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# 1 **Review of Built Heritage Modelling: Integration of** 2 **HBIM and Other Information Techniques**

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10 **Abstract:** Built heritage documentation involves the 3D modelling of the geometry (typically using 3D  
11 computer graphics, photogrammetry and laser scanning techniques) and information management of  
12 semantic knowledge (i.e., using Geographic Information System (GIS) and ontology tools). The recent  
13 developed Building Information Modelling (BIM) technique combines 3D modelling and information  
14 management. One of its modern application is heritage documentation and has generated a new concept of  
15 **Historic/Heritage Building Information Modelling** (HBIM). This paper summarises the applications of  
16 these information techniques on the built heritage documentation. We utilise Web of Science Collection to  
17 monitor the publications on built heritage documentation. We analyse the research trend in heritage  
18 modelling by comparing the attention paid by researchers before and during the 2010s. The results show  
19 that photogrammetry is always the most popular method in heritage modelling. More and more works in  
20 heritage modelling have begun to use laser scanning, computer science, GIS and especially BIM  
21 techniques. Ontologies and 3D computer graphics are traditional ways for heritage documentation.  
22 Moreover, we pay attention to the roles of BIM on heritage documentation and conduct a detailed  
23 discussion on how to extend the HBIM capabilities by integrating with other techniques. The integration  
24 provides possible enhanced functions in HBIM, including accurate parametric modelling from computer  
25 graphics, automatic semantic segmentation of 3D point cloud from reality-based modelling, spatial  
26 information management and analysis by GIS, and knowledge modelling by ontology.

27 **Keywords:** built heritage; BIM; parametric objects; semantics; geometric model; knowledge

## 28 **1. Introduction**

### 29 *1.1. Background*

30 Heritage is our legacy from the past, what we live with today, and what we pass on to future  
31 generations. The documentation of built heritage involves the 3D modelling of the geometry and  
32 information management of semantic knowledge. Currently, lots of information techniques benefit for built  
33 heritage modelling, management and conservation, including 3D computer graphics, photogrammetry,  
34 laser scanning, Geographic Information System (GIS), ontology and recently developed Building  
35 Information Modelling (BIM).

36 The traditional concept of built heritage modelling entails either accurate geometric modelling or  
37 virtual reconstruction, such as the open-source platforms of MicMac<sup>1</sup> (photogrammetry), MeshLab<sup>2</sup> (3D  
38 triangular mesh) and 3DHOP ([3D Heritage Online Presenter](#)) [1]. These 3D models, mainly from 3D  
39 computer graphics, photogrammetry and laser scanning, aspire to illustrate the shape of the heritage yet do  
40 not make access to additional information possible [2]. In addition to highly accurate geometry, more  
41 considerable efforts are needed for the management of historical buildings with more details (semantic,  
42 attribute, material, temporal and relationship) of the object and its sub-elements.

43 Heterogeneous knowledge is another essential asset for built heritage. A complete representation of  
44 architectural heritage also requires a large amount of knowledge related to its history, physical  
45 configuration and condition and a high number of social, political, economic, and cultural issues relating to  
46 the external environment [3]. Knowledge and information model, from ontology and GIS, play important  
47 roles in the knowledge management and analysis of the attribute, semantic and relationship information for  
48 the heritage documentation. But they are limited to describe the detailed geometric information, especially  
49 [referring to](#) the complex and irregular structures of heritage.

50 The recent developed Building Information Modelling (BIM) technique combines 3D modelling and  
51 information management. One of its modern application is heritage documentation and conservation [4–8]  
52 and has generated a new concept of [Historic/Heritage Building Information Modelling](#) (HBIM). Murphy et  
53 al. [9] firstly defined HBIM in 2009, which clearly expressed the prospects of the BIM technique in historic  
54 scenes. HBIM of a historical building can provide: (i) a complete survey and parametric modelling on the

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<sup>1</sup> *MicMac*: <https://micmac.engg.eu/> (Accessed on April 20, 2020)

<sup>2</sup> *MeshLab*: <http://www.meshlab.net/> (Accessed on April 20, 2020)



77 However, there still does not exist a synthetic review of (i) what kinds of roles of these techniques on  
88 heritage documentation, and (ii) how to extend the capability of HBIM by integration to other techniques.

79 In this paper, we revealed the research trend in heritage documentation in a broader sense from the  
80 conventional 3D modelling and knowledge management to recently developed HBIM. Also, we present the  
81 primary roles of HBIM on heritage documentation and pay attention to how to extend the functions of  
82 HBIM and what kinds of problems exist when integrating it with other information techniques.

### 83 1.2. 3D modelling

#### 84 1.2.1. 3D computer graphics

85 3D computer graphics is the earliest to model heritage and is normally dedicated to virtual  
86 reconstruction. Virtual reconstruction commonly refers to a virtual replica of the heritage object  
87 (disappeared, damaged or existing), in which the data source may come from digitalised historical materials  
88 recording the heritage, reality-based photographs and measurable drawings representing the surface.  
89 Therefore, virtual reconstruction may resurrect the past once more, virtualize the current, and predict the  
90 future; yet the visual models are mostly 2.5D models.

