Civil Engineering School of the University of Cantabria

Methodology for the generation of 3D city models and integration of HBIM models in GIS: Case studies

César A. Carrasco[1], Ignacio Lombillo[1], and Javier Sánchez-Espeso[2]

[1]Structural Engineering & Mechanics Department, University of Cantabria, Santander, Spain;
[2]Geographical Engineering & Graphical Expression Techniques Department, University of Cantabria, Santander, Spain.
Email:

Abstract: The Architecture, Engineering and Construction (AEC) industry increasingly demands the availability of semantic and interactive digital models with the environment, capable of simulating decision-making during its life cycle and representing the results achieved. This motivates the need to develop models that integrate spatial information (GIS) and construction information (HBIM), favouring the achievement of the Smart City and Digital Twin concepts. GIS & HBIM platform is a useful tool, with potential applications in the world of built heritage; but it still has certain inefficiencies related to interoperability, the semantics of the formats and the geometry of the models. The objective of this contribution is to suggest a procedure for the generation of 3D visualization models of existing cities by integrating HBIM models in GIS environments. For this, three software and two types of data sources (existing plans and point cloud) are used. The methodology is tested in four locations of different dimensions, managing to identify the advantages/disadvantages of each application.

Keywords: HBIM; GIS; semantic; integration.

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1. Introduction

3D city visualization is already a reality and is becoming more and more popular every day (Hijazi et al., 2020). With the aim of creating a graphical database capable of collecting information about the landscape and the built environment (public services, buildings, etc.) (Hwang et al., 2012; Del Giudice et al., 2015), technicians are working on the development of a more realistic and collaborative methodology, based on the Geographic Information Systems (GIS) and its integration with Building Information Modeling (BIM) (Abd et al., 2020). Such a methodology, which underlies the creation of digital twins of smart cities, will facilitate the overall management of assets and their users (Dou et al., 2020). The implementation of BIM technology in built heritage is called HBIM. BIM is a technology that allows storing information in semantically rich 3D models, which helps all stakeholders in the planning, design, construction, operation and management of a building/facility during its life cycle. GIS is a system designed to capture, store, manipulate, analyze, manage and present geographic space or data (Andrianesi and Dimopoulou, 2020). It works as a database with geographic information that is associated by a common identifier to the graphic objects of a digital map (Hidalgo, 2018). The integration of GIS & HBIM constitutes a powerful tool mainly due to its capacity for data integration, quantitative analysis, and the application of technology for urban management (Song et al., 2017), allowing to obtain benefits from both systems to help document and analyze cultural heritage sites (Baik et al., 2015). However, there are several drawbacks identified when integrating GIS & HBIM, mainly the interoperability of formats and the semantic definition of geometry.

The need to centrally and collaboratively manage the information of a property and its environment has motivated innovation in 3D digital integration. For this, formats and their compatibility must be considered. There are a multitude of formats, distinguishing those proposed by the European Directive 2007/2/EC for the Infrastructure for Spatial Information in Europe (INSPIRE) (Hidalgo, 2018; Noardo et al., 2020), namely *gbXML*, *OGC* (Open Geospatial Consortium, 1994; Sharkawi and Abdul-Rahman, 2013), *LandInfra*, and *IFC*. The most recognized and widely used open standard in GIS is the City Geography Markup Language (*CityGML*), while in BIM/HBIM it is the *IFC* format (Hijazi et al., 2020). The *CityGML* format is the most internationally widespread geometry model, based on *gbXML* (Buyuksalih, Isikdag and Zlatanova, 2013), for storing and exchanging three-dimensional city models with semantics in the geospatial domain (Przybyla, 2010; Fan and Meng, 2012; Popovic et al., 2017). For its part, the *IFC* standard has been developed by Building Smart (El-Mekawy, Östman and Hijazi, 2012) as an open international standard for BIM/HBIM. It is a standard and interoperable format that is object-oriented, being able to represent objects semantically (Dore and Murphy, 2012) and serving as an interchange format between different platforms, allowing models to retain all details. However, the drawback still lies in the inability of the software to recognize all the details at the time of import; therefore, work is still being done with the codification of more standard and open formats.

On the other hand, in an integrated GIS & HBIM model the geometry is directly defined by its semantics. The semantics refers to the “Levels of Detail” (*LoD*) and the “Levels of Development” (*LOD*) with which the model is represented in the different preforms. The *LoD*, specific to GIS, represent the parameters used to measure the degree of semantic accuracy that the HBIM model would have within the GIS platform. They are numbered from *LoD*0 to *LoD*4, increasing the accuracy and complexity of the 3D objects with the *LoD* level (Popovic et al., 2017; Hidalgo, 2018). *LoD*3 and *LoD*4 levels, which contain architectural details such as balconies or windows, rarely exist, because, unlike *LODs*, their construction requires datasets to be acquired with somewhat advanced technologies and often arduous manual work is needed for their generation (Donkers et al., 2016); hence, nowadays, most urban-scale buildings are represented, at most, in *LoD3* (Fan and Meng, 2012). On the other hand, the *LOD*, typical of BIM/HBIM, represent the geometric and information complexity that architectural models can reach, being classified in 5 groups from *LOD 100* to *LOD 500* (Popovic et al., 2017; Hidalgo, 2018; Castellano-Román and Pinto-Puerto, 2019; Andrianesi and Dimopoulou, 2020). The main characteristics of these levels are summarized in (Table 1).

The aim of this work is to propose a procedure for the generation of 3D visualization models of existing cities by integrating HBIM models in GIS environments. Thus, several software have been used integrating 2 types of data sources (existing plans and point cloud) in 4 sites, obtaining useful comparative results to select the most appropriate tool according to the needs of use.

2. Methodology

A methodology with three key stages is proposed in (Figure 1): Stage ① - Data management and initial configuration, Stage ② - Terrain and building footprint definition, and Stage ③ - Generation of the 3D building environment.

Table 1 | Main characteristics of *LoD* and *LOD* levels.

