 30. [CrossRef]
17. López, F.; Lerones, P.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E.; López, F.; Lerones, P.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. A Review of Heritage Building Information Modeling (H-BIM). Multimodal Technologies and Interaction. *Multimodal Technol. Interact.* **2018**, *2*, 21. [CrossRef]
18. Tobiáš, P. BIM, GIS and Semantic Models of Cultural Heritage Buildings. *Geoinfor. FCE CTU* **2016**, *15*, 27–42. [CrossRef]
19. Diara, F. HBIM Open Source: A Review. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 472. [CrossRef]
20. García, E.S.; García-Valldecabres, J.; Blasco, M.J.V. The Use of HBIM Models as a Tool for Dissemination and Public Use Management of Historical Architecture: A Review. *Int. J. Sustain. Dev. Plan.* **2018**, *13*, 96–107. [CrossRef]
21. Santos, D.; Sousa, H.S.; Cabaleiro, M.; Branco, J.M. HBIM Application in Historic Timber Structures: A Systematic Review. *Int. J. Archit. Herit.* **2022**, *17*, 1331–1347. [CrossRef]
22. ICOMOS. International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964). In Proceedings of the IInd International Congress of Architects and Technicians of Historic Monuments, Venice, Italy, 25–31 May 1964.
23. Council of Europe. *Council of Europe Framework Convention on the Value of Cultural Heritage for Society*; Council of Europe: London, UK, 2005.
24. Cursi, S.; Martinelli, L.; Paraciani, N.; Calcerano, F.; Gigliarelli, E. Linking External Knowledge to Heritage BIM. *Autom. Constr.* **2022**, *141*, 104444. [CrossRef]
25. Tsay, G.S.; Staub-French, S.; Poirier, É. BIM for Facilities Management: An Investigation into the Asset Information Delivery Process and the Associated Challenges. *Appl. Sci.* **2022**, *12*, 9542. [CrossRef]
26. Volk, R.; Stengel, J.; Schultmann, F. Building Information Modeling (BIM) for Existing Buildings—Literature Review and Future Needs. *Autom. Constr.* **2014**, *38*, 109–127. [CrossRef]
27. *ISO 55000:2014*; The International Standards Organisation Asset Management—Overview, Principles and Terminology. ISO: Geneva, Switzerland, 2014; Volume 1.
28. IAM. *Asset Management—An Anatomy*; IAM: Bristol, UK, 2015.
29. Global Forum on Maintenance and Asset Management. *The Asset Management Landscape*; Global Forum on Maintenance and Asset Management: Toronto, ON, Canada, 2014; Volume 2.
30. Charef, R.; Emmitt, S.; Alaka, H.; Fouchal, F. Building Information Modelling Adoption in the European Union: An Overview. *J. Build. Eng.* **2019**, *25*, 100777. [CrossRef]
31. Fai, S.; Graham, K.; Duckworth, T.; Wood, N.; Attar, R. Building Information Modelling and Heritage Documentation. In Proceedings of the XXIIIrd International CIPA Symposium, Prague, Czech Republic, 12–16 September 2011.
32. Angulo Fornos, R. Construcción de La Base Gráfica Para Un Sistema de Información y Gestión Del Patrimonio Arquitectónico: Casa de Hylas. *Arqueol. Arquit.* **2013**, *9*, 11–25. [CrossRef]
33. Nieto Julián, J.E. Generación de Modelos de Información Para La Gestión de Una Intervención: La Cárcel de La Real Fábrica de Tabacos de Sevilla. *Virtual Archaeol. Rev.* **2012**, *3*, 63. [CrossRef]
34. Attenni, M. Informative Models for Architectural Heritage. *Heritage* **2019**, *2*, 2067–2089. [CrossRef]
35. Currà, E.; D'amico, A.; Angelosanti, M. HBIM between Antiquity and Industrial Archaeology: Former Segrè Papermill and Sanctuary of Hercules in Tivoli. *Sustainability* **2022**, *14*, 1329. [CrossRef]
36. Fryskowska, A.; Stachelek, J. A No-Reference Method of Geometric Content Quality Analysis of 3D Models Generated from Laser Scanning Point Clouds for HBIM. *J. Cult. Herit.* **2018**, *34*, 95–108. [CrossRef]
37. Carvajal-Ramírez, F.; Martínez-Carridondo, P.; Yero-Paneque, L.; Agüera-Vega, F. UAV Photogrammetry and HBIM for the Virtual Reconstruction of Heritage. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
38. Karachaliou, E.; Georgiou, E.; Psaltis, D.; Stylianidis, E. UAV for mapping historic buildings: From 3D modelling to BIM. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Bergamo, Italy, 6–8 February 2019; Volume 42.
39. Conti, A.; Fiorini, L.; Massaro, R.; Santoni, C.; Tucci, G. HBIM for the Preservation of a Historic Infrastructure: The Carlo III Bridge of the Carolino Aqueduct. *Appl. Geomat.* **2022**, *14*, 41–51. [CrossRef]
40. Lin, G.; Giordano, A.; Sang, K. From site survey to HBIM model for the documentation of historic buildings: The case study of Hexinwu village in China. *Conserv. Sci. Cult. Herit.* **2020**, *20*, 111–123.