91 Currently, advances in computer graphics allowed the parametric design of heritage composing of any  
92 irregular shaped object with high accuracy and very close to the truth by using modelling tools (such as  
93 *Rhino 3D*<sup>3</sup>, *3ds Max*<sup>4</sup>, *Maya*<sup>5</sup>, and *Blender*<sup>6</sup>). The parametric design consists of variable parameters, such as  
94 the values of all sizes, and invariable parameters, such as the relationships between the geometric elements.  
95 The system can automatically maintain the constant settings when the variable parameters change. After  
96 predefinition of a set of programs, the revision of the built model just needs to modify several invariable  
97 parameters [20–22].

98 Also, 3D computer graphics used procedural modelling to model buildings with similar and repetitive  
99 structures by using a rule-based description in a rapid manner [16][23][24]. Procedural modelling has  
100 succeeded in modern urban building modelling [25][26], and some works have extended it to different  
101 styles of historic architectures [27][28][29]. For example, a Generative Modelling Language (GML),

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<sup>3</sup> *Rhino 3D*: <https://www.rhino3d.com/> (Accessed on April 20, 2020)

<sup>4</sup> *3ds Max*: <https://www.autodesk.com/products/3ds-max/> (Accessed on April 20, 2020)

<sup>5</sup> *Maya*: <https://www.autodesk.com/products/maya/> (Accessed on April 20, 2020)

<sup>6</sup> *Blender*: <https://www.blender.org/> (Accessed on April 20, 2020)

102 allowing the generation of highly complex objects based on a set of formal construction rules, is developed  
103 and performed the procedural construction of Gothic church windows efficiently [30].

### 104 1.2.2. Reality-based modelling

105 Until now, multi-platform-based imagery and laser scanning data are all used to geometrically model  
106 the heritage, which focuses on the outline structures and measurement information for the real object. It is  
107 no longer a problem to obtain an accurate 3D geometric model, either by a laser scanner or imagery dense  
108 matching approaches [31]. Although aerial photogrammetry and Light Detection and Ranging (LiDAR)  
109 can be used to generate the **Digital Surface Model** (DSM) of heritage sites, it is difficult to meet the  
110 demands of heritage applications with regard to accuracy and detail [32][33,34]. Built heritage modelling  
111 requires more complex and accurate geometric representations, so terrestrial data combined with  
112 low-altitude UAV data have frequently been adopted thus far [35][36,37].

113 Photogrammetry and laser scanning have generated the accurate 3D point cloud and holistic mesh to  
114 record the shape of heritage. The current challenge is to extend these holistic geometries to semantic [38],  
115 parametric [39] and knowledge [40] models. Particularly, it is anticipated to realise semantic segmentation  
116 and labelling of sub-elements (from façades and roofs to columns, openings, etc.) and microstructures  
117 (sculptures and unique structures peculiar to heritage), and related fields, such as pattern recognition and  
118 machine learning, are rapidly developing. For example, many approaches have been proposed to label  
119 façade elements, typically by inverse procedural modelling [41], RANSAC based segmentation [42],  
120 region growing algorithms [43], Manhattan World assumption [16], and grammar-based methods [44,45].  
121 However, these automatic and semiautomatic segmentation works assumed buildings as a regular structure  
122 with crossing and repetitive pattern, which excluded the complex historical buildings.

### 123 1.3. Information and knowledge management

124 3D computer graphics, photogrammetry and laser scanning paid attention to the documentation of the  
125 geometric aspect of built heritage. On the contrary, GIS and ontology provide the enhanced relative  
126 database for the management and analysis of the semantic, attribute and relationships among the  
127 sub-elements composing heritage. GIS “lets us visualise, question, analyse and interpret data to understand  
128 relationships, patterns and trends” [46], which focuses on managing the spatial relationship and semantic  
129 information [47,48]. Ontology is used to formally represent knowledge and rules of a particular domain to  
130 facilitate computer processing, reasoning, knowledge sharing and re-use [49–51].

### 131 1.3.1. Geographic Information System

132 GIS pays attention to managing, querying and analysing spatial, attribute, and relationship  
133 information among elements. As a tool for heritage site management, GIS can establish databases for  
134 archaeological sites and monuments at regional and national levels [52] [53]. GIS provides tools to query  
135 the data for preservation purposes and to realise advanced analysis [54]. Also, 3D WebGIS is widely  
136 adopted for 3D built heritage models to be visited on websites, which benefits the product management and  
137 popularity. In this manner, a user-centred system is obtained to extend the interoperability and exchange of  
138 data to reach more potential users [55][56,57]. For example, a 3D WebGIS for archaeological research,  
139 called the MayaArch3D project [58], offers a system architecture for managing 3D models and their  
140 associated data so that researchers can view them on the Internet in real-time, analyse them, and compare  
141 them with other models.

142 GIS is not only a management and analysis tool but also a modelling tool that has been widely used to  
143 procedurally model large-scale heritage scenes [26]. For example, *ESRI CityEngine* [59] is a tool that  
144 allows for the efficient modelling of 3D scenes at large scale and with arbitrary detail. The ancient Roman  
145 town, Pompeii, was automatically reconstructed utilizing *CityEngine* on the basis of ground plans  
146 (footprints) and drawings/sketches of selected building types [60]. The famous Rome Reborn 2.0 [61]  
147 reconstructed approximately 7000 domestic buildings using grammar-based procedural modelling [62] and  
148 *CityEngine* based on manual creation of typical monuments and buildings with computer graphics  
149 techniques.