Levels of detail (GIS)	*LoD0*	Digital Terrain Model
	LoD1	Simple cubic extrusions with flat roofs
	LoD2	Add the roof typology to *LoD1*
	LoD3	Present the architectural details of the exterior of the model (e.g., texture of the facades, windows or doors).
	LoD4	Present details of the interior of the model (e.g., partitions).
Levels of development (BIM/HBIM)	*LOD 100*	Conceptual design
	LOD 200	Schematic design
	LOD 300	Detailed design with 60% as-built information
	LOD 400	80% of as-built information
	LOD 500	Almost 100% as-built information

2.1. Stage ① - Data management and initial configuration

The essential data needed to build the model are the following:

- The cadastral base of the city parcels, which is a 2-D GIS layer containing the table of municipal and cadastral attributes, including the qualitative height of each of the buildings in the polygons.
- The data relating to the LIDAR (Laser Imaging Detection and Ranging) point cloud of the geographical area.

The initial configuration refers to the management and definition of the base map, which can be an orthophoto, street map, or a simple canvas with solid color. It is a user-defined option depending on the use of the model.

2.2. Stage ② - Definition of terrain and building location

At this stage we work mainly with the cadastral base of the city parcels from which the location (footprint) of the buildings is extracted (2D polygons necessary to generate the 3D model). However, beforehand, it must be defined whether or not to include the real relief of the terrain. If so, the Digital Terrain Model (DTM) and the Digital Surface Model (DSM) are constructed from the point cloud extracted from the LIDAR flights. The DTM is the ground level model, without trees and buildings. The DSM includes the topography and objects on the ground surface (trees and buildings). The difference between these two models is the Digital Height Model (DHM), allowing to obtain the height of the referred surface elements on the ground.

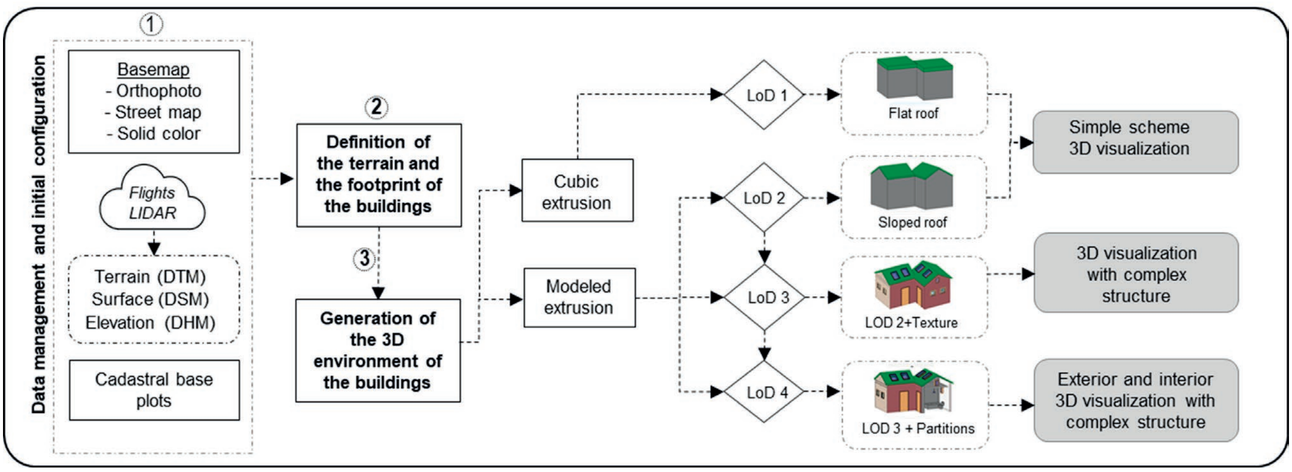


Figure 1 | Methodology to be followed to generate a 3D GIS visualization model integrating HBIM models.

2.3. Stage ③ - Generation of the 3D environment of the buildings

At this stage, the 3D model of the buildings is generated in the GIS platform and the HBIM models are integrated into it. The resulting 3D model will depend on the level of detail (*LoD*) set in the project (*LoD1* to *LoD4*).

To generate the buildings in the GIS environment with *LoD1* level of detail, the footprint of the buildings and their attributes are used. Both are contained in the cadastral base of the city parcels, information managed in stage ②. The attribute "*height*" must be modified since the cadastral base describes the number of levels that the buildings have on the z-axis but does not specify their elevation. To modify this attribute, an algorithm is used that automatically assigns a value to the height of each building based on the number of levels. Once the height is defined, the extrusions of the buildings are automatically generated, thus modeling the 3D built environment.

If it is decided to generate a more complex model, with levels of detail *LoD2* to *LoD4*, the use of raster type tools (digital aerial photographs, satellite images, digital images or even scanned maps) must be used. This tool allows to generate the extrusion considering the slope of the roofs, from the MDH extracted from the point cloud of the LIDAR flight and the footprint of the buildings. The quality of the resulting model will be conditioned by the density of the LIDAR point cloud, so, under this circumstance, some of the facades and roofs will have to be retouched, manually or with algorithms. The modeling of built environments with *LoD3* level of detail involves a more arduous and elaborate work, since it consists of defining textures (multipath) to the volumes of the buildings already generated. These multipaths are photographs or solid colors that are pasted to the polygonal surfaces of the 3D contour of the buildings, either automatically or manually, element by element of the envelope. As for *LoD4* models, in addition to having the texture of their envelope, they have their interior partitions defined. In the case of HBIM models, these are built in the commonly used platforms (e.g. Revit) and then imported into the GIS platform. Thus, the building modeled in HBIM, composed of parametric building elements that already have the external and internal parameters of the building defined, does not require modification of its composition and when integrated into GIS is considered to have directly reached a *LoD4* level of detail.

3. Case studies and results

The methodology is applied and developed in four sites (in Cantabria, Spain) of different sizes, both rural and urban, namely: Santander (area of the University of Cantabria - Las Llamas Campus), historic center of Santillana del Mar, Mogrovejo and San Vicente de la Barquera. The Campus of "Las Llamas" has an area over than 1 km², and it is located in Santander, a Spanish tourist city visited by more than two hundred thousand tourists a year. Santillana del Mar is a village declared a Historic-Artistic Site, in Spain "Conjunto Histórico" (comparable to the British concept of Conservation Area); it has several buildings of interest such as the Collegiate Church of Santa Juliana (12^{th} century), the Tower of Don Beltrán de la Cueva (16^{th} century), the Palace of Viveda (17^{th} century), the Palace of Mijares (16^{th} century), and several houses from the 13^{th} to 14^{th} centuries. Mogrovejo is another village declared a Historic-Artistic Site, whose historic buildings include the stately Mogrovejo Tower (13^{th} century), the Church of Saint Mary of the Assumption (17^{th} century) and several houses from the 16^{th} century. Finally, San Vicente de la Barquera is a historic town with several listed buildings such as the Church of Our Lady of the Angels and the Castle, both dating from the 13^{th} century.

