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3D modeling of built heritage: from geometric models to HBIM

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Abstract

Heritage is our legacy from the past, what we live with today, and what we pass onto future generations. With the trend of information technology, enriched “information” modelling techniques – Building Information Modelling (BIM) can manage the geometry, semantic and attribute information, which have been applied on heritage documentation and conservation. Such potential of BIM in heritage modelling has generated one of the most serious issues that many expects to face – historic/heritage building information modelling (HBIM). Currently, the HBIM process has been applied on the reconstruction of the as-built heritage and the lost heritage.

The traditional approaches obtain the holistic geometric models lacking of semantic and relationship information of the sub-elements, and they are difficult to further add and manage the attribute and material information. The relationship and parametric description is the core for BIM technique. BIM technique obtains the semantic model simultaneously during the geometric modelling process, and the relationship and additional information can be attached and then analyzed.

The research is dedicated to the built heritage documentation utilizing the recently available BIM technique. The obtained HBIM model should contain a parametric, semantic, attributional, and relational description of the elements composing heritage. Specifically, (i) the conventional HBIM modelling workflow (manual drawing) for lost heritage and existing heritage is clarified; (ii) considering the current HBIM modelling is conducted in a manual way, the possibility of automated parametric HBIM modelling using API development is explored; (iii) a solid/or mesh to HBIM workflow to transfer the widely existing graphic model and surface mesh to HBIM is proposed; (iv) and the extension of HBIM capability by adopting existing techniques in the BIM environment is discussed.

Foremost, this thesis presents a possibility for the generation of HBIM models from a point cloud, a surface mesh and a solid geometry with reduced human involvement. Correspondingly, a concept of solid/mesh-to-HBIM is proposed using *Autodesk Dynamo* visual programming, which transfers the parametric “*Family*” and geometric structures to parametric HBIM and semantic HBIM model respectively. The parametric HBIM modelling process involves

conventional manual parametric “*Family*” creation and semi-automated building reconstruction by *Dynamo*. The semantic HBIM modelling process directly transfers the segmented solid geometry and closed mesh to BIM environment. The obtained “*Family*” and semantic HBIM model, however, has limited parameters and lacks explicit geometric description because the automatic generation from geometry returns non-editable solid elements. The semi-automated solid/mesh-to-HBIM modelling reduced lots of human works. And the segmented elements can be stored and managed in the BIM environment with attached attributes information and relationship established among the elements.

So it depends on the users’ need. If the user prefers parametric geometry, a complete and personified “*Family*” has to be drawn manually; on the other hand, if the user prefers the original mesh geometry, a semi-automated generation of a dead “*Family*” will be a time-saving way.

Keywords: HBIM, point cloud, built heritage, semantic, parametric, Dynamo

Résumé

Le relevé du patrimoine bâti a évolué : partant de supports papier, les supports numériques prennent aujourd'hui largement le dessus, les dessins 2D sont remplacés par des modèles 3D, la modélisation géométrique s'est enrichie d'informations supplémentaires et a évolué en modélisation de l'information. Parallèlement à la révolution des technologies de l'information incluant de nouvelles techniques de modélisation globale de l'information – le BIM (*Building Information Modelling*) s'est développé : ces systèmes permettent de gérer les informations géométriques sous forme paramétrique, mais également les informations sémantiques en complément d'autres attributs. L'une des applications récentes du BIM se tourne vers la documentation et la conservation du patrimoine. L'utilisation du BIM dans la modélisation du patrimoine correspond à l'un des enjeux et des problématiques majeures de gestion des bâtiments anciens : la maquette numérique de bâtiments historiques (HBIM). Actuellement, le HBIM est appliqué à la reconstruction du patrimoine tel que construit (TQC) et à la reconstitution du patrimoine perdu.

Les méthodes traditionnelles permettent d'obtenir des modèles géométriques dépourvus d'informations sémantiques ou de structures d'informations descriptives et il est souvent difficile d'y rajouter ou d'y gérer davantage d'informations comme des caractéristiques ou des matériaux. Les relations entre composants et leurs descriptions paramétriques constituent, par contre, le cœur du concept BIM. Le BIM permet de constituer un modèle sémantique simultanément au processus de modélisation géométrique. Une structure reposant sur des relations et des informations supplémentaires peut y être rattachée et de ce fait également analysées.

Cette recherche est dédiée à la documentation du patrimoine bâti en utilisant la technique BIM en plein essor. Le concept original du BIM et le concept du BIM-TQC ont été largement appliqués à la documentation du patrimoine bâti et forment les bases fondamentales de modélisation du HBIM. Le modèle HBIM ainsi obtenu comprend une description paramétrique et sémantique des éléments constitutifs du patrimoine.

La thèse présente des méthodes de constructions HBIM à partir de la documentation historique, de nuages de points (acquis par scanner-laser 3D), de maillage de surface et de géométrie solide. De la même manière, un concept de mesh-to-HBIM est proposé à l'aide de la programmation visuelle d'*Autodesk Dynamo*, qui permet de transformer les « familles » paramétriques et les structures géométriques en modèles paramétriques et sémantiques HBIM, respectivement. La modélisation paramétrique HBIM consiste en la création manuelle de *Familles Revit* paramétriques et une reconstruction de bâtiment semi-automatisée par l'application de scripts *Dynamo*. Le processus de modélisation sémantique HBIM transforme directement des géométries segmentées de maillages ou de solides vers l'environnement BIM. Cependant, les *Familles Revit* et le modèle sémantique HBIM obtenus ne comportent qu'un jeu de paramètres limités et manquent de description géométrique explicite car la production automatique à partir de la géométrie ne génère que des éléments solides non modifiables. La modélisation semi-automatique du *mesh-to-HBIM* a permis de réduire le nombre d'opérations manuelles. Les éléments segmentés et individualisés peuvent être stockés et gérés dans l'environnement BIM avec des compléments d'informations d'attributs et des relations d'association entre éléments.

Les besoins des utilisateurs permettront ainsi de choisir entre l'une ou l'autre méthode. Si l'utilisateur veut pouvoir faire évoluer son modèle sous forme de géométrie paramétrique, une constitution manuelle de *Familles Revit* sera nécessaire avant la modélisation. Si l'utilisateur se repose uniquement sur des géométries issues des maillages d'origine, le processus de maillage-to-BIM (mesh/solid-to-HBIM) permettra de gagner du temps.

Mots-clés : HBIM, nuage de points, patrimoine bâti, sémantique, paramétrique, Dynamo

List of abbreviations

API	Application program interface
AR	Augmented reality
BIM	Building information modelling
CIDOC CRM	International Committee for Documentation Conceptual Reference Model
DTM	Digital terrain models
FEM	Finite element method
GIS	Geographic information system
GML	Generative modelling language
GNSS	Global navigation satellite system
HBIM	Historical/heritage building information modelling
LOD	Level of details
NURBS	Non-uniform rational basis splines
PCL	Point cloud library
RDF	Resource description framework
TLS	Terrestrial laser scanner
VR	Virtual reality

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1 | Introduction

1.1. The study scopes

The recording medium of cultural built heritage has changed from paper materials to digital materials, from 2D drawings to 3D models, and it is changing from geometric modelling to information modelling (Figure 1.1). With the trend of information technology, 3D modelling has been dedicated to representing and visualizing objects, and one of its modern applications is built heritage modelling. As described by El-Hakim *et al.* (2004) and Noh & Sunar (2009), the traditional concept of built heritage modelling entails either measured and accurate geometric modelling or visual and immersive virtual reconstruction.