### 150 1.3.2. Ontology

151 GIS is characterized by managing spatial-related information. By comparison, an ontology provides a  
152 complete representation of built heritage related to its history, physical configuration and condition and a  
153 high number of social, political, economic, and cultural issues relating to the external environment [51][3].  
154 It is increasingly used to overcome the barriers to heterogeneous semantic data sharing and integration  
155 about cultural heritage. Specifically, several advantages of ontology semantics in built heritage include (i)  
156 Homogenous representation. The main advantage of using ontologies is the ability of homogenous  
157 representation and management of all the knowledge related to heritage in a unified semantic network,  
158 including concepts, relationships, functions, rules and constraints [57]. (ii) Sharable and readable in a  
159 scientific community. Ontology semantics can share consensual knowledge agreed by a scientific  
160 community to increase the interoperability in individuals and organizations [63][64]. (iii) Understandable

161 by a computer. The rules defined by an ontology allow checking the data and inferencing new knowledge  
162 [63][57][65].

163 In the cultural heritage context, International Committee for Documentation Conceptual Reference  
164 Model (CIDOC CRM) is the main ontological reference model [66]. This ontology was initially towards  
165 the establishment of standard description and maintenance of museum artefacts. It became the ISO  
166 standard<sup>7</sup> in 2006 to allow the formal and highly specific representation of information about historical  
167 buildings. To date, CIDOC CRM facilitates integration and interchange of heterogeneous cultural heritage  
168 information and support operations of reasoning and inference. While the CIDOC CRM model was  
169 developed mainly to manage the cataloguing of cultural heritage documentation, some other  
170 domain-specific ontologies have been progressively introduced to represent other aspects of the heritage  
171 conservation process [57,67]. Geneva City Geographic Markup Language ontology (Geneva CityGML)  
172 [68] is an ontological equivalent of the CityGML standard and allow to create 3D models of historical  
173 buildings. The Monument Damage Information System (MONDIS) supports the documentation and  
174 analysis of damaged historical structures, their diagnosis, and possible interventions [69].

#### 175 *1.4. BIM and HBIM*

176 BIM was originally used for the management of the life-cycle construction process in the architectural  
177 industry. As-built BIM contributes to the representation of physical and functional characteristics of  
178 existing buildings by reality-based data acquisition and reverse engineering [70]. The aim of introducing  
179 the BIM/as-built BIM technique into heritage modelling underlines the strict relation between object  
180 modelling and information involving various attributes, temporal change and spatial constraints [71][72].

181 HBIM is suitable for the recreation of a historical building from the existing description data (such as  
182 historical documents, bibliographic references, photographs, drawings, etc.), especially for the  
183 past/disappeared heritage. As-built HBIM is increasingly used to restore, model and manage existing  
184 valuable constructions and historic structures by using reality-based recording data (typically 3D point  
185 cloud from laser scanning and photogrammetry).

186 According to the description documents (for HBIM) and reality-based recording data (for as-built  
187 HBIM), a library of parametric and semantic elements (such as wall, roof, stair, door and window) can be  
188 created and then used to establish the heritage [73–77]. The model is not only a virtual representation of the  
189 construction. It is a vital part of the project, where the different elements of the building become advanced

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<sup>7</sup> CIDOC CRM: <http://www.cidoc-crm.org/> (Accessed on April 20, 2020)