Thus, ArcGIS Pro, specialized GIS software, was used to generate the 3D environment of these areas. In addition, in order to evaluate the possible advantages/disadvantages of some HBIM tools applicable to the construction of 3D built environments, Revit and SketchUp have been used. Finally, the integration of HBIM models in GIS environments is also discussed; for this purpose, the model of the Civil Engineering School of the University of Cantabria has been generated and integrated in the GIS 3D built environment of Santander.

In relation to data management and initial configuration, stage ①, to achieve the modeling of the environment of the sites in question, it was decided to use as a base map an orthophoto and a digital terrain with relief. In order to represent the latter, we worked with the point cloud from the LIDAR flights of the 2012 National Aerial Orthophotography Plan of Spain (PNOA), which would be used to generate the DTM. Both the orthophoto and the referred point cloud were obtained from the *Mapas Cantabria-España* download center (Gobierno de Cantabria, 2022).

The definition of the terrain and the footprint of the buildings, stage ②, is developed from the cadastral base of the parcels of each site. This base, called "*Constru*", is obtained from the download center of *Mapas Cantabria-España* (Gobierno de Cantabria, 2022). As can be seen in (Figure 2) the 2D layer "*Constru*" has attached an attribute table with information about the parcels, data necessary to be able to develop the following stages.

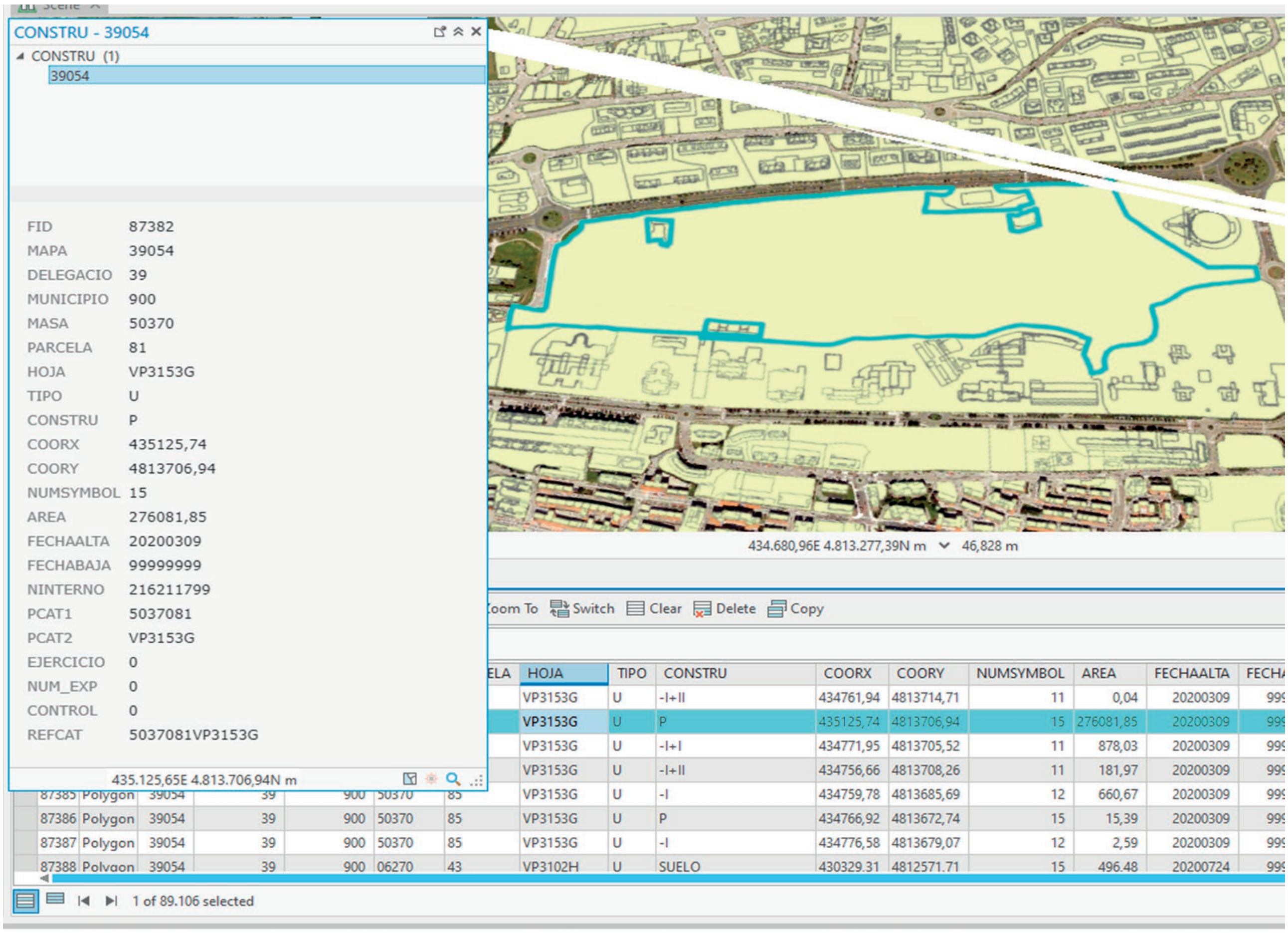


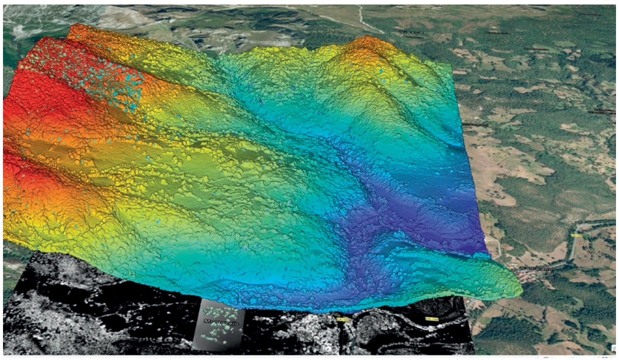
Figure 2 | Filtering and management of the cadastral base of the plots in Santander (Area of the University of Cantabria - Las Llamas Campus).