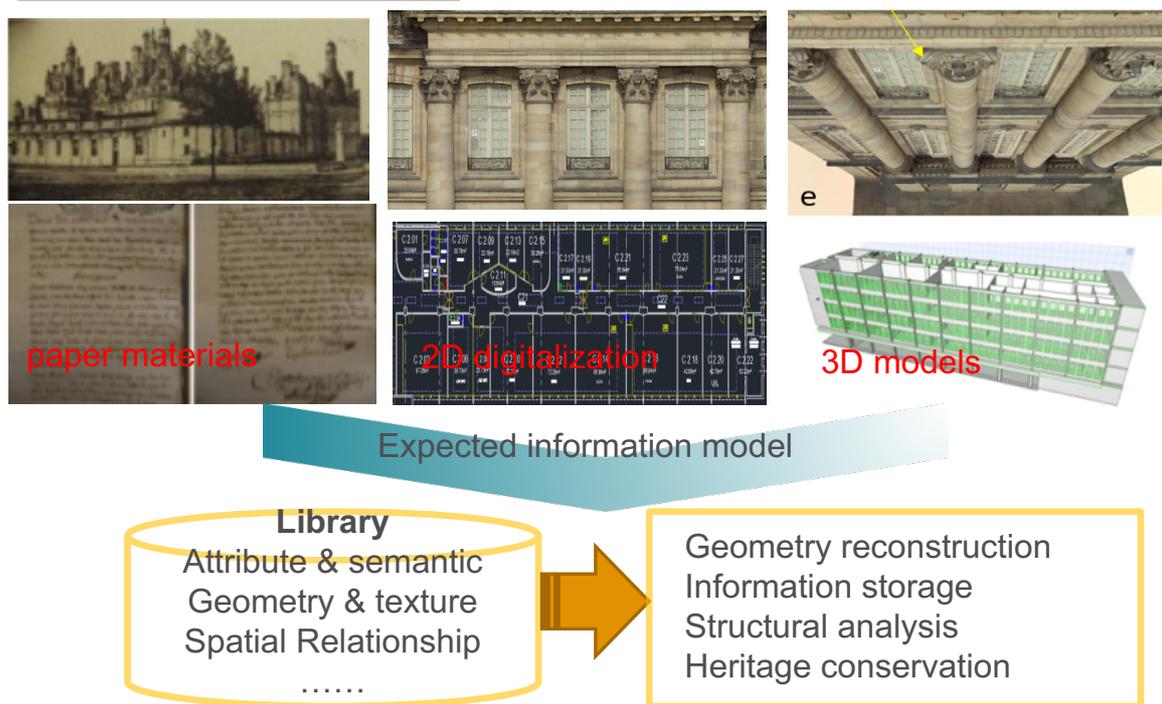


Figure 1.1. Heritage documentation

Chapter 1: Introduction

Virtual reconstruction commonly refers to the surface visualization properties of a heritage object, in which the data source may come from digitalized historic materials recording the heritage, reality-based photographs and measurable drawings representing the surface. The built heritage can be re-created, yielding a virtual replica of damaged heritage from pictures, paintings or other historic material of the original object, and the reconstructed model can be displayed in an interactive environment (Talaba *et al.*, 2010; Girbacia *et al.*, 2013). Therefore, virtual reconstruction may be the past once more, the virtualization of the current, and the prediction of the future, yet the visual models are mostly 2.5D models.

Geometric modelling, to the contrary, focuses on the outline structures and measurement information for the real object. Until now, multi-platform-based imagery and laser scanning data are all used to geometrically model the heritage. It is no longer a problem to obtain an accurate 3D geometric model, either by laser scanner or imagery dense matching approaches. However, it is still highly anticipated to realize semantic segmentation and labelling of sub-elements (from façades and roofs to columns, openings, etc.) and micro-structures (sculptures and special structures peculiar to heritage), and related fields, such as pattern recognition and machine learning, are rapidly developing.

Typically, the open-source platform 3DHOP (<http://vcg.isti.cnr.it/3dhop>) provides the friendly platform for heritage visualization and 3D modelling using. The virtual model is often a virtual visualization of the site, which only aspires to illustrate it and does not make access to additional information possible (Meyer *et al.*, 2007). The increasing accuracy of geometric models reserves the shape features that make it possible to reconstruct them, even if the buildings have some critical evolutions or collapses. As for unique historic buildings, conservation professionals do not only need to navigate through documents and re-create the past, they also need to perform spatial, temporal and multi-criteria queries in a virtual 3D environment to support decisions. Generally speaking, the excessive pursuit of immersive environments and highly accurate geometry in some sense is no longer the key problem compared to more information. Attribute, relationship and temporal information of the sub-elements is needed for the management of historic buildings.

In brief, beyond the combination of both conventional virtual reconstruction and geometric modelling approaches, an expected information-rich heritage model includes not only the visual and geometric information but also semantic, attribute and spatial relationship regarding the building entity, sub-elements and micro-structures.

Enriched “information” modelling techniques – Building Information Modelling (BIM) have been widely developed to manage the geometry, semantic, attribute and energy

information (Boudhaim, 2018). One of its modern applications is heritage documentation and conservation (Fai & Rafeiro, 2014; Murphy *et al.*, 2013). The potential of BIM and as-built BIM in heritage modelling has generated one of the most serious issues that many experts face in the as-built modelling field -- Historic building information modelling (HBIM). Murphy *et al.* firstly defined HBIM in 2007, which clearly expressed the prospects of the BIM technique in historic scenes. In this kind of 3D knowledge-rich parametric models, the representation of built heritage is not only a coherent geometrical modelling of the reality, but also solves the problems typical of semantic, parametric and relationship representations of its elements.

1.2. Motivation

The research is dedicated to the built heritage documentation utilizing recently available BIM technique. The obtained HBIM model possess parametric, semantic, attributional, and relational description of the elements composing the heritage. Considering the current HBIM is generally constructed in a time-consuming manual-drawing way, the purpose of this thesis is to explore some new ways to help the transformation from the traditional geometric models to parametric/semantic HBIM models.

Specifically, the research aims of this thesis involves:

- (i) To explore the general HBIM workflows including the HBIM concept for lost built heritage and the as-built HBIM concept for existing built heritage;
- (ii) To compare the traditional geometric model and HBIM model in the aspect of parameters, semantics, relationship, and possible applications (including structural analysis and the connection with ontology);
- (iii) To transfer the traditional geometric models to HBIM models with reduced human involvement using API development and *Dynamo* visual programming.

1.3. Organization of thesis

The content of the thesis will be organized into six chapters and a general conclusion including perspectives for future works.

Chapter 2 firstly reviews the traditional techniques modelling the built heritage, including the surveying, photogrammetry, laser scanning, and computer graphics. The current BIM technique on heritage documentation is summarized including the traditional BIM concept and as-built BIM concept. Two other kinds of information management techniques, GIS and ontology, play important roles on heritage knowledge modelling and analysis. Finally, the research trend in the field of built heritage documentation and the potential of combining HBIM and other techniques are discussed.

Chapter 3 (red part in the Figure 1.2) introduces the current HBIM workflows by the original BIM concept (mostly for the damaged historical buildings) and as-built BIM concept (for existing built heritage). The HBIM models of the study areas including façade of Rohan Palace, St-Pierre-le-Jeune church, beam frame of the Castle of Haut-Kœnigsbourg, France, are built from a photogrammetric point cloud; and the HBIM models of the INSA Strasbourg building and two damaged historical buildings (Petit château du Meisenbach and a church of the Abbey of Niedermunster), are built from the existing documentation and geometric models. *Revit*, *Revit API*, and *Dynamo*, the typical HBIM modelling platform and tools are also introduced.

Chapter 4 (green part in the Figure 1.2), taking the beam frame system of Castle of Haut-Kœnigsbourg as an example, explains the improvement of HBIM modelling platform compared to the traditional geometric modelling, and introduces how to utilize *Revit API* to develop plugins for the HBIM modelling.

Chapter 5 (blue part in the Figure 1.2) proposes a new workflow of transferring the conventional geometric models (3D model and holistic mesh) to HBIM models using *Dynamo* visual programming. The proposed mesh-to-HBIM outline can create the HBIM model with reduced human involvement.

Chapter 6 (black part in the Figure 1.2) explores the possible applications with the created HBIM models and presents two cases of the integration of ontology and structural analysis.

Finally, the general conclusion and the future perspectives of this study are presented.