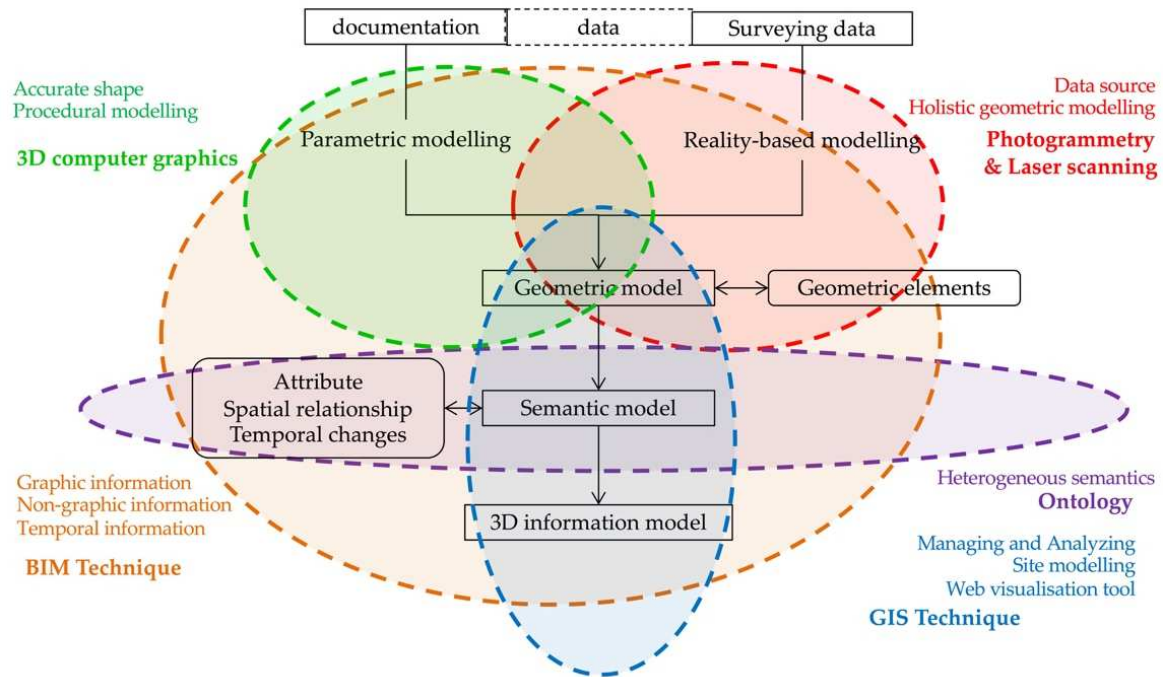


190 objects with parametric intelligent, including the quantitative and qualitative description and strict  
191 relationship information. As a typical parametric design application, HBIM realises the linkage of the  
192 information storage and modification, in which the elements can be modified by altering parameters and the  
193 relations to other objects remain unchanged.

194 Currently, the HBIM modelling workflow tends to combine both descriptive and reality-based data to  
195 document the built heritage [4,78,79]. BIM software is firstly used to construct the parametric elements  
196 regarding the historical buildings based on documentation. The application of inverse engineering, which  
197 maps the parametric elements to the reality-based data, makes it possible to refine the parameters and obtain  
198 a current-state diagnosis [80][81]. Therefore, an HBIM project needs to organise the protocol created  
199 simultaneously or interactively by analysing documentation- and reality-based data. That is, how to fit the  
200 standard shapes and BIM components into the 3D point cloud are essential processing that could be  
201 performed via manual interpretation (currently) and 3D structure similarity measurement [82].

### 202 *1.5. Brief Summary*

203 As in the above description, each technique has an advantage in built heritage modelling and covers  
204 the heritage documentation from data sources to different levels of models (Figure 2). 3D computer  
205 graphics focus on accurate description using parametric design, large-scale areas using procedural  
206 modelling and virtual reconstruction with enhanced visual effect. Reality-based shape information is  
207 obtained by photogrammetry and laser scanning with non-contact tools, which is accordant with the  
208 concept of heritage conservation. Automated or semi-automated algorithms are expected to realize  
209 semantic segmentation of the holistic geometry. GIS is used to manage the attribute and spatial information,  
210 and webGIS provides an available web access tool for 3D models. Ontology deals with the heterogeneous  
211 knowledge describing the heritage. Recently developed BIM techniques provide a more powerful  
212 environment that combines 3D geometric modelling and information management.



213

214 **Figure 2.** The overall scheme of built heritage modelling with combined techniques215 **2. Literature Analysis**

216 On the basis of the Web of Science™ Core Collection, we indexed the publications with combinations  
 217 of key terms and analysed the tendency of each technique. To limit the broad scope to 3D built heritage  
 218 modelling, structured queries on Web of Science using combinations of key terms and their synonyms  
 219 (heritage/"historic\* building\*" AND 3D) were conducted, yielding a total of 2848 records until the year of  
 220 2019. Then, to analyse the transformation from geometric modelling to semantic- and information-enriched  
 221 heritage modelling, typical publications utilizing BIM techniques are marked.

222 Due to the applied query method, the review excludes research currently underway that is not  
 223 available in the mentioned databases, journals or conferences that are not included in the Web of Science™  
 224 Core Collection, or studies that have not been published in English yet.

225 *2.1. What types of techniques are popular within certain time span*

226 We firstly take related key terms (Table 1) to monitor the publications on heritage documentation  
 227 using different techniques. Two periods are considered, including all years in the database (from 1975 to  
 228 2019) and 2010s. The number of publications can reflect the focuses of the researchers in the field of  
 229 heritage documentation. The result shows heritage documentation draws increasing attention, considering  
 230 that 87% of the works are published in the 2010s.

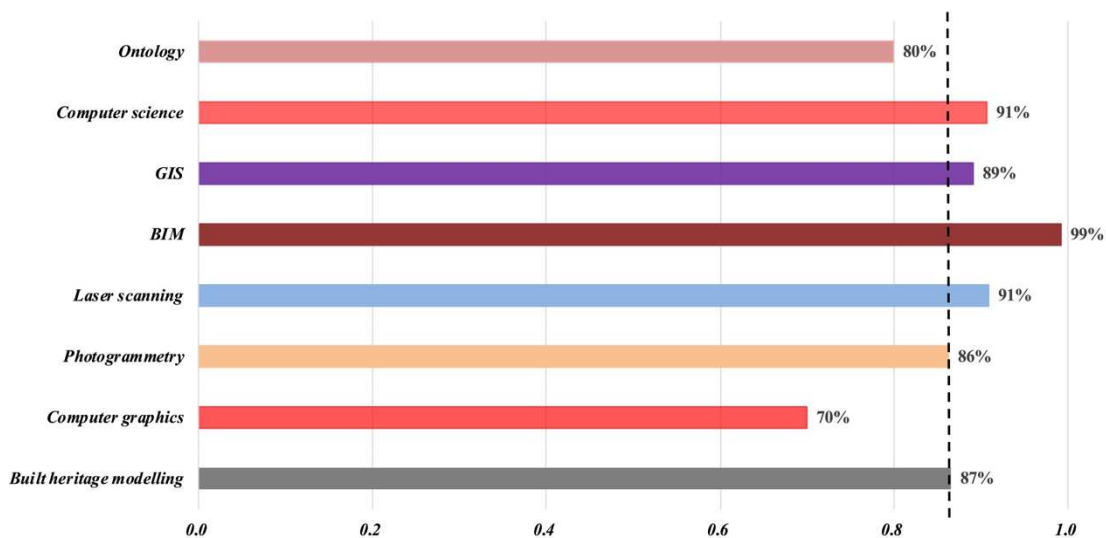
231 A rate (Eq. 1) is calculated by the ratio of publication numbers during the 2010s among the total  
 232 publications, which are dedicated to mirroring the change of the hotspot issues. That is, the higher the value  
 233 is, the more attention has been paid in recent days. As shown in Figure 3, built heritage modelling (with the  
 234 rate 87%) has been attracting emphasis in the 2010s, which serves as the baseline to find the increasingly  
 235 popular and potential techniques in the field of heritage documentation.