For each site a terrain with relief is considered and therefore the DTM and DSM have to be created. For this purpose, the points corresponding to the terrain in the point cloud of the LIDAR flight are filtered out (Figure 3a), which, through algorithms implemented in the GIS software, are combined with the assigned orthophoto, finally obtaining a terrain with relief and realistic texture as shown in (Figure 3b), which represents the textured topography obtained in the town of San Vicente de la Barquera.

Once the terrain and the footprint of the buildings are defined, the 3D environment of the buildings is generated, step ③. For this purpose, to identify advantages/disadvantages of constructing a building environment with GIS software (ArcGIS Pro) vs HBIM modeling software (Revit and SketchUp), several sites with different levels of detail are modeled below.

3.1. 3D built environment generated with Revit-Dynamo (*LoD1*)

To illustrate this application, the case of the site University of Cantabria – Las Llamas Campus (Santander) is presented. Revit is very intuitive and easy to use, and it is usually the carrier of most of the federated BIM/HBIM models of the projects and the most interoperable software in the market. To generate a *LoD1* environment with Revit, visual programming with Dynamo is required. After the design of a simple algorithm, (Figure 4), the DTM plus the footprint of the buildings is automatically generated. This footprint is automatically extruded as “*masses*” at a height defined by the software and not by the user. The level of detail achieved with this tool is *LoD1*, with no possibility of automating to *LoD2* or higher.



(a) Point cloud from PNOA 2012 LIDAR flight over Mogrovejo.

(b) Textured DTM of San Vicente de la Barquera.

Figure 3 | Terrain definition and building footprint.

3.2. 3D building environment generated with SketchUp (*LoD1*)

As in the previous case, the site University of Cantabria – Las Llamas Campus (Santander) is used to illustrate this application. SketchUp, like Revit, is one of the best-known commercial software used in technical offices. SketchUp allows importing 3D models already generated through the installable plugin "*skp2osm*" of OpenStreetMap. Another way to import models with better level of detail is to download the model from "*cadmapper*", a platform that allows to specify the height of the buildings and the possibility to download it in other formats (AutoCAD or Rhino, among others). The model can also be downloaded from "*placemarker*", a platform that allows to achieve even better levels of detail and to work with imports of trees and terrain. (Figure 5) illustrates the referred Las Llamas Campus in *LoD1* generated with SketchUp. An advantage of this model is that it can be exported to other object type formats (3D image), very useful for layout and three-dimensional printing. The level of detail is medium, being fully editable, but without the possibility of automating to a *LoD2* or higher.

3.3. 3D built environment generated with ArcGIS Pro (*LoD1*)

The "*Constru*" layer generated in step ② contains in its attribute table a field of the same name. This field

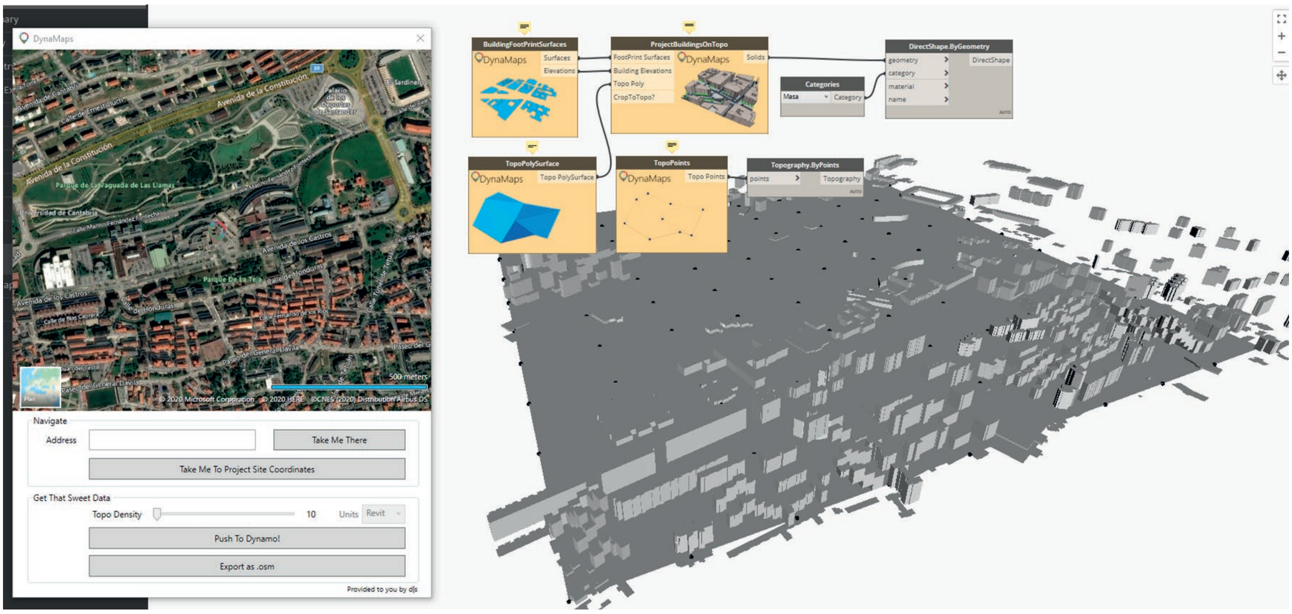


Figure 4 | 3D environment of Las Llamas in *LoD1* with Revit-Dynamo visual programming.