Chapter 1: Introduction

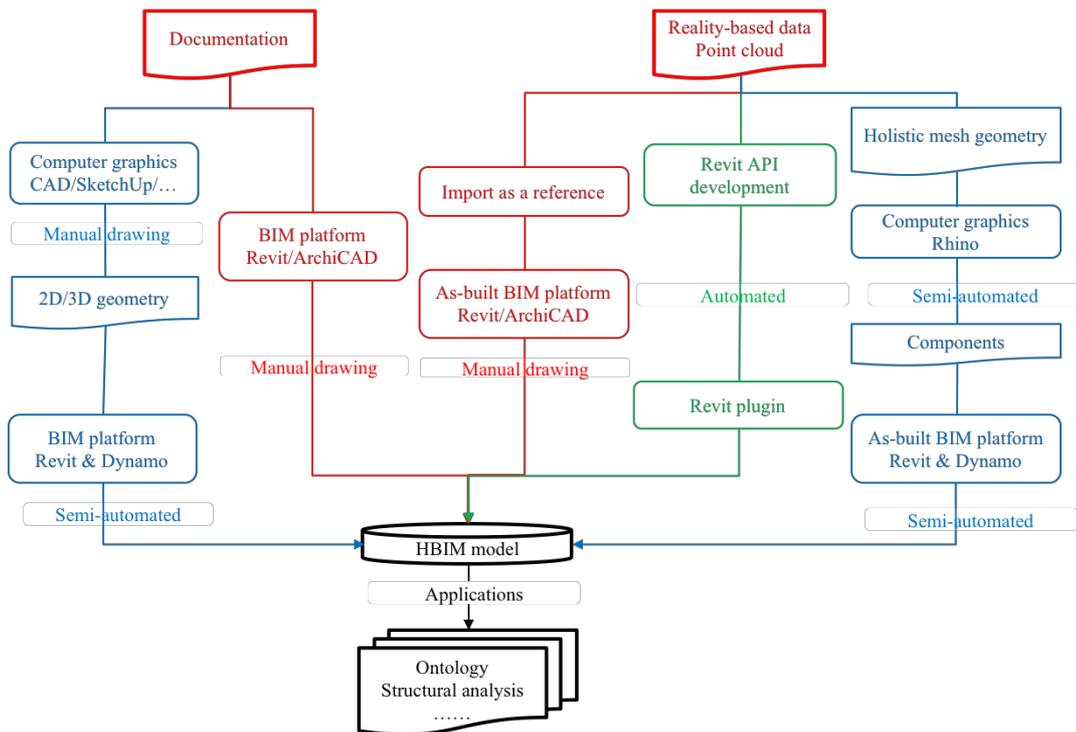


Figure 1.2. Workflows of HBIM modelling using different approaches

1.4. Definition of terms

This thesis focuses on the built heritage documentation, and there have been kinds of models to represent different levels of information (Figure 1.3):

Geometric model: The model recreate the real entity in coherent 3D models. Currently, reality-based modelling techniques can obtain the accurate geometric model for the built heritage using photogrammetry and laser scanning.

Semantic model: With the mature of high accurate geometric model, lots of fields related to 3D models have become more interested in organizing and sharing the related “semantics” of a geometric model. The semantic model endow the meaning of the elements composing the built heritage.

Parametric model: Parametric design generates geometry from the definition of a “Family” of initial parameters. Built heritage is characteristic of complex shape and similar structures for the same architectural style, which makes the parametric modelling popular in the field of computer graphics and BIM.

Information model: It not only models the geometric information, but also builds database with attached attribute, material, and relationship information about the entity and its components. Users can conduct information management and analysis on the model, which is important for heritage conservation. Current BIM and GIS provides the possible environment for the 3D modeling and information management.

Knowledge model: It pays more attention on heterogeneous semantic information of the heritage instead of the geometric aspect. Ontology is recognized as a basis for efficient solution to build the knowledge model.

HBIM model: Heritage/Historical BIM utilizes BIM environment to document built heritage. It realizes the visualization of 3D geometry and 2D plan, parametric modelling of the components, semantic representation of the object’s meaning and properties, fixed relationships between the entities, and temporal characteristics.

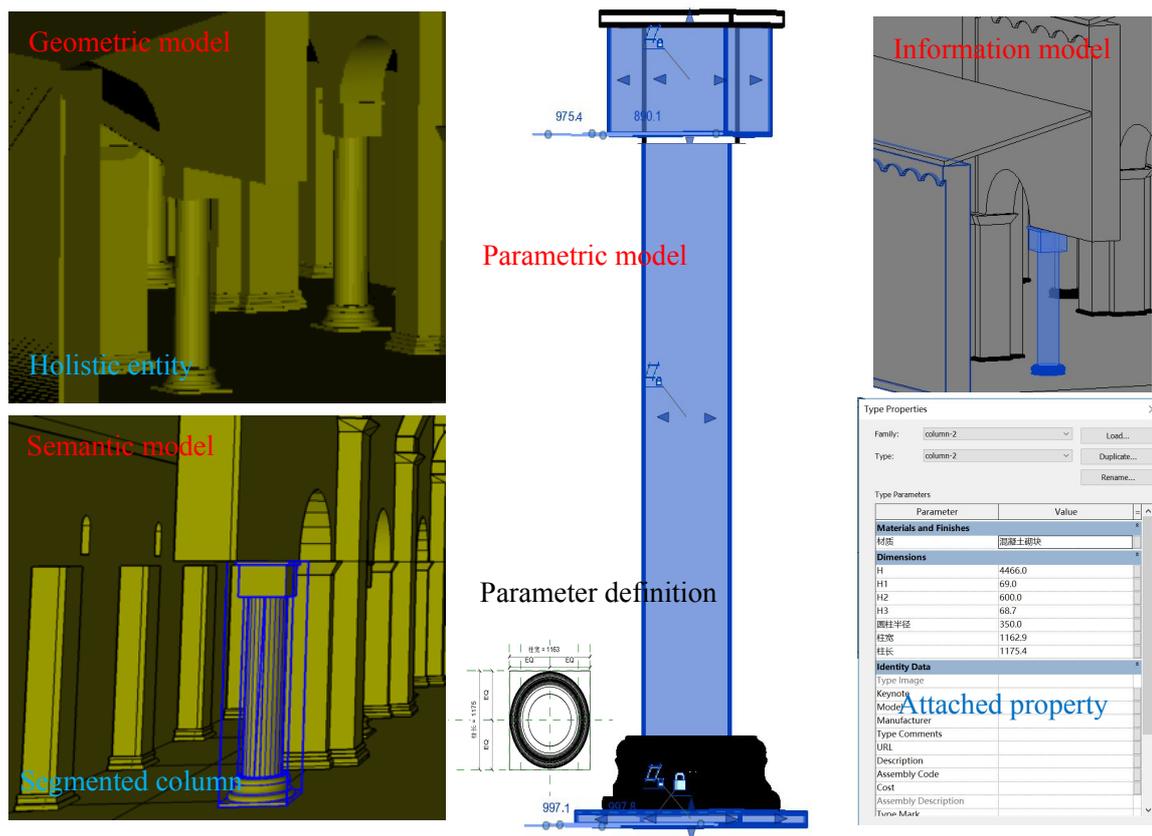


Figure 1.3. A column is described in different types of models

Revit Family: HBIM consists of a detailed semantic model and a library of parametric components. The library of parametric element classes (defined as “Family” in Revit) needs to be built to define the basic architectural elements of the historic building. A “Family” is a group of elements with a standard set of parameters and similar graphical representation, which can be modified by the users. The parametric objects are dynamic to some extent and can instantly alter the shape, size and other properties by tuning parameters. This kind of parametric family is the essential characteristic of BIM. Many BIM’s default families regard only modern and contemporary buildings. Therefore, they are not useful to describe existing architectures, which require the creation of ad hoc families (Cursi *et al.*, 2015).

LOD (Level of details): LOD is how deep the detail is in the model element and a measure indicating their grade and scale, which has been widely utilized in IFC and CityGML schemas (See Section 3.2 Level of details (LOD)). The “detail” in historic building information modelling is how complex, accurate and changed the elements are, considering the specific spatial and temporal scale characteristics about the heritage.



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Built heritage documentation involves the 3D modelling of the geometry and information management of the semantic knowledge. The wealth of complementary data available of the built heritage from both measurement and historical documentation provide the base for reality-based geometric modelling and virtual reconstruction. Meanwhile, GIS and ontology provides the possible tools for the knowledge management and analysis of the attribute, semantic and relationship information for the heritage documentation. The recent developed Building Information Modelling (BIM) technique combines the 3D modelling and information management together. One of its modern application is heritage documentation and conservation and has generated a new concept of historic/heritage building information modelling (HBIM). HBIM not only provide the 3D platform for parametric and semantic modelling of the geometry but also manage the attribute, material and relationship of the elements. This chapter will synthetically summarize the applications of different techniques, including the surveying, computer graphics, photogrammetry and laser scanning, BIM, GIS and ontology, on the built heritage documentation. Then the statistics of the publications indicate the current research trends on the built heritage modelling, and the roles of BIM on built heritage are presented. Furthermore, the integration of HBIM and other information techniques are discussed and demonstrate the potential to extend the HBIM capabilities.