41. Bródka, J.; Wałek, M. 'The modernist refugium': The heritage of polish post-war residential architecture of Jerzy Ziętek's villa in Ustroń in the perspective of documentation techniques. *Int. J. Conserv. Sci.* **2022**, *13*, 865–878.
42. Martínez-Carricondo, P.; Carvajal-Ramírez, F.; Yero-Paneque, L.; Agüera-Vega, F. Combination of Nadiral and Oblique UAV Photogrammetry and HBIM for the Virtual Reconstruction of Cultural Heritage. Case Study of Cortijo Del Fraile in Níjar, Almería (Spain). *Build. Res. Inf.* **2020**, *48*, 140–159. [CrossRef]

43. Castellano-Román, M.; Pinto-Puerto, F. Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The Model of the Charterhouse of Jerez (Cádiz, Spain). *Digit. Appl. Archaeol. Cult. Herit.* **2019**, *14*, e00110. [CrossRef]
44. Bryan, P.; Blake, B.; Bedford, J. *Metric Survey Specifications for Cultural Heritage*; Historic England: London, UK, 2020.
45. D'Amico, A.; Currà, E. From TSL Survey to HBIM, Issues on Survey and Information Modeling Implementation for the Built Heritage The Case Study of the Temple Di Bacco Ravello. In Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe, Rome, Italy, 20–22 September 2017; pp. 39–48.
46. Antón, D.; Medjdoub, B.; Shrahily, R.; Moyano, J. Accuracy Evaluation of the Semi-Automatic 3D Modeling for Historical Building Information Models. *Int. J. Archit. Herit.* **2018**, *12*, 790–805. [CrossRef]
47. Reina Ortiz, M.; Weigert, A.; Dhanda, A.; Yang, C.; Smith, K.; Min, A.; Gyi, M.; Su, S.; Fai, S.; Santana Quintero, M. A theoretical framework for multi-scale documentation of decorated surface. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
48. Barrile, V.; Bernardo, E.; Bilotta, G. An Experimental HBIM Processing: Innovative Tool for 3D Model Reconstruction of Morpho-Typological Phases for the Cultural Heritage. *Remote Sens.* **2022**, *14*, 1288. [CrossRef]
49. Ermenyi, T.; Enegbuma, W.I.; Isaacs, N.; Potangaroa, R. Building Information Modelling Workflow for Heritage Maintenance. In Proceedings of the International Conference of Architectural Science Association, Auckland, New Zealand, 26–27 November 2020; Volume 1.
50. De la Plata, A.R.M.; Franco, P.A.C.; Franco, J.C.; Bravo, V.G. Protocol Development for Point Clouds, Triangulated Meshes and Parametric Model Acquisition and Integration in an HBIM Workflow for Change Control and Management in a UNESCO's World Heritage Site. *Sensors* **2021**, *21*, 1083. [CrossRef]
51. Moyano, J.; Nieto-Julián, J.E.; Bienvenido-Huertas, D.; Marín-García, D. Validation of Close-Range Photogrammetry for Architectural and Archaeological Heritage: Analysis of Point Density and 3d Mesh Geometry. *Remote Sens.* **2020**, *12*, 3571. [CrossRef]
52. Borin, P.; Cavazzini, F. Condition assessment of RC bridges. Integrating machine learning, photogrammetry and BIM. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
53. Mandujano Rodríguez, M.G. Integration of Historic Building Information Modeling and Valuation Approaches for Managing Cultural Heritage Sites. In Proceedings of the 27th Annual Conference of the International Group for Lean Construction, IGLC 2019, Dublin, Ireland, 27 July 2019.
54. Bitelli, G.; Castellazzi, G.; D'Altri, A.M.; de Miranda, S.; Lambertini, A.; Selvaggi, I. On the Generation of Numerical Models from Point Clouds for the Analysis of Damaged Cultural Heritage. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Florence, Italy, 16–18 May 2018; Volume 364.
55. Bruno, S.; Fatiguso, F. Building Conditions Assessment of Built Heritage in Historic Building Information Modeling. *Int. J. Sustain. Dev. Plan.* **2018**, *13*, 36–48. [CrossRef]
56. Garcia-Gago, J.; Sánchez-Aparicio, L.J.; Soilán, M.; González-Aguilera, D. HBIM for Supporting the Diagnosis of Historical Buildings: Case Study of the Master Gate of San Francisco in Portugal. *Autom. Constr.* **2022**, *141*, 104453. [CrossRef]
57. Solla, M.; Gonçalves, L.M.S.; Gonçalves, G.; Francisco, C.; Puente, I.; Providência, P.; Gaspar, F.; Rodrigues, H. A Building Information Modeling Approach to Integrate Geomatic Data for the Documentation and Preservation of Cultural Heritage. *Remote Sens.* **2020**, *12*, 4028. [CrossRef]
58. Achille, C.; Lombardini, N.; Tommasi, C. BIM and Cultural Heritage: Compatibility Tests in an Archaeological Site. *WIT Trans. Built Environ.* **2015**, *149*, 593–604.