$$236 \quad \text{rate} = \frac{\text{publication numbers during the 2010s}}{\text{all publication numbers}} \quad (1)$$

237 **Table 1.** Key terms used to estimate the publication number (during the 2010s/total)

Terms (indexed on 01 January 2020)	Results
TS = ((heritage OR "historic* building*") AND "3D")	2465/2848
TS = ((heritage OR "historic* building*") AND "3D" AND ("computer graphics" OR "3D graphics"))	70/100
TS = ((heritage OR "historic* building*") AND "3D" AND (Image OR photogrammetry))	1125/ 1304
TS = ((heritage OR "historic* building*") AND "3D" AND ("laser scan*" OR LiDAR))	700/770
TS = ((heritage OR "historic* building*") AND "3D" AND ("feature matching" OR "computer vision" OR "machine learning"))	78/86
TS = ((heritage OR "historic* building*") AND (BIM OR "building information model*"))	258/260
TS = ((heritage OR "historic* building*") AND "3D" AND (GIS OR "Geograph* information system*" OR CityGML))	164/184
TS = ((heritage OR "historic* building*") AND (ontology OR ontologies))	327/409

238



239

240 **Figure 3.** Publication rate during recent years. The vertical dash line indicates the publication rate in the field of  
 241 built heritage modelling. Generally, the higher rate of the specific technique means the potential, while the lower  
 242 rates suggest the traditional or not well-known techniques.

243 Through this study, it becomes clear that photogrammetry is the most popular method in heritage  
244 modelling. The reasons may be that photogrammetry can provide not only images for documentation  
245 purposes but also accurate geometry models with low costs in time and money. Imagery is also an  
246 interesting supplement for laser scanning, and machine learning in computer vision provides new  
247 opportunities for image-based semantic modelling.

248 More and more works in heritage modelling have begun to use laser scanning, computer science, GIS  
249 and especially BIM techniques. Laser scanning is becoming cheaper and portable, which broadens its  
250 applications. With the easy acquisition of accurate geometry by photogrammetry and laser scanning, the  
251 semantic segmentation has become a critical issue. BIM techniques can create the parametric element  
252 library, restore the graphics geometry information and non-graphic attribute and relationship information,  
253 and manage the 3D temporal model. These advantages make it go further in the necessity of semantic  
254 modelling, although the time-consuming manual operation is needed, especially when preserving complex  
255 and irregular structures. GIS can manage and analyse the multi-dimensional information in the web access,  
256 which is accordant with the heritage conservation and popularity demands. Once BIM and GIS deal well  
257 with complex structures, semantic or information modelling of built heritage will be solved. However, there  
258 will still be a long road for semi-automatic or automatic parameterization of the elements. Currently,  
259 objects in certain scenes can be recognised and labelled with machine learning and pattern recognition  
260 approaches. It is highly anticipated to realise the semantic segmentation of 3D heritage geometric models or  
261 2D imagery, although such an application needs a large amount of training data and addresses simple  
262 scenes.

263 The role of ontologies on built heritage documentation has not yet obtained due attention. The early  
264 research paid more attention on the management of artefacts [57], similarly to the CIDOC CRM that was  
265 originally developed for the standard description and maintenance of museum artefacts. Ontology-based  
266 knowledge model for architectural heritage is growing in recent years, especially with the integration of  
267 geometric modelling, BIM and GIS.

268 It seems that computer graphics is developing relatively slowly in the heritage modelling field. The  
269 reasons may be that virtual reconstruction has been relatively mature compared to semantic information,  
270 and business corporations spend more effort than academic fields on better visual effects.

## 271 2.2. Roles of BIM techniques in built heritage

272 We selected about 60 typical articles related to built heritage modelling utilizing BIM techniques  
273 (Table 2). Via the research statistics, current BIM in heritage modelling has focused on semantic modelling  
274 by historical materials with the BIM concept or reality-based data with the as-built concept. Documentation  
275 materials, including 2D drawings [83], 2D floor plans [84], archival documents [85] and architectural  
276 pattern books [86], are used to re-create the heritage by parameterizing the new elements in the BIM library.  
277 Yet some firstly build a virtual or geometric model using computer graphics software and just improve it to  
278 a parametric model using BIM software [71,87]. Laser scanning has been widely used to reconstruct  
279 existing heritage and import it into BIM software to build the elements as a reference. Most works utilizing  
280 combined data from documentation and photogrammetry just follow the common HBIM process, mapping  
281 the parametric elements to the point cloud [62,88], although several works obtained two separate models  
282 with separate procedures under the BIM and as-built BIM concept [71,89]. The ideal model deduced from  
283 historic architectonic patterns and real geometry can be compared between the past and current [90].