2.1. 3D geometric modelling of built heritage

2.1.1. Surveying

The surveying approaches, including traditional topographic surveys with Total Station (Atkinson *et al.*, 2010; Del Giudice & Osello, 2013) the Global Navigation Satellite System (GNSS) (Al-kheder *et al.*, 2009), are surely the most well-established methods. They can obtain highly accurate single-point positioning, which serves as the reference point of 3D surface reconstruction or the control point for other techniques, and realize large-scale modelling/mapping.

Surveying methods observe the spatial coordinates of sparse feature points and build the 3D surface based on interpolation or fitting algorithms. GNSS and Total Station are conventionally used for developing Digital Terrain Models (DTM) of the heritage site/buildings. The GNSS technique can collect 3D coordinates for selected elevation points around the surface, produce accurate 3D plan drawings, and place them in the exact location of the heritage in the field (GNSS 3D modelling). Further, Total Station can collect more elevation points to form a strongly connected geometric network of elevation points on the basis of GNSS points.

They require lengthy survey time, acquire sparse points, and must be performed directly on-site. They are no longer used to provide high-resolution measurements directly in 3D due to the development of photogrammetry and laser scanners. Topography or single-point measurement methods are, however, helpful and necessary to validate the sensor calibration and orientation, register different data together and the results (Georgopoulos & Ioannidis, 2004; Achille *et al.*, 2015). In many applications, information derived from CAD models, measured surveys or GNSS may also be used as an auxiliary and reliable dataset and integrated with the sensor data.

2.1.2. Photogrammetry and laser scanning

Photogrammetry and laser scanning obtains information with non-contact tools, which is accordant with heritage conservation without contact. Various sensors record different object information based on different theories: optical sensors for surface information, laser scanners for 3D spatial information, and other special band sensors monitoring specific attributes regarding heritage conservation (X-ray (Sarmiento *et al.*, 2008), thermal infrared (Costanzo *et al.*, 2014), SAR (Tang *et al.*, 2016), etc.). To provide high precise and

geometric accuracy data, digital photogrammetry and three-dimensional laser scanning have become very important within the documentation of built heritage.

Aerial heritage modelling

Regional-scale heritage modelling, traditionally called heritage mapping, often use products with an aerial platform. Aerial photogrammetry and LiDAR are widely used to generate the DSM of heritage sites. Considering the near-vertical view direction and relatively low resolution (in centimeter level), the detected buildings are yet generalized 3D boxing models (Gimenez *et al.*, 2015) with low level of detail. Although recently developed oblique aerial imagery enables recording with a vertical extent of façade information (Höhle 2013; Yang *et al.*, 2015), it is still difficult to meet the demands of heritage applications with regard to accuracy and detail. Built heritage modelling requires more complex geometric representations that are not accessible from standard airborne data with low resolution or viewpoint restrictions, so terrestrial data combined with low-altitude UAV data have frequently been adopted thus far.

Close-range optical image modelling

Terrestrial and UAV photogrammetry are the main data source for built heritage modelling applications, which are widely utilized by image-based geometric 3D modelling. Image-based Modelling (IBM) is widely used for geometric surface reconstruction (Remondino & El-Hakim, 2006). Currently, photogrammetry can build accurate 3D models rapidly through free or low-cost software and are beginning to challenge the precision of laser-based reconstructions. Yet the obtained models contain purely geometric visualization; for heritage conservation and management, it is of great importance to combine 3D databases with semantic interpretations of structures and sub-elements.

Image segmentation and recognition refers to detecting and labelling interested objects from the background. If excluding the irregular architectures, regular buildings can be recognized as solid models with simplified facades and roof structures (Gröger *et al.*, 2012), which are typically presented at LOD2 and have been successfully reconstructed as Google Maps for modern buildings. To enrich 3D models and reach higher levels of detail (CityGML LOD3 (Gimenez *et al.*, 2015)), there are plenty of works on realizing semantic segmentation, from production rules-based unsupervised methods to machine learning-based supervised approaches, from 2D image space processing to 3D point cloud segmentation, and from conventional bottom-up analyses to top-down model-driven methods. Therefore, it is highly anticipated to improve the accurate geometry model to

semantic modelling, typically as semantic CityGML models (Gröger & Plümer, 2012), and information modelling, typically as parametric IFC models (Xiong *et al.*, 2013) and the ontology knowledge models (Drap *et al.*, 2017), utilizing recently developed techniques.

Terrestrial Laser Scanning

The laser scanning directly captures the 3D geometric information of the object, which provides a highly detailed and accurate representation of the shapes. Laser scanning is the dramatic development within the field of 3D object scanning, and has been developing into a standard tool for built heritage reconstruction. The pipeline of accurate 3D modelling derived from laser scanning generally consists of data acquisition, point cloud registration, cleaning, mesh generation and texture mapping (Bernardini & Rushmeier, 2002; El-Hakim *et al.*, 2008 Oreni *et al.*, 2014).

Similar as the photogrammetry-based geometry model, the challenge for laser scanning to heritage modelling is also to extend the 3D point clouds and holistic mesh to semantic and information model. Lots of current works utilizing terrestrial laser scanning data paid attention to segment building elements from the point cloud. Many approaches have been proposed to extract façade geometry, typically by inverse procedural modelling (Musialski *et al.*, 2013), RANSAC procedure based segmentation (Boulaassal *et al.*, 2007), region growing algorithms (Pu & Vosselman, 2009), and Manhattan World assumption (Vanegas *et al.*, 2010). Some also parsed façade typically utilizing grammar-based methods (Ripperda & Brenner 2009; Becker & Haala, 2009), considering the similarity and repetitive patterns of windows and floors. However, most automatic segmentation and parsing works assumed façade as regular structure with crossing and repetitive pattern, and excluded the complex heritage façade. The detection of opening structures tend to its accurate position, whereas the geometry structures are ignored.

Current laser scanner equipment can acquire the textured image information with the 3D point cloud, which seems to replace the image based modelling. But photogrammetry has some advantages of being operated by light sensors that can be carried onboard unmanned aerial vehicle systems, such platforms are useful for data acquisition over roofs and other non-accessible places. Meanwhile, the cost of laser scanning is relatively expensive, photogrammetry is easily to be acquired. The time complexity of laser scanning data acquisition and processing is more than photogrammetry.

In summary, most of current (semi-)automatic 3D reconstruction and semantic segmentation works assumed the regular plane characteristic of buildings, so that historic

buildings are mostly excluded. In general, the specificity of historical components makes this task very difficult.

2.1.3. 3D computer graphics

3D computer graphics techniques were the earliest utilized to model heritage and are normally dedicated to virtual reconstruction. Unlike the previous reality-based modelling approaches, which require on-site data collection, graphics techniques rely only on documents or photos, which are available for most historic buildings. As for built heritage modelling, the key concept is to create a virtual replica of the heritage object (disappeared, damaged or existing) using computer graphics and virtual reality (VR) technologies.

Accurate modelling in 3D graphics software

Any irregular shaped object can be dealt accurately and very close to the truth with the help of 3D graphics software. There are plenty of graphics tools, and ones, such as *SketchUp*, *3ds Max* and *Rhino 3D*, are the most popular. *SketchUp* and *3ds Max* are polygon-modelling software with low modelling precision, which are widely used for general linear construction. *Rhino 3D Non-Uniform Rational Basis Splines (NURBS)* modelling software uses mathematical logic with high modelling accuracy, which can be used for nonlinear heritage buildings of any shape. Further, *Rhino 3D* provides a graphical algorithm editor, *Grasshopper*, to realize the parametric design. The parametric design consists of variable parameters, such as the values of all sizes, and invariable parameters, such as the relationships between the geometric elements. The system can automatically maintain the invariable parameters when the variable parameters change. After predefinition of a set of programs, the revision of the built model just needs to modify several invariable parameters. Therefore, the *Grasshopper*-based *Rhino 3D* modelling tools are widely used to generate accurate heritage building models of complex and irregular geometries.

The NURBS-based model describes the object surface in 3D space, and photogrammetry can obtain a high-resolution point cloud representing the object surface. The combination of computer graphics and point clouds in a reverse engineering concept can help reduce the manual processing (De Luca *et al.*, 2006). Therefore, custom algorithms have been developed to automatically rebuild complex and irregular geometries from meshes towards the creation of a NURBS-based 3D model (Barazzetti *et al.*, 2015).