59. Rechichi, F. Chimera: A BIM+GIS System for Cultural Heritage. In Proceedings of the 2020 XXIV ISPRS Congress, Nice, France, 31 August–2 September 2020; Volume XLIII-B4-2020.
60. Brusaporci, S.; Tata, A.; Maiezza, P. The "LoH—Level of History" for an Aware HBIM Process. In Proceedings of the 42th International Conference of Representation Disciplines Teachers, Messina, Italy, 16–18 September 2021.
61. Colucci, E.; Iacono, E.; Matrone, F.; Ventura, G.M. A BIM-GIS Integrated Database to Support Planned Maintenance Activities of Historical Built Heritage. In *Geomatics and Geospatial Technologies*; Communications in Computer and Information Science; Springer: Cham, Switzerland, 2022; Volume 1507. [CrossRef]
62. *Historic England BIM for Heritage: Developing a Historic Building Information Model*; Historic England: Swindon, UK, 2017.
63. Jordan-Palomar, I.; Tzortzopoulos, P.; García-Valldecabres, J.; Pellicer, E. Protocol to Manage Heritage-Building Interventions Using Heritage Building Information Modelling (HBIM). *Sustainability* **2018**, *10*, 908. [CrossRef]
64. Nieto-Julián, J.E.; Lara, L.; Moyano, J. Implementation of a Teamwork-HBIM for the Management and Sustainability of Architectural Heritage. *Sustainability* **2021**, *13*, 2161. [CrossRef]
65. Banfi, F. BIM Orientation: Grades of Generation and Information for Different Type of Analysis and Management Process. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ottowa, ON, Canada, 28 August–1 September 2017; Volume 42.
66. Maiezza, P.; Tata, A. Standard for Geometric and Informative Reliabilities in HBIM Models. *DISEGNARECON* **2021**, *14*. [CrossRef]
67. Inzerillo, L.; lo Turco, M.; Parrinello, S.; Santagati, C.; Valenti, G.M. Bim and Architectural Heritage: Towards an Operational Methodology for the Knowledge and the Management of Cultural Heritage. *DISEGNARECON* **2016**, *9*.
68. Guerrero Vega, J.M.; Pizzo, A. Análisis Arquitectónico y Aplicación de Metodología Bim En El Santuario Extraurbano de Tusculum. *Archeol. Calc.* **2021**, *32*, 99–116. [CrossRef]

69. Aricò, M.; Lo Brutto, M. From scan-to-BIM to heritage building information modelling for an ancient arab-norman church. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *XLIII-B2-2022*, 761–768. [CrossRef]
70. Banfi, F. HBIM, 3D Drawing and Virtual Reality for Archaeological Sites and Ancient Ruins. *Virtual Archaeol. Rev.* **2020**, *11*, 16–33. [CrossRef]
71. Martinelli, L.; Calcerano, F.; Gigliarelli, E. Methodology for an HBIM Workflow Focused on the Representation of Construction Systems of Built Heritage. *J. Cult. Herit.* **2022**, *55*, 277–289. [CrossRef]
72. Martínez-Carricondo, P.; Carvajal-Ramírez, F.; Yero-Paneque, L.; Agüera-Vega, F. Combination of HBIM and UAV Photogrammetry for Modelling and Documentation of Forgotten Heritage. Case Study: Isabel II Dam in Níjar (Almería, Spain). *Herit. Sci.* **2021**, *9*, 95. [CrossRef]
73. Sztwiertnia, D.; Ochałek, A.; Tama, A.; Lewińska, P. HBIM (Heritage Building Information Modell) of the Wang Stave Church in Karpacz–Case Study. *Int. J. Archit. Herit.* **2021**, *15*, 713–727. [CrossRef]
74. Yang, X.; Lu, Y.C.; Murtiyoso, A.; Koehl, M.; Grussenmeyer, P. HBIM Modeling from the Surface Mesh and Its Extended Capability of Knowledge Representation. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 301. [CrossRef]
75. Campari, M.; D'Uffizi, F. BIM Models to Manage and Make Use of Cultural Heritage. In Proceedings of the IMEKO International Conference on Metrology for Archaeology and Cultural Heritage, MetroArchaeo, Lecce, Italy, 23–25 October 2017.
76. Banfi, F. The Evolution of Interactivity, Immersion and Interoperability in HBIM: Digital Model Uses, VR and AR for Built Cultural Heritage. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 685. [CrossRef]
77. Machete, R.; Falcão, A.P.; Gonçalves, A.B.; Godinho, M.; Bento, R. Development of a Manueline Style Object Library for Heritage BIM. *Int. J. Archit. Herit.* **2021**, *15*, 1930–1941. [CrossRef]
78. Pratali Maffei, S.; Canevese, E.; de Gottardo, T. The real in the virtual. The 3D model in the cultural heritage sector: The TIP of the iceberg. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Bergamo, Italy, 6–8 February 2019; Volume 42.