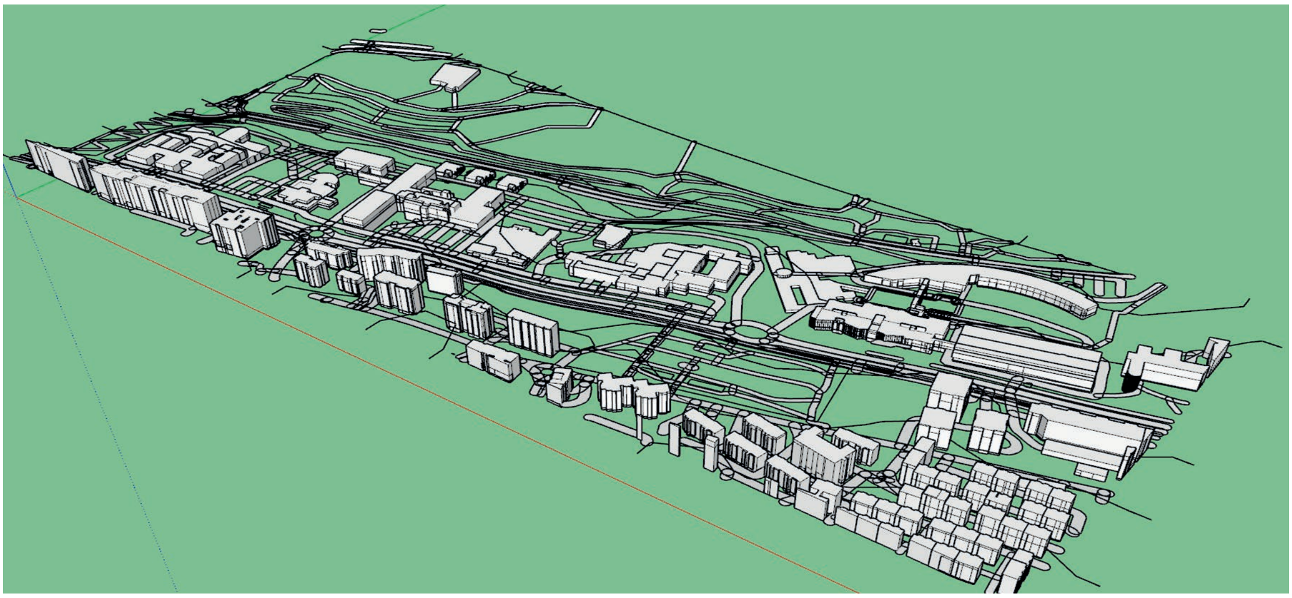


Figure 5 | 3D environment of the "Campus de La Llamas" in *LoD1* with SketchUp.

describes the heights of each building (Figure 6-box 1). Such height is encoded in Roman numerals; thus, "I" means that the building is 1 height, "II" is 2 heights, and so on. However, the height is not defined by a quantitative value, so in order to generate an extrusion, a numerical value must be assigned to the height variable (in this case "constru"). For this purpose, an algorithm is used (Figure 6-box 2) that converts heights in Roman numerals to numerical heights (Figure 6-box 3). In this case an average height between floors of 3m has been adopted, finally generating the environment in *LoD1*, (Figure 7).

3.4. 3D building environment generated with ArcGIS Pro (*LoD2* and *LoD3*)

To illustrate this application, different models generated for the four sites in *LoD2* combined with *LoD3* (this last level of detail applied to emblematic buildings according to each case) are presented. To obtain a *LoD2* level of detail, a function is automated to recognize in the MDH the height of the buildings and the difference in elevation of the high points of the buildings (roofs), thus defining the slope of the roofs of the buildings. In order to obtain a LoD 3 level of detail, a more realistic character must be given to the building envelopes. For this, as already mentioned, multipath type tools are used which are based on introducing texture to the buildings by means of photographs taken of the facades and roofs. (Figure 8) shows the *LoD2* and *LoD3* models of the four experimental sites.

Another method to texturize building volumes is by means of the construction of meshes through drone flights (Reality Mesh), creating files in **kml* or **kmz* format. This solution is used when the interest in the level of detail of the envelopes is important and there are not enough resources to generate a 3D HBIM modeling. Its disadvantage is that it only works as a 3D visualization and does not provide information of its buildings, i.e. it has no associated attributes. An example of these models is the Reality Mesh of Google Earth maps.

3.5. 3D built environment generated with ArcGIS Pro (*LoD4*-HBIM)

Modeling a site with *LoD4* level of detail is costly or, in some cases, unfeasible, so this level of detail is usually applied to certain buildings for which greater definition is required. Thus, to illustrate this application, the Santander site has been selected, integrating the Civil Engineering School HBIM LOD 300 model into the GIS 3D built environment of Las Llamas Campus. Therefore, an environment with a higher level of detail (*LoD4*-HBIM LOD 300) is obtained.

To generate the geometry of the HBIM models we usually proceed in two ways:

- Performing the survey from existing plans, considerably reducing the need to use advanced technological resources.