Procedural modelling for built heritage modelling

Procedural modelling, not depending on data but relying on present rules, is widely used on generating and modelling complex objects, such as large urban scenes (Vanegas *et al.*, 2010) (typically based on L-system), irregular artificial objects (typically shape grammars), and natural objects (typically fractal geometry) (Krispel *et al.*, 2015). Procedural modelling is frequently used in building visualization where lots of buildings share similar structures, especially when (mostly artificial) structures are too complex to be modelled in complete detail (Zotti 2008). A limited set of rules can yield an acceptably realistic model as long as with the repetitive constitution. Procedural modelling has succeeded in modern urban building modelling (Wonka *et al.*, 2003) and the typical work by Schwarz & Müller (2015) has completed large urban areas with the help of shape grammars or split grammars. It has been widely accepted and utilized in the GIS modelling tool *CityEngine*, which has realized modern city modelling and is expected for complex heritage modelling.

Procedural modelling allows typical building styles to be modelled in a rapid manner. It creates the rule-based description first and it is suitable for large-scale urban environments. Some works have extended it to different styles of historic architectures. A Generative Modelling Language (GML), allowing the generation of highly complex objects based on a set of formal construction rules, is developed. It becomes rule design instead of shape design and encodes architectural details in multiple resolutions. It has realized procedural construction of gothic church windows efficiently (Havemann & Fellner, 2004) and the creation of a Catmull-Clark subdivision surface in the required resolution with only a few control polygons plus functions in GML (Berndt *et al.*, 2005). The multi-resolution solution is thus also suited for transferring complex geometric 3D models in a web application. Birch *et al.* (2002) described such a system that allows the rapid generation of simple house models. These can be used as ‘vernacular’ buildings that fill the scene between more interesting buildings that have to be modelled in detail. Merrell and Manocha generated complex building models using a model synthesis algorithm with geometric constraints (Merrell & Dinesh, 2011).

Nevertheless, a grammar-based modelling approach may not be suited for very irregular architectural structures, and how to balance the accuracy and efficiency is still a problem.

VR/AR for built heritage modelling

Virtual reality creates a virtual 3D space that is a replica of the real space. VR technologies offer heritage virtual reconstruction with improved immersion awareness, high-definition stereoscopic images, large field of view, collective visualization, and collaboration between several users (Girbacia *et al.*, 2013). Further, Augmented Reality (AR) allows creation of a mixed space with the combination of a computer-generated virtual space and the real physical world. In contrast to VR, where the user is immersed in the world of the computer, AR encompasses everything from reality (the real world) to complete virtuality (a completely immersive virtual world) (Stanco *et al.*, 2012). The AR technique is important and has been widely used to popularize the heritage model (Noh & Sunar, 2009). It is used to provide users with a better understanding of built heritage, even through web-access.

The development of the AR technique can produce more benefits in built heritage modelling besides visualization: mainly accurate modelling of the present, change analysis and more immersive environments. Firstly, it can help to refine the reality-based geometry modelling with the real scenario. Secondly, it can help the conservation and restoration of built heritage, as it has the power to generate hybrid environments (real and virtual), mixing non-existing and demanded past parts, real present scenarios, and predicted future changes. Thirdly, users can move around in the mixed reality environment with AR-improved virtual heritage, which re-creates the ancient status and real scenario with their present state; thus, AR improves user immersion and helps them understand heritage. Obviously, the main challenge is to keep the computer-generated objects accurately registered to the real world. Accurate tracking in real-time still requires further research, as accuracy is crucial, and this will essentially depend on the nature and resolution of the sensors (for example, GNSS, inertial navigation system (INS) or vision-based) or the methodologies applied (Portalés *et al.*, 2009).

In summary, computer graphics play an important role in built heritage modelling, which can be utilized to show past and disappeared scenes, provide an attractive model for the public, and help model complex structures. By creating ancient culture simulations, virtual heritage applications become a link between the users of ancient culture and modern users. Other techniques are dedicated to restoring heritage information accurately and thus are aimed towards specialists, graphics are dedicated to representing the object vividly for the public, and augmented reality for mixed environments is a popular trend of virtual museums. Although computer graphics focus on virtual reconstruction or visual models, the accurate geometric modelling of any irregular and complex structures has been widely accepted as

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the basis procedure for heritage modelling, and procedural modelling is suitable for repetitive structures and is increasingly used in historic building modelling; both are necessary for Heritage modelling.

2.2. BIM in built heritage modelling

The conventional computer graphics and reality-based modelling techniques provide a tangible representation of the built heritage, yet it is also expected to improve the representation of the relationships between tangible and intangible heritage information. The recently developed BIM and as-built BIM technique help to parameterize and enrich the virtual or geometric model with measurement, semantic, attribute and relationship information. BIM is originally dedicated to digitally creating new buildings, which is similar to computer graphics-based heritage modelling utilizing existing description data to some extent. Moreover, BIM entails both graphical and non-graphical aspects of the entire building and helps to segment and parameterize the entity-based virtual reconstruction to object-oriented information modelling. As-built BIM contributes to building information models for existing buildings by remote-sensing data acquisition and reverse engineering techniques, which also go further than traditional geometric modelling with additional parametric information. BIM is therefore called a rich model, considering that all objects composing it have properties and relationships and that this information can be used for data mining to develop simulations or calculations using the model data (Aravici, 2008).

2.2.1. Traditional BIM concept for built heritage modelling

BIM was originally used for management of the life-cycle construction process in the architectural industry, which is suitable for parametrically re-creating historical building based on documentation data and recording the temporal representation of heritage sites. According to the documentation data, re-creating the past/disappeared heritage is similar to the BIM construction process: parametric modelling of the elements, establishing the relations, and then integrating the entire detailed heritage building.

The computer graphics and BIM fields for built heritage modelling have formed documentation-based approaches, which are non-real measurement-based approaches utilizing historic materials describing heritage, such as historical documents, bibliographic references, photographs, drawings, etc. BIM goes further than Graphics to improve the virtual reconstruction of an information rich model by parameterizing and semanticizing the elements. The model is not only a virtual representation of the construction. It is a key part of the project, where the different elements of the building become advanced objects with parametric intelligent. As a typical parametric design application, BIM realizes the linkage of the information storage and modification, in which the elements can be modified

without redrawing and the relations to other objects remain unchanged.

According to the historic manuscripts and architectural pattern books, a library of architectural elements can be created. It is usually a manually time-consuming concept in BIM software to parametrically model the historic elements, and they are limited in their ability to create complicated irregular geometry. That is, the time complexity and geometric accuracy for parameterizing the complex and irregular historic structure elements are the main challenges.

The aim of introducing the BIM technique into heritage modelling underlines the strict relation between object modelling and information involving various attributes and spatial constraints (Oreni, 2013). Although BIM-based semantic modelling manually attaches various attributes, such as the thickness of the walls, the materials the organization of elements and the different construction periods of every part of the structure (Brumana *et al.*, 2014), it automatically connects the sub-elements and builds their strict spatial relationships compared to former manual thematic information-based methods. The information model has been increasingly applied to heritage management (Toldo & Carrara, 2014), conservation (Gigliarelli & Quattrone, 2014) and structural analysis (Titomanlio & Faella, 2014; Bernardino *et al.*, 2015).

2.2.2. As-built BIM concept

As-built BIM is increasingly used to restore, model and manage existing valuable constructions and historic structures by reality-based remote-sensing recording data. The relevance of BIM as a digital representation of physical and functional characteristics of existing buildings has already been introduced and widely discussed in (Arayici, 2008). “As-built” BIM utilizes photogrammetry and laser scanning data to reconstruct existing (historic) buildings based on reverse engineering. It aims to accurately rebuild current historic geometric models and generate semantically rich representations with additional spatial relationships and attribute information.

