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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 MicMac¹ (photogrammetry), MeshLab² (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.

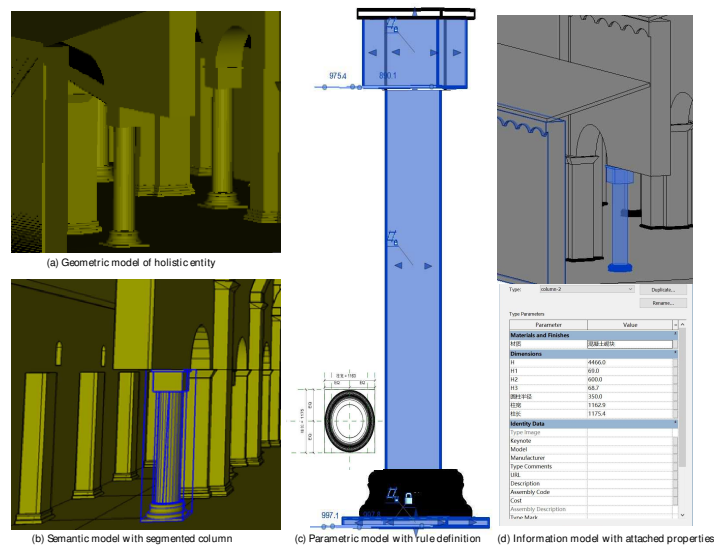
50 The recent developed Building Information Modelling (BIM) technique combines 3D modelling and
51 information management. One of its modern application is heritage documentation and conservation [4–8]
52 and has generated a new concept of [Historic/Heritage Building Information Modelling](#) (HBIM). 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

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

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

55 geometry aspect; (ii) attribute, material and relationship information of the sub-elements; (iii) possible
 56 deformations and changes over time.

57 In brief, four kinds of 3D models (Figure 1) are discussed in this paper. (i) Geometric model
 58 reconstructs the real entity with a holistic shape. (ii) The semantic model recognises and endows the
 59 meaning of the elements of heritage. (iii) Parametric model defines and alters the shape of the elements by
 60 parameters [10–12]. (iv) Information model builds a database with the attached attribute, material, and
 61 relationship information about the entity and its components as well as the 3D geometry. Besides, a
 62 knowledge model is considered, which pays more attention to heterogeneous semantic details of the
 63 heritage instead of geometric aspect.



64
 65 **Figure 1.** A column described in different types of 3D models, including geometric, semantic, parametric and
 66 information model

67 In literature, related review papers from different views for built heritage modelling are available.
 68 Chane et al. [13] surveyed the imaging systems and their applications for the study of cultural
 69 heritage. Remondino [14] reviewed the actual optical 3D measurement sensors and 3D modelling
 70 techniques, with their limitations and potentialities, requirements and specifications on heritage
 71 recording. Rütther et al. [15] presented the pipeline and challenges of laser scanning in heritage
 72 documentation. Vanegas et al. [16] provided an overview of methods spanning computer graphics and
 73 related fields involved in complex building modelling, rendering, visualization and simulation. Yang et al.
 74 [5], Pocobelli et al. [17], and Logothetis et al. [18] described the potential and challenges of HBIM on
 75 historical buildings modelling, while Bruno and Roncella [19] introduced the capability and workflow of
 76 HBIM on heritage conservation.

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*³, *3ds Max*⁴, *Maya*⁵, and *Blender*⁶). 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),

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

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

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

⁶ *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 standard⁷ 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

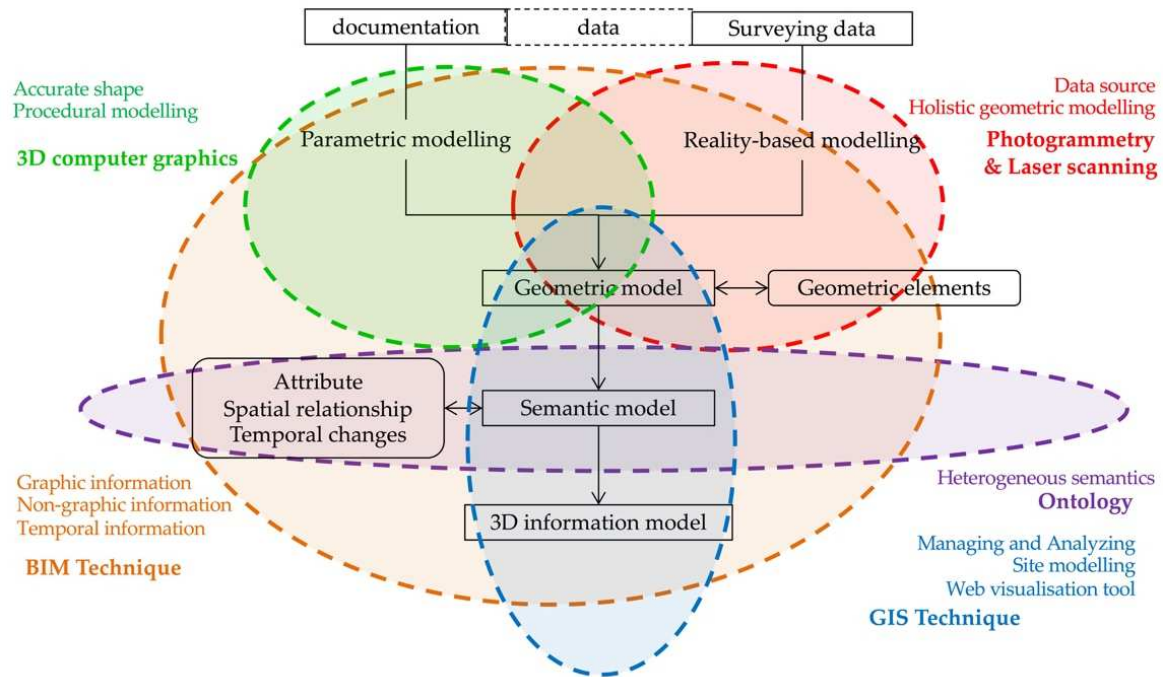
⁷ CIDOC CRM: <http://www.cidoc-crm.org/> (Accessed on April 20, 2020)