79. Bouzas, Ó.; Cabaleiro, M.; Conde, B.; Cruz, Y.; Riveiro, B. Structural Health Control of Historical Steel Structures Using HBIM. *Autom. Constr.* **2022**, *140*, 104308. [CrossRef]
80. Reina Ortiz, M.; Yang, C.; Weigert, A.; Dhanda, A.; Min, A.; Gyi, M.; Su, S.; Fai, S.; Santana Quintero, M. Integrating heterogeneous datasets in HBIM of decorated surfaces. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
81. Bruno, N.; Roncella, R. HBIM for Conservation: A New Proposal for Information Modeling. *Remote Sens.* **2019**, *11*, 1751. [CrossRef]
82. Ursini, A.; Grazzini, A.; Matrone, F.; Zerbinatti, M. From Scan-to-BIM to a Structural Finite Elements Model of Built Heritage for Dynamic Simulation. *Autom. Constr.* **2022**, *142*, 104518. [CrossRef]
83. Adami, A.; Scala, B.; Spezzoni, A. Modelling and Accuracy in a Bim Environment for Planned Conservation: The Apartment of Troia of Giulio Romano. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Nafplio, Greece, 1–3 March 2017; Volume 42.
84. Massafra, A.; Predari, G.; Gulli, R. Towards digital twin driven cultural heritage management: A HBIM-based workflow for energy improvement of modern buildings. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Prague, Czech Republic, 7–8 February 2022; Volume 46.
85. Fregonese, L.; Taffurelli, L.; Adami, A.; Chiarini, S.; Cremonesi, S.; Helder, J.; Spezzoni, A. Survey and Modelling for the BIM of Basilica of San Marco in Venice. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Nafplio, Greece, 1–3 March 2017; Volume 42.
86. Zhang, J.; Kwok, H.H.L.; Luo, H.; Tong, J.C.K.; Cheng, J.C.P. Automatic Relative Humidity Optimization in Underground Heritage Sites through Ventilation System Based on Digital Twins. *Build. Environ.* **2022**, *216*, 108999. [CrossRef]
87. Reinoso-Gordo, J.F.; Rodríguez-Moreno, C.; Gómez-Blanco, A.J.; León-Robles, C. Cultural Heritage Conservation and Sustainability Based on Surveying and Modeling: The Case of the 14th Century Building Corral Del Carbón (Granada, Spain). *Sustainability* **2018**, *10*, 1370. [CrossRef]
88. Lo Brutto, M.; Ebolese, D.; Fazio, L.; Dardanelli, G. 3D Survey and Modelling of the Main Portico of the Cathedral of Monreale. In Proceedings of the 2018 IEEE International Conference on Metrology for Archaeology and Cultural Heritage, MetroArchaeo 2018—Proceedings, Cassino, Italy, 22–24 October 2018.
89. Rodríguez-Moreno, C.; Reinoso-Gordo, J.F.; Rivas-López, E.; Gómez-Blanco, A.; Ariza-López, F.J.; Ariza-López, I. From Point Cloud to BIM: An Integrated Workflow for Documentation, Research and Modelling of Architectural Heritage. *Surv. Rev.* **2018**, *50*, 212–231. [CrossRef]
90. Alshawabkeh, Y.; Baik, A.; Fallatah, A. As-Textured as-Built Bim Using Sensor Fusion, Zee Ain Historical Village as a Case Study. *Remote Sens.* **2021**, *13*, 5135. [CrossRef]
91. Gigliarelli, E.; Calcerano, F.; Cessari, L. Heritage Bim, Numerical Simulation and Decision Support Systems: An Integrated Approach for Historical Buildings Retrofit. In Proceedings of the Energy Procedia, Matera, Italy, 12–13 May 2017; Volume 133.
92. Pepe, M.; Costantino, D.; Alfio, V.S.; Restuccia, A.G.; Papalino, N.M. Scan to BIM for the Digital Management and Representation in 3D GIS Environment of Cultural Heritage Site. *J. Cult. Herit.* **2021**, *50*, 115–125. [CrossRef]
93. Barrile, V.; Fotia, A. A Proposal of a 3D Segmentation Tool for HBIM Management. *Appl. Geomat.* **2022**, *14*, 197–209. [CrossRef]

94. Moyano, J.; León, J.; Nieto-Julián, J.E.; Bruno, S. Semantic Interpretation of Architectural and Archaeological Geometries: Point Cloud Segmentation for HBIM Parameterisation. *Autom. Constr.* **2021**, *130*, 103856. [CrossRef]
95. Colucci, E.; Xing, X.; Kokla, M.; Mostafavi, M.A.; Noardo, F.; Spanò, A. Ontology-Based Semantic Conceptualisation of Historical Built Heritage to Generate Parametric Structured Models from Point Clouds. *Appl. Sci.* **2021**, *11*, 2813. [CrossRef]
96. Nieto-Julián, J.E.; Farratell, J.; Bouzas Cavada, M.; Moyano, J. Collaborative Workflow in an HBIM Project for the Restoration and Conservation of Cultural Heritage. *Int. J. Archit. Herit.* **2022**, *16*, 1–20. [CrossRef]
97. Román, J.; Lerones, P.M.; Llamas, J.; Zalama, E.; Gómez-García-Bermejo, J. Towards the automatic 3D parametrization of non-planar surfaces from point clouds in HBIM applications. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
98. Argiolas, R.; Bagnolo, V.; Cera, S.; Sanna, G. Analytical representation of architectural built heritage. A sketch-to-BIM approach. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Mantua, Italy, 2–4 March 2022; Volume 46.