Laser scanning and photogrammetry captures the most accurate documentation of reality, serving as the data source of as-built BIM, which concentrates on attribute and spatial relationship management based on semantic and parametric elements composing the building. Similar to the main challenge of semantic segmentation for accurate geometric models in heritage 3D reconstruction, no BIM software as of yet has proven adequate to automatically build an information model with semantic and attribute information from 3D point clouds. When importing the 3D point clouds representing the geometric surface of

heritage into the conventional BIM software, the 2D drawing attribute has a conflict with the 3D description, as it is difficult to parameterize the elements even manually. Recent commercial plugins such as *Scan-to-BIM* (Klein *et al.*, 2012) and *Leica CloudWorx* (Gil, 2016) for *Revit* have explored the semantic modelling with point clouds as reference. The regular building structures can be dealt with easily, but the problem also lies in the complex and irregular structures.

2.2.3. Combination of documentation and reality-based data

The workflow combining both historic documentation and reality-based data, has been explored in the BIM platform, combining documentation and laser scanning data (Murphy *et al.*, 2013). BIM software is firstly used to build the parametric elements regarding the historic building based on documentation. The application of inverse engineering, which maps the parametric elements to the reality-based remote-sensing data, makes it possible to refine the parameters and obtain a current-state diagnosis. M. Ludwig *et al.* (2013) used a total station survey, photogrammetric survey, drawings, and footprints of the building and parametrically modelled the Church of St. Catherine in Nuremburg in *Revit*. Fai *et al.* (2014) built a *Revit* “*Family*” of openings based on manuscript data and adjusted the element objects in the point cloud data. In the process, they also stressed the important level of detail of historic modelling. Therefore, an HBIM project needs to organize the protocol created simultaneously or interactively by analyzing documentation- and reality-based data. That is, how to fit the standard shapes and families of BIM components into the reality-based surface point clouds is essential processing that could be performed via manual interpretation (currently) and 3D structure similarity measurement.

In summary, most commercial BIM packages were mainly developed for modern buildings with regular shapes. Historic buildings have very complex and irregular geometry that can be difficult to rigorously reconstruct in BIM software. The creation of new HBIM libraries is a very time-consuming operation, especially considering the importance of preserving details and avoiding simplification. Although laser scanning point clouds provide dense representations of the external surfaces, geometric anomalies (such as verticality deviations) pose new challenges in the generation of as-built BIM models. Introducing BIM into the heritage modelling process still requires a methodological discussion and practical experimentation to obtain detailed models of irregular historical objects, especially from manual modelling to semi-automatic/automatic modelling.

2.3. Information and knowledge management

HBIM approaches includes enriched information directly related to the heritage or its parts (both tangible and intangible such as material, dating, deterioration), yet there are still many challenges, such as information querying and extraction, spatial information analyzing and describing a large amount of semantics about different context aspects (for example historical context, social information, environmental resources, other heritage artefacts information, etc.).

Both GIS and ontology provided the enhanced relative database for the management and analysis of the semantic, attribute and relationships among the sub-elements. GIS “lets us visualize, question, analyze and interpret data to understand relationships, patterns and trends” (ESRI, 2016), which focuses on managing the spatial relationship and semantic information. Ontology is used to formally represent knowledge and rules of a particular domain for the purposes of facilitating computer processing, reasoning, knowledge sharing and re-use (Simeone *et al.*, 2015).

2.3.1. Geographic Information System

Managing, querying and analyzing detailed information

GIS modelling is rich in information because it is a computer-based tool for analyzing and managing spatial, attribute, and relationship information among elements. When addressing the spatial relationship and query-based problems, GIS allows users to create interactive queries, analysis, and spatial information. GIS was utilized to manage heritage information in the 1990s in landscape-related applications (Richards, 1998), such as the Electronic Atlas on Ancient Maya Sites (EAAMS) project (<http://mayagis.smv.org/index.htm>). GIS as a tool for heritage site management can establish databases for archaeological sites and monuments at regional and national levels (Richards, 1998). GIS have been effective instruments for managing architectural heritage data, in order to query the data for preservation purposes and to realize advanced analysis (Cerutti *et al.*, 2015).

GIS in heritage Modelling

GIS is not only a management and analysis tool, but also a modelling tool that has been widely used to procedurally model large-scale residential scenes. Although CityGML was

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designed for city modelling (e.g. for planning or disaster management), because of its capabilities and interoperable design, some studies have tested its effectiveness in built heritage modeling (Cursi *et al.*, 2015). Schwarz & Müller (2015) utilized GIS modelling in modern residential areas and developed the CGA and CGA++ shape grammar language for the procedural modelling of architecture. ESRI *CityEngine* is a tool that enables efficient modelling of 3D scenes at large scale and with arbitrary detail (Haegler *et al.*, 2009). It can easily build a 3D model by inputting GIS data, such as building footprints or height maps. A destroyed Roman town, Pompeii, was reconstructed utilizing *CityEngine* on the basis of ground plans (footprints) and drawings/sketches of selected building types (Müller *et al.*, 2005). The famous Rome Reborn 2.0 (<http://romereborn.frischerconsulting.com/>) reconstructed approximately 7000 domestic buildings using grammar-based procedural modelling and *CityEngine* on the basis of manual creation of typical monuments and buildings with CG techniques. Grammar-based procedural modelling techniques have been used to create a parametric façade that can automatically combine parametric library objects generated with GDL using classical proportions and rules. This tool provides users with full control over the object with parametric and graphical editing to manipulate the object (Dore & Murphy, 2013). Therefore, procedural modelling is a valid tool to reconstruct similar detail in a scene.

Web access tool

WebGIS is widely adopted for 3D built heritage models to be visited on websites, which benefits the product management and popularity. In this distributed manner, the interoperability and exchange of modelling should be extended to the cooperation partners all over the world. A 3D WebGIS for archaeological research, called the MayaArch3D project (<http://www.mayaarch3d.org/language/en/sample-page/>), offers a system architecture for managing 3D models and their associated data so that researchers can view them on the Internet in real-time, analyze them, and compare them with other models. Researchers can explore 3D models of cities and landscapes in connection with associated archaeological data. In this manner, the interoperability and exchange of data should be extended not just to different professionals working on the same area but also to people studying physically distant architectures (Bianco *et al.*, 2013). More generally, the ultimate goal is to obtain a user-centered system for dissemination of information regarding historical architecture on the Web to reach more potential users. Many works are dedicated to spreading and sharing the entire data system on the web by systems of map sharing based on Google Earth (Casu *et al.*, 2013; Quattrini & Baleani, 2015).

2.3.2. Ontology Semantics

Although GIS can manage the attribute and spatial information, a complete representation of architectural heritage also requires a large amount of knowledge related to its history, physical configuration and condition and a high number of social, political, economic, and cultural issues relating to the external environment (Toldo & Carrara, 2014). These extremely heterogeneous knowledge is an essential asset for built heritage.

An ontology is a knowledge model relative to an area of knowledge, generally called domain that represents its primary entities (domain objects), the relations between them, the attributes (called properties) of these entities and their values (Simeone *et al.*, 2014). It is increasingly used to overcome the barriers to heterogeneous semantic data sharing and integration about the cultural heritage (Drap *et al.*, 2015). Specifically, several advantages of ontology semantics in built heritage include:

- (1) Homogeneity. The main advantage of using ontologies is the ability of homogenous representation and management of all the knowledge related to heritage in a unified semantic network, including concepts, relationships, functions, rules and constraints. (Cursi *et al.*, 2015; Acierno *et al.*, 2017)
- (2) Sharable and readable in a scientific community. Ontology semantics can share consensual knowledge agreed by a scientific community to increase the interoperability in individuals and organizations (Messaoudi *et al.*, 2018; Tibaut *et al.*, 2018). Ontology exchanges information in a meaningful way, in a human readable format and with a minimum of human intervention (Quattrini *et al.*, 2017b).
- (3) Reasoning and understandable by a computer. Ontology defines formal rules to associate the entities, relations and attributes, which makes it understandable by a computer (Messaoudi *et al.*, 2018). The rules allow checking the data and inferencing new knowledge. For examples, specific reasoning and inference rules allow checking of the model for coherence, to reduce information discrepancies, inconsistencies and errors (Acierno *et al.*, 2017); the rules also allow creating new knowledge based on that one formalized in the conceptual model, according to the properties assigned to the various entities and relationships (Simeone *et al.*, 2014; Kim *et al.*, 2018).