284 Some have also explored specific analytical applications and heritage management on the basis of  
285 BIM parametric models. Meanwhile, some works have proposed approaches dedicated to heritage  
286 modelling applications while just conducting them in modern buildings at the present stage. Many works  
287 have realised the semi-automatic segmentation of the point cloud and built the semantic model in the BIM  
288 platform [91], while current results are conducted in regular buildings and expected the further  
289 development of heritage buildings. The irregular and complex shapes of heritage yield more difficulties,  
290 especially for semi-automatic element extraction.

291 There are also three reviews to explore the potential of BIM in heritage modelling. [92] focused on the  
292 3D modelling of heritage building by point cloud and analysed “as-built” BIM characterization including  
293 element shape, relations and attributes; [18] mainly summarised the current BIM platforms and illustrated  
294 the common HBIM process for historical buildings; and [17] reviewed the parametric modelling of  
295 heritage structures in BIM platform and the potential of HBIM for cultural heritage conservation and  
296 management.

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**Table 2.** The roles of BIM in built heritage documentation

Roles of HBIM		References
3D parametric modelling	Documentation-based (Red)	
	Laser scanning based (Blue)	
	Photogrammetry based (Green)	
Analysis, management, & conservation		[6,7,19,51,71,86,90,93-100]
Expected to HBIM		[101-105]
Review		[17,18,92]

306

### 307 3. Discussion on the integration of HBIM and other techniques

308 BIM provides the possibility to combine the geometric, semantic and parametric modelling and  
 309 attribute, temporal and relationship information management to the uniform platform. However, it still  
 310 exists lots of limitations, especially when it comes to heritage documentation. It is highly anticipated to  
 311 extend BIM functions on heritage-related issues by integrating traditional information techniques.

#### 312 3.1. Generate complex element by the combination with computer graphics

313 It is usually a manually time-consuming concept in BIM software to parametrically model the  
 314 historical elements, and they are limited in their ability to create complicated irregular geometry. That is,  
 315 the time complexity and geometric accuracy for parameterizing the complex and irregular historic structure  
 316 elements are the main challenges.

317 Thus far, there exist mainly two ways to parametrically model the irregular elements not included in  
 318 the BIM library. The first one is the manual modelling of the elements in a BIM software platform directly

319 (e.g. *Revit*<sup>8</sup> and *ArchiCAD*<sup>9</sup>). The main drawback is its low efficiency and how hard it is to ensure geometric  
 320 accuracy. The other is the resort to programming, including the *Geometric Description Language (GDL)* of  
 321 *ArchiCAD* library parts and *Autodesk Dynamo* visual programming for *Revit*. The parametric *GDL* and  
 322 *Dynamo* elements could be completely described as 2D symbols, 3D geometric models, attribute  
 323 specifications and additional spatial relationships in the BIM platform.

324 Both the computer graphics and the original BIM concept for built heritage modelling have formed  
 325 documentation-based parametric modelling using historical materials, such as historical documents,  
 326 bibliographic references, photographs and drawings. BIM goes further than computer graphics to improve  
 327 the virtual reconstruction of an information-rich model by semanticizing the elements.

328 Currently, BIM is increasingly paying attention to irregularly shaped modelling by introducing  
 329 computer graphics modelling techniques. Some works build the irregular structures with the help of  
 330 computer graphics software, such as *Rhino 3D* [106,107] or *Sketchup* [108], which could address any  
 331 irregularly shaped object compared to BIM platforms [99]. For example, *Rhino 3D* software is able to  
 332 generate accurate and free-formed models of complex and irregular geometries, especially using NURBS to  
 333 represent surfaces.

334 The current tight combination of graphics geometry modelling and BIM semantic modelling, such as  
 335 the *Rhino 3D-Grasshopper-ArchiCAD* connection developed by *ArchiCAD* and *Rhino 3D*, empowers  
 336 architects to start and modify their designs in any of the three design environments (*Rhino 3D*, *Grasshopper*  
 337 or *ArchiCAD*). Also, *Rhino 3D* builds BIM semantic models and has been expanded to *Rhino BIM*. The  
 338 design of *Rhino 3DBIM* is 3D-centric, where the design is modelled and captured in a 3D database  
 339 compared to the conventional BIM software.

### 340 3.2. Automate as-built HBIM based on point cloud processing approaches

341 Built heritage geometric modelling has often been conducted using reality-based data [109–111]. BIM  
 342 goes further than the traditional geometric model with parametric and semantic elements. As a 3D  
 343 information modelling environment, BIM software is increasingly supportive of 3D point cloud  
 344 representing the entity surface, which is called as a scan-to-BIM process. By importing the point cloud into  
 345 the BIM software, the solid building components can be created using the existing BIM IFC classes and  
 346 self-defined structures.