99. Quattrini, R.; Pierdicca, R.; Morbidoni, C. Knowledge-Based Data Enrichment for HBIM: Exploring High-Quality Models Using the Semantic-Web. *J. Cult. Herit.* **2017**, *28*, 129–139. [CrossRef]
100. López, F.J.; Lerones, P.M.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. A Framework for Using Point Cloud Data of Heritage Buildings toward Geometry Modeling in A BIM Context: A Case Study on Santa Maria La Real De Mave Church. *Int. J. Archit. Herit.* **2017**, *11*, 965–986. [CrossRef]
101. Kyriakaki-Grammatikaki, S.; Stathopoulou, E.K.; Grilli, E.; Remondino, F.; Georgopoulos, A. Geometric primitive extraction from semantically enriched point clouds. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Mantua, Italy, 2–4 March 2022; Volume 46.
102. Picone, R. Universal Design and Interoperable Digital Platforms Between Conservation and New Fruition Opportunities. The Case Study of Arianna's Domus in Pompeii. In Proceedings of the International Conference on Universal Design: Transforming our World through Universal Design for Human Development, Brescia, Italy, 7–9 September 2022; pp. 459–466.
103. Walsh, M.; Bernardello, R.A. Heritage Visualisation and Potential Speculative Reconstructions in Digital Space: The Medieval Church of St. Anne in Famagusta, Cyprus. *DISEGNARECON* **2018**, *11*.
104. Angulo, R.; Pinto, F.; Rodríguez, J.; Palomino, A. Digital Anastylosis of the Remains of a Portal by Master Builder Hernán Ruiz: Knowledge Strategies, Methods and Modelling Results. *Digit. Appl. Archaeol. Cult. Herit.* **2017**, *7*, 32–41. [CrossRef]
105. Ruffino, P.A.; Permadi, D.; Gandino, E.; Haron, A.; Osello, A.; Wong, C.O. Digital Technologies for Inclusive Cultural Heritage: The Case Study of Serralunga d'alba Castle. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Ávila, Spain, 1–5 September 2019; Volume 4.
106. Nieto-Julián, J.E.; Antón, D.; Moyano, J.J. Implementation and Management of Structural Deformations into Historic Building Information Models. *Int. J. Archit. Herit.* **2020**, *14*, 1384–1397. [CrossRef]
107. Prizeman, O.; Jones, C.B.; Parisi, M.; Pezzica, C. How Can Century-Old Architectural Hierarchies for the Design of Public Libraries Be Re-Interpreted and Re-Used? *J. Cult. Herit. Manag. Sustain. Dev.* **2018**, *8*, 481–494. [CrossRef]
108. Chiabrando, F.; Lo Turco, M.; Santagati, C. Digital Invasions: From Point Clouds to Historical Building Object Modeling (h-BOM) of a Unesco WHL Site. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Nafplio, Greece, 1–3 March 2017; Volume 42.
109. Capone, M.; Lanzara, E. Parametric Library for Ribbed Vaults Indexing. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Beijing, China, 28 August–1 September 2021; Volume 46.
110. Capone, M.; Lanzara, E. Scan-to-BIM vs 3D ideal model HBIM: Parametric tools to study domes geometry. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Bergamo, Italy, 6–8 February 2019; Volume 42.
111. Murphy, M.; Meegan, E.; Keenaghan, G.; Chenaux, A.; Corns, A.; Fai, S.; Chow, L.; Zheng, Y.; Dore, C.; Scandurra, S.; et al. Shape Grammar Libraries of European Classical Architectural Elements for Historic Bim. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Beijing, China, 28 August–1 September 2021; Volume 46.
112. Bagnolo, V.; Argiolas, R.; Cuccu, A. Digital Survey and Algorithmic Modeling in HBIM. Towards a Library of Complex Construction Elements. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Casablanca, Morocco, 10–11 October 2018; Volume 42.
113. di Donato, D.; Morganti, R.; Tosone, A.; Abita, M. Procedural modelling for HBIM of Italian railways iron bridges. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Mantua, Italy, 2–4 March 2022; Volume 46.
114. Scianna, A.; Gaglio, G.F.; La Guardia, M. BIM Modelling of Ancient Buildings. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Nicosia, Cyprus, 29 October–3 November 2018; Volume 11196 LNCS, pp. 344–355. [CrossRef]
115. Oreni, D.; Brumana, R.; Georgopoulos, A.; Cuca, B. HBIM for Conservation and Management of Built Heritage: Towards a Library of Vaults and Wooden Bean Floors. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Strasbourg, France, 2–6 September 2013; Volume 2.