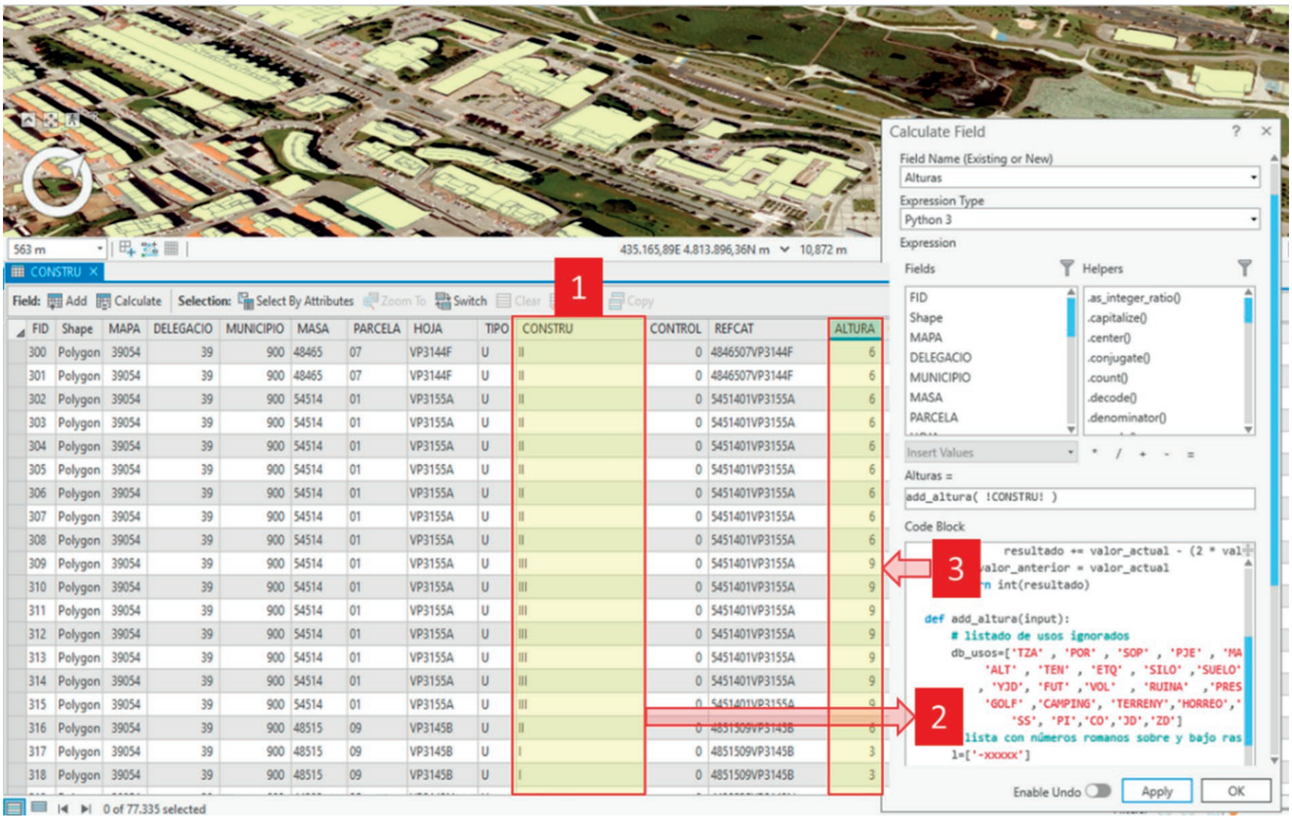


Figure 6 | Configuration for assigning a fixed height to buildings.

- Perform it by 3D laser scanner or terrestrial photogrammetry, and, if necessary, by aerial photogrammetry from images captured via unmanned aerial vehicles (UAVs), such as drones.

In this experimental case it has been performed both from plans and by 3D laser scanner, identifying the advantages/disadvantages of one way over the other. Figure 9 illustrates the interior of the HBIM LOD 300 model created from plans.

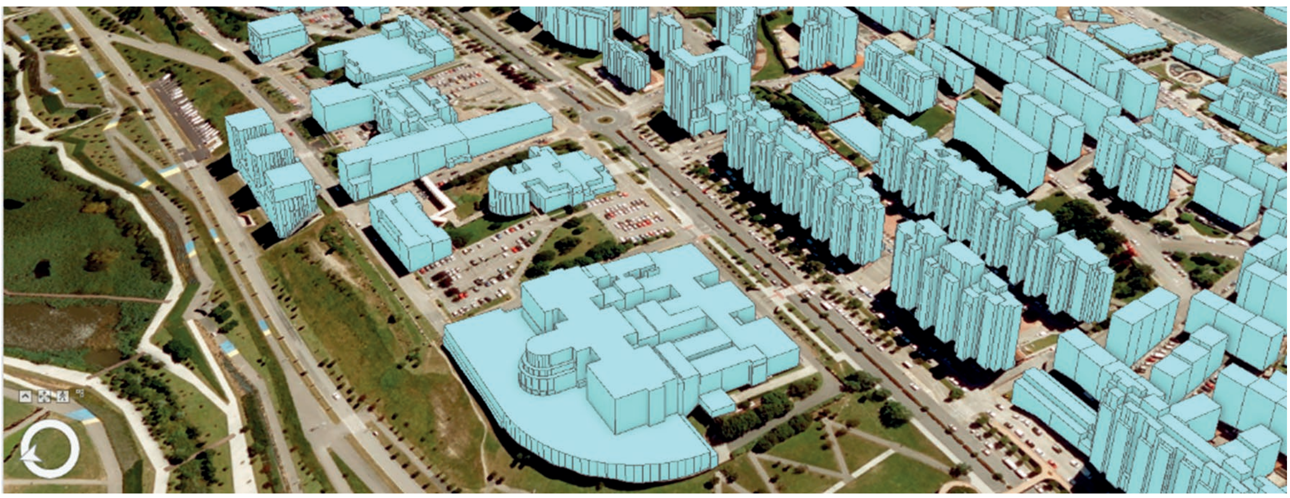
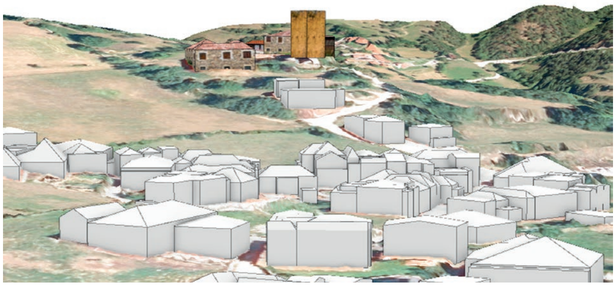


Figure 7 | 3D environment of Las Llamas Campus in *LoD1* with ArcGIS Pro.

(a) Las Llamas Campus in *LoD2* and *LoD3* (university buildings).



(b) Mogrovejo in *LoD2* and *LoD3* (medieval tower and surroundings).

(c) San Vicente de la Barquera in *LoD2* and *LoD3* (castle and church).

(d) Santillana del Mar in *LoD3* (buildings in Town hall square).

Figure 8 | 3D environments with ArcGIS Pro and multipath of some buildings of the sites studied.

This model involved the investment of quite a few hours of unskilled labor and expensive equipment. It is a model that proves to be useful for the creation of virtual libraries and thus facilitates the visualization of information in a 3D built environment (Carrasco et al., 2022). However, the drawback of this model is the precision in the measurements of the elements that compose it. It also does not include the as-built state.