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<sup>8</sup> *Revit* <https://www.autodesk.com/products/revit> (Accessed on April 20, 2020)

<sup>9</sup> *ArchiCAD*: <https://www.graphisoft.com/archicad/> (Accessed on April 20, 2020)

347 Unfortunately, the scan-to-BIM process remains mostly a manual process [81,106,112], and a key  
348 challenge today is thus to automate the process leading to as-built BIM from a point cloud. To reduce the  
349 manual work in such scan-to-BIM process, many commercial tools and algorithms exist. Many works  
350 utilised the commercial scan-to-BIM plugins in *Autodesk Revit* platform, including *ClearEdge3D*  
351 *Edgewise*, *IMAGINit Scan to BIM*, *Pointsense* and *Leica CloudWorx*. Some tried to automate the  
352 scan-to-BIM process by self-developed algorithms [91,113,114]. Although they show excellent progress  
353 for the automation reconstruction of as-built BIM from point clouds, those works only deal with planar  
354 walls and floors and some other regular structures (i.e., rectangular openings and cylinder columns).

355 That is, most commercial BIM packages and scan-to-BIM algorithms were mainly developed for  
356 modern buildings with regular shapes. Historical buildings are composed of complicated and irregular  
357 architectural elements, which makes it problematic to segment and parameterise the elements. For the  
358 irregular structures widely existing on built heritage, the current scan-to-HBIM process is time-consuming  
359 manual modelling. Although existing BIM platforms are supportive of the point cloud, the parametric  
360 modelling tools are still limited because most of BIM software is not 3D-centric modelling environment  
361 and cannot directly parametrically design the shape on the reference of the point cloud in 3D space. It is  
362 usually a manually time-consuming concept in BIM software to parametrically model the historical  
363 elements, and they are limited in their ability to create complicated irregular geometry. That is, the time  
364 complexity and geometric accuracy for parameterizing the complex and irregular historic structure  
365 elements are the main challenges.

366 Besides, there have been lots of point cloud processing libraries and algorithms available in the field  
367 of reality-based modelling. These approaches pay attention on the semantic segmentation of the holistic  
368 geometric models, and they need additional platforms to manage the semantic and relationship information.  
369 In contrast, the relationship and parametric description is the core for (H)BIM technique. The  
370 scan-to-(H)BIM obtain the semantic, parametric, attribute and relationship during the modelling process.  
371 The scan-to-(H)BIM is still a new topic and its integration with point cloud processing algorithms can help  
372 to reduce the human involvement in the modelling process. But this kind of integration relies on the  
373 progress of the BIM platforms to support advanced point cloud processing algorithms.

### 374 3.3. Information management by BIM-GIS integration

375 BIM provides high editing functionalities for parametric modelling and achieves semantic models.  
376 But BIM is limited to storing semantic and attribute aspects thus far since it lacks query (attribute and



377 spatial) functions. GIS has a priority in information management (attribute, semantic, and relationship  
378 information analysis and management).

379 The current trend concerns the convergence of both concepts on lots of fields, such as the AEC  
380 industry [115], facility management [116], urban architectural [117], and so on. The separate standards, for  
381 instance, the two most popular standards of Industrial Foundation Class (IFC) for BIM and CityGML for  
382 GIS, seem to be widely accepted for exchanging semantic 3D information and geographical for BIM and  
383 GIS [118]. During the integration process, some significant details are lost due to the extraction and  
384 simplification of data from one system to another [38,115].

385 When it comes to the historical buildings composed of complex elements, the BIM-GIS integration is  
386 also the trend. It faces the new challenge because both BIM and GIS are originally developed for modern  
387 buildings. A typically two-stage outline involving HBIM for 3D modelling and GIS for further  
388 management and analysis has been defined by Dore and Murphy [119]. But it is critical to minimise  
389 information loss in the conversion process [120,121]. Many studies have been performed to minimise the  
390 information loss in integrating BIM and GIS. The common process is to extend the models from BIM to  
391 GIS, and a CityGML extension called GeoBIM to get semantic IFC data into the GIS context is developing  
392 well [122]. BuildingSMART IFC is also extending itself for GIS project application, such as the new entity  
393 for spatial zones, geographic elements and external spaces. A united system integrating GIS and BIM  
394 concepts without information loss is not foreseen.

395 It benefits information consistency among the different BIM software, GIS software and other  
396 modelling software if the representation of the complexity of the irregular shapes of the elements tends to  
397 be simplified. Unfortunately, when the simplification causes the loss of the details of the architectural  
398 surface, it goes against the aim of heritage conservation. The complexity of many elements and the lack of  
399 unified criteria make it difficult to simultaneously minimise information loss and optimise geometric  
400 architectural conservation during the exchange process between the two types of information systems.

#### 401 *3.4. Heterogeneous knowledge management by the connection with ontology*

402 HBIM provides a modelling environment where geometrical information and some intangible data are  
403 structured in a coherent database, and GIS provides a management environment where geometrical,  
404 attribute and relationship can be queried and analysed. But they still leave out of the model a large amount  
405 of knowledge, not directly relatable to heritage's components but still needed to fully represent the object  
406 [51].

407 Thus, ontology plays increasingly important roles in connection with HBIM to comprehensively  
408 represent the historical buildings [123–125]:

409 (i) Knowledge modelling: Ontology-based knowledge model is combined with HBIM to enrich the  
410 semantic information. Ontology serves as a data collector to represent a large amount of semantics  
411 possibly independent from the built heritage (for example historical context, social information,  
412 environmental resources, other heritage information, etc.) [126].