In the cultural heritage context, CIDOC (International Committee for Documentation) Conceptual Reference Model (CIDOC CRM) (<http://www.cidoc-crm.org/>) is the main ontological reference model (Doerr, 2003). This ontology was initially towards the

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establishment of standard description and maintenance of museum artifacts, and became the ISO standard in 2006 to allow the formal and highly specific representation of information about historical buildings. To date, CIDOC CRM facilitate integration and interchange of heterogeneous cultural heritage information, and support operations of reasoning and inference. While the CIDOC CRM model was developed mainly to manage the cataloguing of cultural heritage documentation, other domain-specific ontologies have been progressively introduced to represent other aspects of the heritage conservation process (Zalamea *et al.*, 2018; Acierno *et al.*, 2017). For example, Geneva City Geographic Markup Language ontology (Geneva CityGML) (Kolbe, 2009) is an ontological equivalent of the CityGML standard and allow to create 3D models of historic buildings. The Monument Damage Information System (MONDIS) supports the documentation and analysis of damaged historical structures, their diagnosis, and possible interventions (Cacciotti *et al.*, 2013).

2.4. Integrated research

As in the above description, each technique has an advantage in built heritage modelling. Traditional surveying provides a reliable reference for other processing techniques. Remote-sensing techniques acquire the basic data. Remote-sensing, photogrammetry and computer vision approaches can calculate the accurately measurable geometric model and try to automate/semi-automate the semantic segmentation. Computer graphics is suitable for improving the model representation, both in visual effects and geometric accuracy. Recently developed BIM techniques help to improve the geometry or visualization model into a semantic enriched model and have the potential to simulate the possible future and past conditions. GIS is good at managing and analyzing the obtained information-rich model, which is dedicated to extending the application. Ontology based knowledge model involves a homogeneous representation and integration of all the information collected and used during of the activities of investigation, intervention, use and management of heritage buildings.

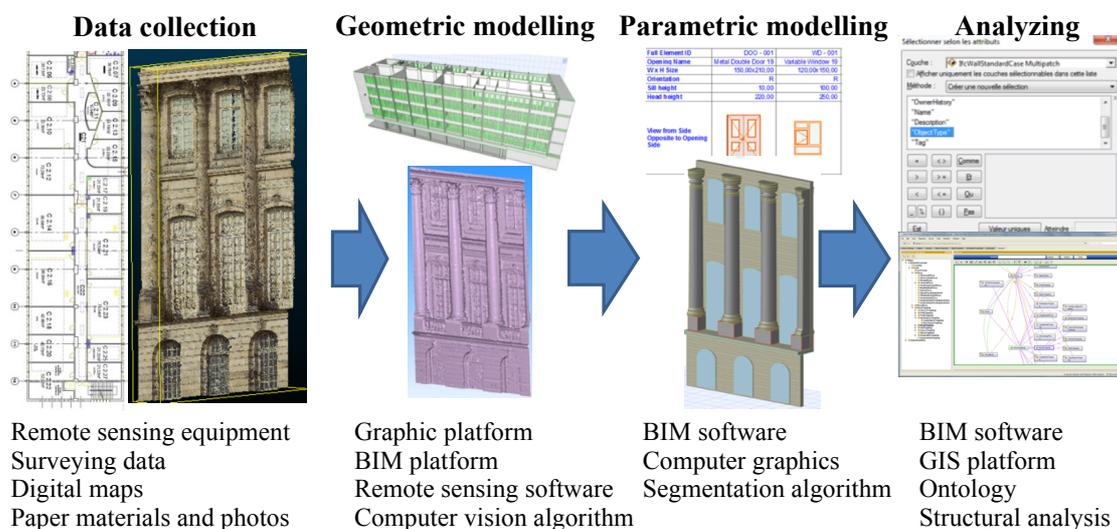


Figure 2.1. Commonly interdisciplinary process of built heritage modelling

Hence, the synergism of the information modelling techniques may successfully be used for built heritage modelling applications. Although there is a long road for enriched historic building modelling to become mature, the common process (Figure 2.1) of built heritage modelling consists of: (i) multi-source data acquisition, mainly including documentation materials, historic photos, maps, surveying, and reality-based remote-sensing data; (ii) geometry extraction, element segmentation and labelling mainly based on 3D graphics,

RS/CV and BIM approaches; (iii) BIM parametric modelling with additional semantic and spatial relationship information; and (iv) a GIS and ontology platform to manage and analyze the geometric and semantic information-rich model.

To review the different techniques utilized in built heritage modelling, related key terms (Table 3) were analyzed to present their research trend in heritage modelling (Section 2.4.1). BIM technique shows the dramatic potential on heritage documentation, and it is increasingly connected with other techniques in Section 2.4.2 (including computer graphics, photogrammetry, GIS and ontology).

2.4.1. Research trends

On the basis of the Web of ScienceTM Core Collection, we indexed the publications with combinations of key terms and analyzed the tendency of each technique on the heritage documentation. Due to the applied query method, the review excludes research currently underway that is not available in the mentioned databases, journals or conferences that are not included in the core collection of web of science, or studies that have not been published in English yet.

To review the different techniques utilized in built heritage modelling, we take related key terms (Table 2-1) and analyze the application potential in heritage modelling by comparing the attention paid by researchers before and during the 2010s. A ratio rate is calculated by the ratio of publication numbers during the 2010s and the entire publications, which are dedicated to mirroring the focuses of the researchers. That is, the higher the value is, the more attention has been paid in recent days. As shown in Figure 2.2, Built Heritage Modelling (with the rate 0.812) has been increasingly attracting emphasis, which serves as the baseline to find the increasingly hot and potential techniques.

Photogrammetry is always the most popular method in heritage modelling. The reasons may be that photogrammetry can obtain accurate geometry models with low costs in time and money, imagery information is the supplement for laser scanning, and machine learning in computer vision provides new opportunities for image-based semantic modelling.

More and more works in Heritage modelling have begun to utilize laser scanning, computer science, GIS and especially BIM techniques. Laser scanning, as the biggest development of 3D object scanning in past years, is becoming cheaper and portable, which broadens its applications. With the easy acquisition of accurate geometry by photogrammetry and laser scanning, the semantic segmentation has become the key issue. BIM techniques can create

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the parametric element library, restore the graphic geometry information and non-graphic attribute and relationship information, and manage the 3D temporal model. These advantages make it go further in the urgent semantic modelling, although time-consuming manual operation is needed, especially when preserving complex and irregular structures. GIS can manage and analyze the multi-dimensional information in the web access, which is accordant with the heritage conservation and popularity demands. Once BIM and GIS deal well with complex structures, semantic or information modelling of built heritage will be solved, although there will still be a long road for semi-automatic or automatic parameterization of the elements. Currently, objects in certain scenes can be soundly recognized and labelled with machine learning and pattern recognition approaches. It is highly anticipated to realize the semantic segmentation of 3D heritage geometric models or 2D imagery, although such an application needs a large amount of training data and addresses simple scenes, mainly in 2D space.

Ontologies have been a traditional way for heritage documentation. While the early research focused on the management of artifacts (Acierno *et al.*, 2017), just as the CIDOC CRM is developed initially for the standard description and maintenance of museum artifacts. Ontology-based knowledge model for architectural heritage is increasingly developing in recent years, especially with the integration of geometric modelling, BIM and GIS.

It seems that CG and VR are developing relatively slowly in the heritage modelling field. The reasons may be that virtual reconstruction has been relatively mature compared to semantic information, and business corporations spend more effort than academic fields on better visual effects or virtual/mixed reality.