116. Prizeman, O.E.C. HBIM and Matching Techniques: Considerations for Late Nineteenth- and Early Twentieth-Century Buildings. *J. Archit. Conserv.* **2015**, *21*, 145–159. [CrossRef]
117. Kontoudaki, A.; Georgopoulos, A. HBIM library development for a doric temple column. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2022**, *XLIII-B2-2022*, 1153–1158. [CrossRef]
118. Baik, A. *Heritage Building Information Modelling for Implementing UNESCO Procedures: Challenges, Potentialities, and Issues*; Routledge: London, UK, 2020.
119. Cheng, Y.M.; Mou, C.C.; Lu, Y.C.; Yen, Y.N. HBIM in Cultural Heritage Conservation: Component Library for Woodwork in Historic Buildings in Taiwan. In Proceedings of the Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Nicosia, Cyprus, 29 October–3 November 2018; Volume 11196 LNCS, pp. 376–385. [CrossRef]
120. José López, F.; Martin Lerones, P.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. Semi-Automatic Generation of Bim Models for Cultural Heritage. *Int. J. Herit. Archit. Stud. Repairs Maintence* **2017**, *2*, 293–302. [CrossRef]
121. Brumana, R.; Condoleo, P.; Grimoldi, A.; Previtali, M. Towards a semantic based hub platform of vaulted systems: HBIM meets a GEODB. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
122. Pinti, L.; Bonelli, S. A Methodological Framework to Optimize Data Management Costs and the Hand-Over Phase in Cultural Heritage Projects. *Buildings* **2022**, *12*, 1360. [CrossRef]
123. Chiabrando, F.; Sammartano, G.; Spanò, A. Historical buildings models and their handling via 3D survey: From points clouds to user-oriented HBIM. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2016**, *XLI-B5*, 633–640. [CrossRef]
124. Oostwegel, L.J.N.; Jaud, Š.; Muhič, S.; Malovrh Rebec, K. Digitalization of Culturally Significant Buildings: Ensuring High-Quality Data Exchanges in the Heritage Domain Using OpenBIM. *Herit. Sci.* **2022**, *10*, 10. [CrossRef]
125. Diara, F.; Rinaudo, F. IFC Classification for FOSS HBIM: Open Issues and a Schema Proposal for Cultural Heritage Assets. *Appl. Sci.* **2020**, *10*, 8320. [CrossRef]
126. Diara, F.; Rinaudo, F. From reality to parametric models of cultural heritage assets for HBIM. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
127. Beltramo, S.; Diara, F.; Rinaudo, F. Evaluation of an Integrative Approach between HBIM and Architecture History. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
128. Richard Petrie IFC 4.3—A Major Milestone Introduction and Overview of the Current Status. Available online: https://www.buildingsmart.org/ifc-4-3-a-major-milestone-introduction-and-overview-of-the-current-status/ (accessed on 13 February 2023).
129. Delpozzo, D.; Treccani, D.; Appolonia, L.; Adami, A.; Scala, B. HBIM and thematic mapping: Preliminary results. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Mantua, Italy, 2–4 March 2022; Volume 46.
130. Hull, J.; Ewart, I.J. Conservation Data Parameters for BIM-Enabled Heritage Asset Management. *Autom. Constr.* **2020**, *119*, 103333. [CrossRef]
131. England, H. *BIM for Heritage: Developing the Asset Information Model*; Historic England: London, UK, 2019.
132. Angulo-Fornos, R.; Castellano-Román, M. HBIM as Support of Preventive Conservation Actions in Heritage Architecture. Experience of the Renaissance Quadrant Facade of the Cathedral of Seville. *Appl. Sci.* **2020**, *10*, 2428. [CrossRef]
133. Cornaro, C.; Bovesecchi, G.; Calcerano, F.; Martinelli, L.; Gigliarelli, E. An HBIM Integrated Approach Using Non-Destructive Techniques (NDT) to Support Energy and Environmental Improvement of Built Heritage: The Case Study of Palazzo Maffei Borghese in Rome. *Sustainability* **2023**, *15*, 11389. [CrossRef]
134. Delpozzo, D.; Appolonia, L.; Scala, B.; Adami, A. Federated HBIM models for cultural heritage: Survey model and conceptual model. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Mantua, Italy, 2–4 March 2022; Volume 46.