413 (ii) Information extraction and querying: The combination of ontology can extend the HBIM model with  
414 the capabilities of information extraction and querying. The typical workflow is to use *Autodesk Revit*  
415 as HBIM platform and *Protégé* for editing ontologies and then to export the project database and query  
416 the information by *Revit DBLink* [127]. Besides, based on ontology-based feature modelling, ifcXML  
417 is utilised to conduct query processing to extract information relevant to construction practitioners  
418 from a given HBIM [128].

419 (iii) Connect and transfer the information between HBIM and GIS: Ontological framework can be built for  
420 dealing with the interoperability issue between BIM hierarchy structure and GIS relational database.  
421 HBIM model and GIS model are first mapped to ontology respectively and then connected and queried  
422 using ontology rules [129,130].

423 (iv) Help to create the parametric model: This kind of combination could be the basis for automated HBIM  
424 parametric design, although no work has thus far paid attention to the ontology-based BIM modelling.  
425 Lin [131] mentioned the possibility to applied ontology to computer graphics parametric design which  
426 can automate the modelling work to some degree.

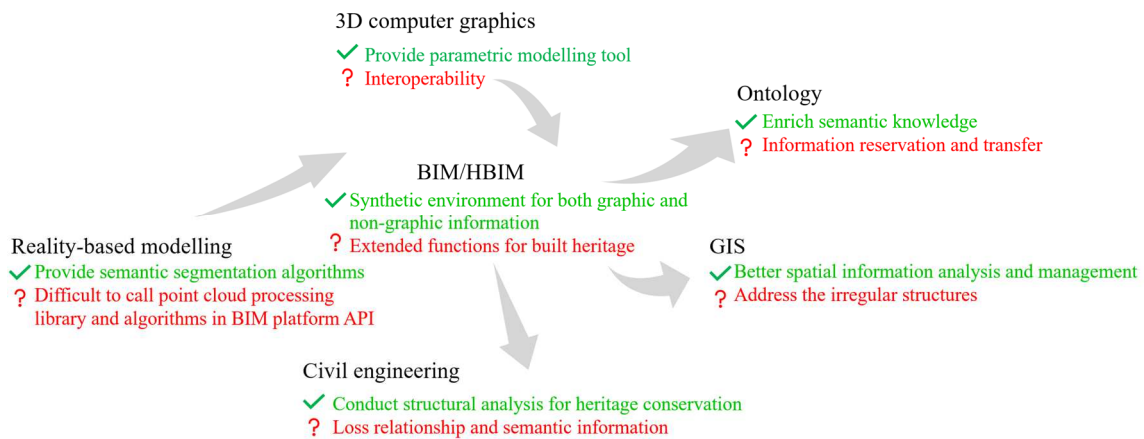
427 To fully represent and comprehend a historical/archaeological artefact, an integration with BIM and  
428 ontology can provide both object-oriented information (typically found in BIM software) and semantic  
429 information (typically found in ontological modelling systems). Currently, ontology semantics can be  
430 connected to BIM by direct ad-hoc development in BIM platform [51], migrating IFC files to RDF/OWL  
431 [132] and developing a unified platform [57].

### 432 3.5. Brief summary

433 HBIM environment increasingly facilitates the interoperability of data sets and data exchange with  
434 reality-based modelling, computer graphics, ontology and GIS. Shown as Figure 4, the integration can  
435 extend HBIM capabilities, such as accurately parametric modelling of irregular structures by computer  
436 graphics, enhanced semantic segmentation based on reality-based modelling approaches, enhanced

437 management and analysis of semantic knowledge and spatial information, and structural analysis for  
 438 conservation.

439 But the integration and transformation among different environments still face various challenges,  
 440 including how to address the irregular and complex structures in the scan-to-HBIM and HBIM-GIS  
 441 integration, how to realize the interactive parametric design between computer graphics and HBIM, and  
 442 how to avoid the information loss during the model transfer.



443

444 **Figure 4.** Merits (in green colour) and challenges (in red colour) in the integration of HBIM and other  
 445 techniques.

#### 446 **4. Conclusions**

447 This paper reviewed studies on heritage documentation using geometric modelling (3D computer  
 448 graphics and reality-based modelling), knowledge management (GIS and ontology) and recently developed  
 449 BIM technique. The monitoring of publications indicated that heritage documentation had drawn  
 450 increasing attention in recent years, considering that 87 percent of papers were published in the 2010s.  
 451 Also, the publication in the field of heritage documentation displayed that laser scanning, GIS and  
 452 especially BIM techniques became increasingly important, photogrammetry was always the most popular  
 453 method, and ontologies and 3D computer graphics were traditional ways.

454 This paper also reviewed the typical roles of HBIM, firstly proposed in 2009, in recent years to  
 455 reconstruct, manage and conserve the built heritage. HBIM provided a unified platform for  
 456 semantic/parametric modelling, 2D/3D visualization, and spatial/attribute database and management of the  
 457 built heritage. The integration of existing techniques can extend the capability of HBIM on heritage  
 458 documentation and management, such as computer graphics for parametric modelling of irregular  
 459 structures, reality-based modelling for automated semantic segmentation, GIS for spatial information

460 analysis and ontology for heterogeneous semantics management. However, the integration still faces  
 461 challenges to enhance interoperability and reduce information loss among different platforms. A unified  
 462 HBIM platform for better heritage documentation can be generated when addressing these challenges.

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