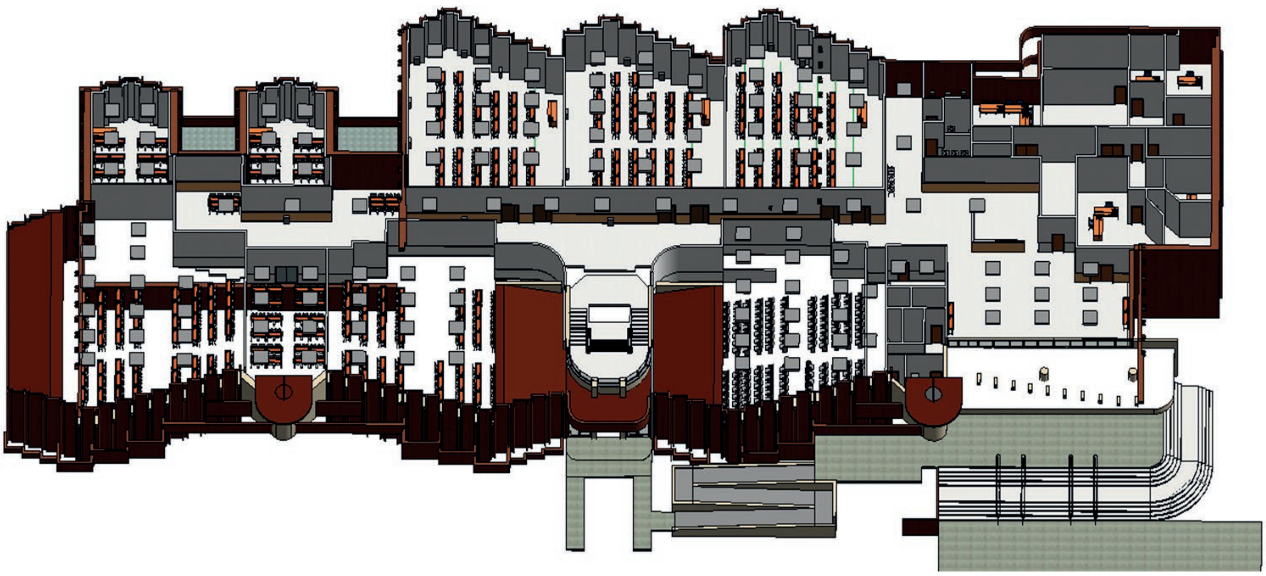


Figure 9 | Interior of the 2nd floor of the HBIM LOD 300 model of the Civil Engineering School of the University of Cantabria, generated from the existing plans.

Figure 10 | 3D laser scanning process and Point cloud obtained (visualized in Revizto software).

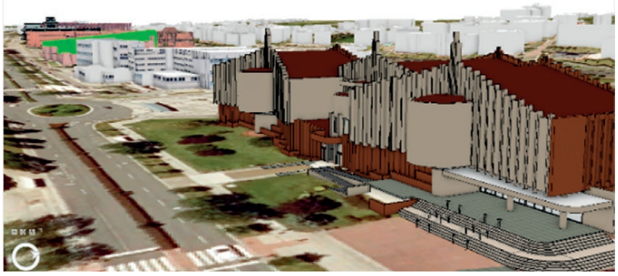


Figure 11 | BIM model of the Civil Engineering School of the University of Cantabria integrated in the GIS 3D built environment.

On the other hand, the HBIM model generated from the 3D laser scanner is more accurate, matching the actual dimensions of the existing building, (Figure 10).

However, it requires specialized manpower for both data capture and point cloud generation, and, of course, to be equipped with the necessary technological resources, which are quite costly.

Finally, (Figure 11) illustrates the HBIM model of the building generated once integrated in the GIS built environment of the Las Llamas Campus. Table 2 summarizes the most relevant aspects achieved in this work.

4. Conclusions

HBIM models and geospatial technologies offer 3D data models that provide information about buildings and the surrounding environment. GIS & HBIM are widely used platforms in the building industry due to their diverse individual characteristics. Although there are technical inefficiencies related to the integration of GIS & HBIM, few theoretical studies address how to fully integrate their respective strengths.

Table 2 | Advantages/disadvantages and utilities of the tools and method used to generate 3D environments integrating GIS and HBIM.

Tool	Advantages	Disadvantages	Recommended for
Revit (Dynamo)	Very intuitive and easy to use software. Supports most of the federated BIM/HBIM models. Low economic investment.	It requires knowledge in visual programming. The resulting model is very basic. Level of detail LoD 1 (low)	When you want to place the HBIM model in a 3D environment only as a volumetric reference.
SketchUp	Well-known and widely used software. Allows export to other formats.	It requires the use of several plugins and access to external resources. The generated model is simple. Level of detail LoD 1 (medium)	Layout for 3D printing. Basic and fast modeling of cities and environments.
ArcGIS Pro	The generated model is optimal. Allows to manage all the information of the model and its families. synchronization with *rvt file types. Import of IFC, Kml, Obj, etc. models.	Requires knowledge of programming languages.	Creation and management of digital twins. Creation and management of HBIM virtual libraries. Generate graphs and evaluate variables of the integrated model of a city.
HBIM from existing drawings	Simple generation. Useful for life cycle management applications. Relatively inexpensive.	The dimensions are not accurate with respect to the actual building dimensions. The as-built model is not generated.	Asbuilt. GMAO. Creation and management of virtual HBIM libraries. It can be used to simulate and manage a building rehabilitation and maintenance work.
HBIM from point cloud	Dimensions are accurate to the actual dimensions of the building. Generation of the as-built model. Higher performance than the previous one. Useful for both building life cycle management and building use management applications.	Requires skilled labor. Requires expensive technological resources.	

This paper has presented a useful procedure to generate a 3D model of cities through various software commonly used in the Architecture, Civil Engineering and Construction sector. This methodology has proved to be very useful in favoring the visualization of the built environment of the project and other applications related to simulation in decision making.

Certain advantages/disadvantages in the use of these tools were detected, being relevant the problem of the synchronization of formats and the representation of the detail levels of the models. In this regard, the usefulness of each tool and data source was identified, thus being able to recommend the most appropriate application to be given to each one.

As future guidelines, we are currently working on making the models generated useful for optimizing tourism management and building maintenance and use management (facility management, classroom management, building conservation management, etc.).