135. Lee, J.; Kim, J.; Ahn, J.; Woo, W. Context-Aware Risk Management for Architectural Heritage Using Historic Building Information Modeling and Virtual Reality. *J. Cult. Herit.* **2019**, *38*, 242–252. [CrossRef]
136. Croce, P.; Landi, F.; Puccini, B.; Martino, M.; Maneo, A. Parametric HBIM Procedure for the Structural Evaluation of Heritage Masonry Buildings. *Buildings* **2022**, *12*, 194. [CrossRef]
137. Calvano, M.; Martinelli, L.; Calcerano, F.; Gigliarelli, E. Parametric Processes for the Implementation of HBIM—Visual Programming Language for the Digitisation of the Index of Masonry Quality. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 93. [CrossRef]
138. Lo Turco, M.; Giovannini, E.C.; Tomalini, A. Parametric and Visual Programming BIM Applied to Museums, Linking Container and Content. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 411. [CrossRef]
139. Costantino, D.; Pepe, M.; Restuccia, A.G. Scan-to-HBIM for Conservation and Preservation of Cultural Heritage Building: The Case Study of San Nicola in Montedoro Church (Italy). *Appl. Geomat.* **2021**, *15*, 607–621. [CrossRef]
140. Banfi, F. The Integration of a Scan-To-HBIM Process in BIM Application: The Development of an Add-in to Guide Users in Autodesk Revit. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.

141. Logothetis, S.; Stylianidis, E. BIM Open Source Software (OSS) for the Documentation of Cultural Heritage. *Virtual Archaeol. Rev.* **2016**, *7*, 28–35. [CrossRef]
142. Diara, F.; Rinaudo, F. Open Source HBIM for Cultural Heritage: A Project Proposal. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Riva del Garda, Italy, 4–7 June 2018; Volume 42.
143. Agustín, L.; Quintilla, M. Virtual reconstruction in BIM technology and digital inventories of heritage. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.
144. Tommasi, C.; Fiorillo, F.; Jiménez Fernández-Palacios, B.; Achille, C. Access and WEB-sharing of 3D digital documentation of environmental and architectural heritage. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Bergamo, Italy, 6–8 February 2019; Volume 42.
145. Werbrouck, J.; Pauwels, P.; Bonduel, M.; Beetz, J.; Bekers, W. Scan-to-Graph: Semantic Enrichment of Existing Building Geometry. *Autom. Constr.* **2020**, *119*, 103286. [CrossRef]
146. Quintilla, M.; Agustín, L. 3D Survey and Virtual Reconstruction of Heritage. The Case Study of the City Council and Lonja of Alcañiz. *Vitruvio* **2021**, *6*, 12–25. [CrossRef]
147. Gabriele, M.; Previtali, M. HBIM-GIS integration with an IFC-to-shapefile approach: The palazzo trotti vimercate pilot case study. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, New York, NY, USA, 11–14 October 2021; Volume 8.
148. Colucci, E.; de Ruvo, V.; Lingua, A.; Matrone, F.; Rizzo, G. HBIM-GIS Integration: From IFC to CityGML Standard for Damaged Cultural Heritage in a Multiscale 3D GIS. *Appl. Sci.* **2020**, *10*, 1356. [CrossRef]
149. Matrone, F.; Colucci, E.; De Ruvo, V.; Lingua, A.; Spanò, A. HBIM in a Semantic 3D GIS Database. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
150. Murphy, M.; Pavia, S.; Cahill, J.; Lenihan, S.; Corns, A. An Initial Design Framework for Virtual Historic Dublin. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
151. Bruno, N.; Rechichi, F.; Achille, C.; Zerbi, A.; Roncella, R.; Fassi, F. Integration of Historical GIS Data in a HBIM System. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, XXIV ISPRS Congress, Nice, France, 31 August–2 September2020; Volume XLIII-B4-2020.
152. Tsilimantou, E.; Delegou, E.T.; Nikitakos, I.A.; Ioannidis, C.; Moropoulou, A. GIS and BIM as Integrated Digital Environments for Modeling and Monitoring of Historic Buildings. *Appl. Sci.* **2020**, *10*, 1078. [CrossRef]
153. UNESCO; International Centre for the Study of the Preservation and Restoration of Cultural Property. *The Nara Document on Authenticity (1994)*; UNESCO: Paris, France, 1994.
154. Esponda, M.; Piraino, F.; Stanga, C.; Mezzino, D. Log houses in les laurentides. From oral tradition to an integrated digital documentation based on the re-discovery of the traditional constructive-geographical 'repertoires' through digital BIM data archive. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *IV-2/W2*, 75–82. [CrossRef]
155. Gargaro, S.; del Giudice, M.; Ruffino, P.A. Towards a Multi-Functional HBIM Model. *SCIRES-IT* **2018**, *8*, 49–58. [CrossRef]
156. Brumana, R.; Ioannides, M.; Previtali, M. Holistic Heritage Building Information Modelling (HBIM): From Nodes to Hub Networking, Vocabularies and Repositories. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
157. *ISO 21127:2014*; Information and Documentation—A Reference Ontology for the Interchange of Cultural Heritage Information. International Organisation for Standardisation: Geneva, Switzerland, 2020.
158. Kuo, C.L.; Cheng, Y.M.; Lu, Y.C.; Lin, Y.C.; bin Yang, W.; Yen, Y.N. A Framework for Semantic Interoperability in 3D Tangible Cultural Heritage in Taiwan. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Nicosia, Cyprus, 29 October–3 November 2018; Volume 11197 LNCS.