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.

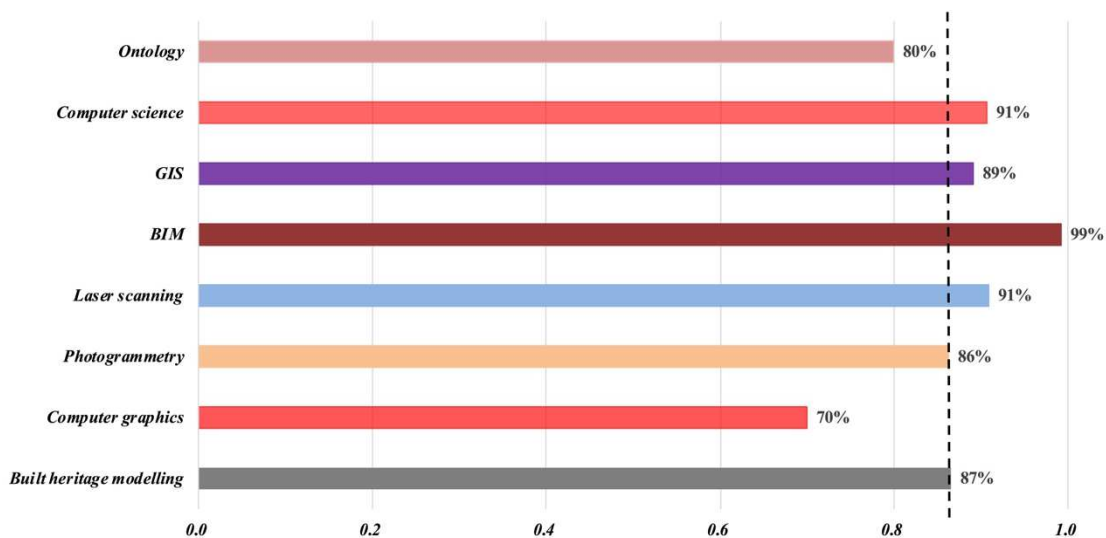
231 A rate (Eq. 1) is calculated by the ratio of publication numbers during the 2010s among the total
 232 publications, which are dedicated to mirroring the change of the hotspot issues. That is, the higher the value
 233 is, the more attention has been paid in recent days. As shown in Figure 3, built 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.

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

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*⁸ and *ArchiCAD*⁹). 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.

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

⁹ *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.

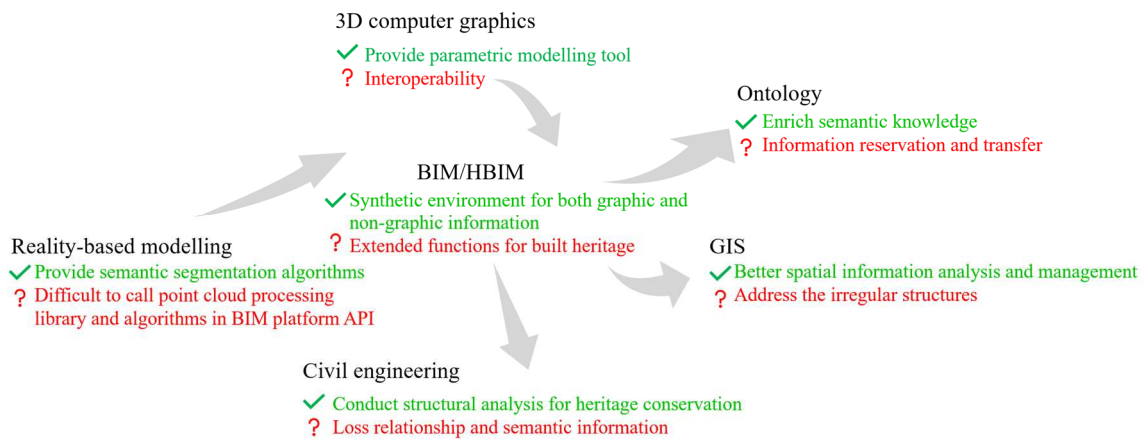
427 To fully represent and comprehend a historical/archaeological artefact, an integration with BIM and
428 ontology can provide both object-oriented information (typically found in BIM software) and semantic
429 information (typically found in ontological modelling systems). Currently, ontology semantics 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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