Bibliography

Abd, A.M., Hameed, A.H., Nsaif, B.M. 2020. 'Documentation of construction project using integration of BIM and GIS technique', *Asian Journal of Civil Engineering*, *21*(7), 1249–1257. https://doi.org/10.1007/s42107-020-00273-9

Andrianesi, D.E., Dimopoulou, E. 2020. 'an integrated bim-gis platform for representing and visualizing 3d cadastral data', in *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Copernicus GmbH, pp. 3–11. https://doi.org/10.5194/isprs-annals-VI-4-W1-2020-3-2020

Baik, A., Yaagoubi, R., Boehm, J. 2015. 'Integration of jeddah historical bim and 3D GIS for documentation and restoration of historical monument', in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. International Society for Photogrammetry and Remote Sensing, pp. 29–34. https://doi.org/10.5194/isprsarchives-XL-5-W7-29-2015

Buyuksalih, I., Isikdag, U., Zlatanova, S. 2013. 'Exploring the processes of generating LOD (0-2) CityGML models in greater municipality of Istanbul', in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. International Society for Photogrammetry and Remote Sensing, pp. 19–24. https://doi.org/10.5194/isprsarchives-XL-2-W2-19-2013

Carrasco, C., Lombillo, I., Blanco, H., Boffill, Y., Sánchez-Haro, J. 2022. 'integración de HBIM & GIS para la visualización 3D de bibliotecas virtuales en edificios existentes: caso de estudio', in *REHABEND 2022*. Spain, p. 11. Available at: https://www.rehabend.unican.es/2022/.

Castellano-Román, M., Pinto-Puerto, F. 2019. 'Dimensions and Levels of Knowledge in Heritage Building Information Modelling, HBIM: The model of the Charterhouse of Jerez (Cádiz, Spain)', *Digital Applications in Archaeology and Cultural Heritage*, *14*. https://doi.org/10.1016/j.daach.2019.e00110

Del Giudice, M., Osello, A., Patti, E. 2015. 'BIM and GIS for district modeling', in *eWork and eBusiness in Architecture, Engineering and Construction - Proceedings of the 10th European Conference on Product and Process Modelling, ECPPM 2014*. CRC Press/Balkema, pp. 851–854. https://doi.org/10.1201/b17396-136

Donkers, S., Ledoux, H., Zhao, J., Stoter, J. 2016. 'Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings', *Transactions in GIS*, *20*(4), 547–569. https://doi.org/10.1111/tgis.12162

Dore, C., Murphy, M. 2012. 'Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites', in *Proceedings of the 2012 18th International Conference on Virtual Systems and Multimedia, VSMM 2012: Virtual Systems in the Information Society*, pp. 369–376. https://doi.org/10.1109/VSMM.2012.6365947

Dou, S., Zhang, H., Zhao, Y., Wang, A., Xiong, Y., Zuo, J. 2020. 'Research on construction of spatio-temporal data visualization platform for GIS and BIM Fusion', in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*. International Society for Photogrammetry and Remote Sensing, pp. 555–563. https://doi.org/10.5194/isprs-archives-XLII-3-W10-555-2020

El-Mekawy, M., Östman, A., Hijazi, I. 2012. 'A unified building model for 3D urban GIS', *ISPRS International Journal of Geo-Information*, *1*(2), 120–145. https://doi.org/10.3390/ijgi1020120

Fan, H., Meng, L. 2012. 'A three-step approach of simplifying 3D buildings modeled by cityGML', *International Journal of Geographical Information Science*, *26*(6), 1091–1107. https://doi.org/10.1080/13658816.2011.625947

Gobierno de Cantabria 2022. *Mapas Cantabria*. [WWW document]. URL https://mapas.cantabria.es/ (Accessed: 6 July 2022).

Hidalgo, S.F. 2018. 'Interoperabilidad entre SIG y BIM aplicada al patrimonio arquitectónico. Exploración de posibilidades mediante la realización de un modelo digitalizado de la Antigua Iglesia de Santa Lucía y posterior análisis', p. 73. [WWW document]. URL: https://idus.us.es/handle/11441/79394.

Hijazi, I., Krauth, T., Donaubauer, A., Kolbe, T. 2020. '3DCITYDB4BIM: A system architecture for linking BIM server and 3D CityDB for BIM-GIS-integration', in *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Copernicus GmbH, pp. 195–202. https://doi.org/10.5194/isprs-Annals-V-4-2020-195-2020

Hwang, J.R., Kang, H.Y., Hong, C.H. 2012. 'A Study on the Platform Design for Efficient Interoperability of BIM and GIS', *Journal of Korea Spatial Information Society*, *20*(6). https://doi.org/10.12672/ksis.2012.20.6.099

Noardo, F., Harrie, L., Ohori, K.A., Biljecki, F., Ellul, C., Krijnen, T., Eriksson, H., Guler, D., Hintz, D., Jadidi, M.A., Pla, M., Sanchez, S., Soini, V.P., Stouffs, R., Tekavec, J., Stoter, J. 2020. 'Tools for BIM-GIS integration (IFC georeferencing and conversions): Results from the GeoBIM benchmark 2019', *ISPRS International Journal of Geo-Information*, *9*(9). https://doi.org/10.3390/ijgi9090502

Open Geospatial Consortium 1994.. [WWW document]. URL https://www.ogc.org/standards/citygml (Accessed: 10 January 2021).

Popovic, D., Govedarica, M., Jovanovic, D., Radulovic, A., Simeunovic, V. 2017. '3D Visualization of Urban Area Using Lidar Technology and CityGML', in *IOP Conference Series: Earth and Environmental Science*. Institute of Physics Publishing. https://doi.org/10.1088/1755-1315/95/4/042006

Przybyla, J. 2010. 'The Next Frontier for BIM: Interoperability With GIS', *Journal of Building Information Modeling. An official publication of the National Institute of Building Sciences buildingSMART alliance*™, Fall2010.

Sharkawi, K.H., Abdul-Rahman, A. 2013. 'Improving semantic updating method on 3D city models using hybrid semantic-geometric 3D segmentation technique', in *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Copernicus GmbH, pp. 261–268. https://doi.org/10.5194/isprsannals-II-2-W1-261-2013

Song, Y., Wang, X., Tan, Y., Wu, P., Sutrisna, M., Cheng, J., Hampson, K. 2017. 'Trends and opportunities of BIM-GIS integration in the architecture, engineering and construction industry: A review from a spatio-temporal statistical perspective', *ISPRS International Journal of Geo-Information*. MDPI AG. https://doi.org/10.3390/ijgi6120397