159. Ciuffreda, A.L.; Coli, M.; Donigaglia, T.; Mariotti, P.I.; Salvatici, T.; Simoni, G. The Tarantola Etruscan Pediment: NDT and 3D Model Content. In Proceedings of the COMPDYN Proceedings, Athens, Greece, 28–30 June 2021; Volume 1, pp. 1153–1169. [CrossRef]
160. Brumana, R.; Banfi, F.; Cantini, L.; Previtali, M.; Della Torre, S. HBIM Level of Detail-Geometry-Accuracy and Survey Analysis for Architectural Preservation. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
161. Trizio, I.; Marra, A.; Savini, F.; Fabbrocino, G. Survey methodologies and 3D modelling for conservation of historical masonry bridges. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Beijing, China, 28 August–1 September 2021; Volume 8.
162. Malinverni, E.S.; Mariano, F.; Di Stefano, F.; Petetta, L.; Onori, F. Modelling in HBIM to Document Materials Decay by a Thematic Mapping to Manage the Cultural Heritage: The Case of "Chiesa Della Pietà" in Fermo. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
163. Coli, M.; Ciuffreda, A.L.; Micheloni, M. An Informative Content 3d Model for the Hall Holding the Resurrection of Christ by Piero Della Francesca Mural Painting at Sansepolcro, Italy. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.

164. León-Robles, C.A.; Reinoso-Gordo, J.F.; González-Quiñones, J.J. Heritage Building Information Modeling (H-BIM) Applied to a Stone Bridge. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 121. [CrossRef]
165. Heesom, D.; Boden, P.; Hatfield, A.; Rooble, S.; Andrews, K.; Berwari, H. Developing a Collaborative HBIM to Integrate Tangible and Intangible Cultural Heritage. *Int. J. Build. Pathol. Adapt.* **2021**, *39*, 72–95. [CrossRef]
166. Slocombe, M. *The SPAB Approach to the Conservation and Repair of Old Buildings*; The Society for the Protection of Ancient Buildings: London, UK, 2022.
167. Historic England. *Conservation Principles, Policies and Guidance*; Historic England: London, UK, 2008.
168. Adami, A.; Fregonese, L.; Rosignoli, O.; Scala, B.; Taffurelli, L.; Treccani, D. Geometric survey data and historical sources interpretation for HBIM process: The case of mantua cathedral façade. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *XLII-2/W11*, 29–35. [CrossRef]
169. Maiezza, P. As-Built Reliability in Architectural HBIM Modeling. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Bergamo, Italy, 6–8 February 2019; Volume 42.
170. Parisi, P.; Lo Turco, M.; Giovannini, E.C. The value of knowledge through h-BIM models: Historic documentation with a semantic approach. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Bergamo, Italy, 6–8 February 2019; Volume 42.
171. Banfi, F.; Bolognesi, C.M.; Bonini, J.A.; Mandelli, A. The Virtual Historical Reconstruction of the Cerchia Dei Navigli of Milan: From Historical Archives, 3D Survey and HBIM to the Virtual Visual Storytelling. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Beijing, China, 28 August–1 September 2021; Volume 46.
172. Argiolas, R.; Bagnolo, V.; Cera, S.; Cuccu, S. Virtual environments to communicate built cultural heritage: A HBIM based virtual tour. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Prague, Czech Republic, 7–8 February 2022; Volume 46.
173. Udeaja, C.; Mansuri, L.E.; Makore, B.C.N.; Gyau Baffour Awuah, K.; Patel, D.A.; Trillo, C.; Jha, K.N. Digital Storytelling: The Integration of Intangible and Tangible Heritage in the City of Surat, India. In Proceedings of the Lecture Notes in Computer Science (Including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Virtual Event, 24–29 July 2021; Volume 12794.
174. Banfi, F.; Brumana, R.; Stanga, C. A Content-Based Immersive Experience of Basilica of Sant'ambrogio in Milan: From 3d Survey to Virtual Reality. In Proceedings of the ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Milan, Italy, 8–10 May 2019; Volume 42.
175. Jouan, P.; Moray, L.; Hallot, P. Built heritage visualizations in immersive environments to support significance assessments by multiple stakeholders. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Mantua, Italy, 2–4 March 2022; Volume 46.
176. Bolognesi, C.M.; Balin, S.; la Conca, A. Management of h-BIM model in holographic visualization. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Prague, Czech Republic, 7–8 February 2022; Volume 46.
177. Xi, W.; Cong, W. Remote Practice Methods of Survey Education for HBIM in the Post-Pandemic Era: Case Study of Kuiwen Pavilion in the Temple of Confucius (Qufu, China). *Appl. Sci.* **2022**, *12*, 708. [CrossRef]
178. Pybus, C.; Graham, K.; Doherty, J.; Arellano, N.; Fai, S. New realities for Canada's parliament: A workflow for preparing heritage bim for game engines and virtual reality. In Proceedings of the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, Ávila, Spain, 1–5 September 2019; Volume 42.