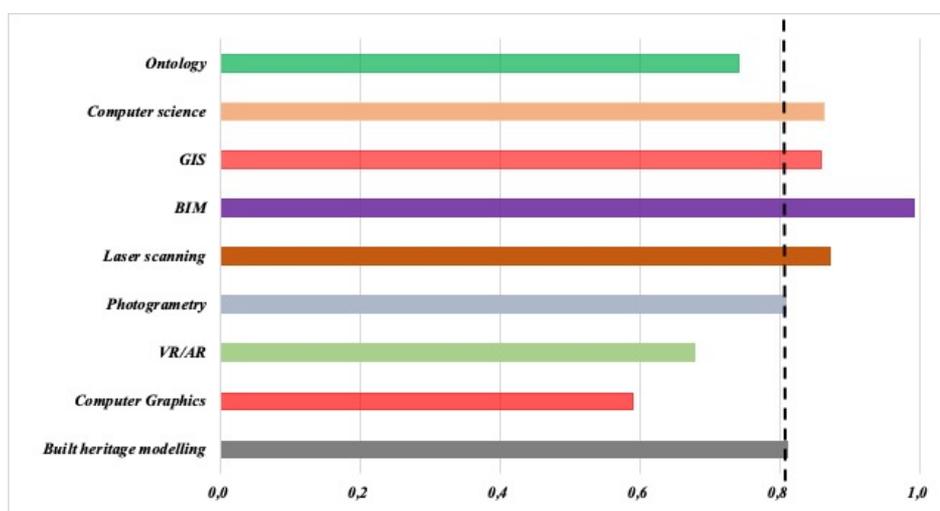


Figure 2.2. Publication rate: (2010-2017)/all publication numbers

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Table 2-1. Key terms

Terms (before 01/01/2018, indexed on 10/01/2018)	Results(during the 2010s/total)
TS = ((heritage OR "historic* building*") AND "3D")	1631/2009
TS = ((heritage OR "historic* building*") AND "3D" AND ("computer graphics" OR "3D graphics"))	49/83
TS = ((heritage OR "historic* building*") AND "3D" AND ("virtual reality" OR "augment reality" OR "mixed reality"))	127/187
TS = ((heritage OR "historic* building*") AND "3D" AND (Image OR photogrammetry))	755/ 933
TS = ((heritage OR "historic* building*") AND "3D" AND ("laser scan*" OR LiDAR))	492/564
TS = ((heritage OR "historic* building*") AND "3D" AND ("laser scan*" OR LiDAR) AND (Image OR photogrammetry))	320/362
TS = ((heritage OR "historic* building*") AND "3D" AND ("feature matching" OR "computer vision" OR "machine learning"))	57/66
TS = ((heritage OR "historic* building*") AND (BIM OR "building information model*"))	115/116
TS = ((heritage OR "historic* building*") AND "3D" AND (GIS OR "Geograph* information system*" OR CityGML))	122/142
TS = ((heritage OR "historic* building*") AND ontology	232/313

2.4.2. Integration of BIM and other techniques in heritage documentation

Combined with computer graphics for complex element generation

Both the CG and the original BIM concept for built heritage modelling have formed documentation-based parametric modelling, which are non-real measurement-based approaches utilizing historic materials describing heritage, such as historical documents, bibliographic references, photographs, drawings, etc. BIM goes further than CG to improve the virtual reconstruction of an information rich model by semanticizing the elements.

It is usually a manually time-consuming concept in BIM software to parametrically model the historic elements, and they are limited in their ability to create complicated irregular geometry. That is, the time complexity and geometric accuracy for parameterizing the complex and irregular historic structure elements are the main challenges. Thus far, there exist mainly two ways to parametrically model the irregular elements not included in the BIM library. The first one is the manual modelling of the elements in the BIM software platform directly (*Revit*, *ArchiCAD*) (Aubin, 2013). The main drawback is its low efficiency

and how hard it is to ensure geometric accuracy. The other is the utilization of programming, including the *Geometric Description Language (GDL)* of *ArchiCAD* library parts (Martens & Peter, 2002) and *Autodesk Dynamo* visual programming for *Revit*. The parametric *GDL* and *Dynamo* elements could be completely described as 2D symbols, 3D geometric models, attribute specifications and additional spatial relationships in the BIM platform.

BIM is increasingly paying attention to irregularly shaped modelling by introducing CG modelling techniques. Some works build the irregular structures with the help of CG software, such as *Rhino 3D* (Garagnani & Manferdini, 2013; Osello *et al.*, 2013; Oreni *et al.*, 2014) or *Sketchup* (Osello *et al.*, 2013; Wu *et al.*, 2013), which could accurately address any irregularly shaped object compared to BIM platforms (Barazzetti *et al.*, 2015). For example, *Rhino 3D* software is able to generate accurate and free-formed models of complex and irregular geometries, especially using NURBS to represent surfaces. BIM software could then add and manage the attribute and spatial relationship information.

The current tight combination of graphics geometry modelling and BIM semantic modelling, such as the *Rhino-Grasshopper-ArchiCAD* connection developed by *ArchiCAD* and *Rhino 3D*, empowers architects to start and modify their designs in any of the three design environments (*Rhino 3D*, *Grasshopper* or *ArchiCAD*). Meanwhile, BIM software is incorporated with NURBS-based parametric modelling tools. Currently, *Rhino 3D* also builds BIM semantic models and has been expanded to *RhinoBIM*. The design of *RhinoBIM* is 3D-centric, where the design is modelled and captured in a 3D database compared to the conventional BIM software. Moreover, *Rhino 3D* has been developed further for the architectural industry, yielding software called *RhinoBIM*. It is a powerful, accurate, free-form geometry modeller. The design is 3D-centric, where the design is modelled and captured in a 3D database compared to conventional BIM software.

As-built HBIM Introducing traditional geometric models for as-built heritage

Built heritage geometric modelling has often been conducted using reality-based data (Grussenmeyer *et al.*, 2008; Remondino, 2011; R  ther *et al.*, 2012; Georgopoulos & Stathopoulou, 2017). Up until now, multi-platform-based imagery and laser scanning data are all used to geometrically model heritage. The increasing accuracy of geometric models preserves the current shape condition of heritage object, monitors the later changes, and reconstructs them even if the historic buildings should have some critical evolutions or damages. It is no longer a problem to obtain an accurate 3D geometric model, yet it is still highly anticipated to perform semantic segmentation and labelling of elements. The

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documentation and conservation of heritage not only means the geometric modelling of the object but also expects the detailed information recording about the semantic segmented elements and their attribution information (Remondino & Rizzi, 2010).

As-built BIM is increasingly used to model, restore and manage existing valuable constructions and historic structures by reality-based remote-sensing recording data acquisition and reverse engineering techniques (Barazzetti *et al.*, 2015). BIM goes further than traditional geometric model with parametric and semantic elements. As a 3D information modelling environment, BIM software is increasingly supportive of 3D point clouds representing the entity surface, which is called as a scan-to-BIM process. By importing the point clouds into the BIM software, the solid building components can be created using the existing BIM IFC classes and self-defined structures. The model is not only a virtual representation of the construction. It is a key part of the project, where the different elements of the building become advanced objects with parametric intelligent including the quantitative and qualitative description and strict relationship information.

Unfortunately, the scan-to-BIM process remains mostly a manual process (Garagnani and Manferdini, 2013; Fai and Rafeiro, 2014; Murphy *et al.*, 2013), and a key challenge today is thus to automate the process leading to as-built BIM from point clouds (Macher *et al.*, 2017). To reduce the manual work in such scan-to-BIM process, many commercial tools and algorithms exist. Many jobs utilised the commercial scan-to-BIM plugins in *Autodesk Revit* platform, including *ClearEdge3D Edgewise*, *IMAGINit Scan to BIM*, *Pointsense* and *Leica CloudWorx*. Some tried to automate the scan-to-BIM process by self-developed algorithms (Xiong *et al.*, 2013; Thomson and Boehm, 2015; Macher *et al.*, 2017). Although they show excellent progress for the automation reconstruction of as-built BIM from point clouds, those works only deal with planar walls and floors and some other regular structures (i.e., rectangular openings and cylinder columns).

That is, most commercial BIM packages and scan-to-BIM algorithms were mainly developed for modern buildings with regular shapes. Historic buildings are composed of complicated and irregular architectural elements, which makes it problematic to segment and parameterize the elements. For the irregular structures widely existing on built heritage, the current scan-to-HBIM process is totally time-consuming manual modelling. Although current BIM platforms are supportive of point cloud, the parametric modelling tools are still limited because most of BIM software are not 3D-centric modelling environment and cannot directly parametrically design the shape on the reference of the point clouds in 3D space.

Transferred to GIS for information management

BIM are recognized as systems suitable for the 3D modelling of historical buildings. They provide high editing functionalities for parametric modelling and achieved semantic models with semantics, topology and appearance properties. Sometimes due to the lack of spatial analysis and information querying capabilities in BIM, HBIM models are incorporated into 3D GIS environment for further analysis.

GIS has the priority in information management (attribute, semantic, and relationship information analysis and management), while BIM is limited to storing semantic and attribute aspects thus far since it lacks query (attribute and spatial) functions. GIS should play an important role in 3D information model management and analysis, from 2D to 3D, from local to web service, from regular to irregular, and from stable to dynamic.

The current trend concerns the convergence of both concepts on lots of fields, such as AEC industry (Song *et al.*, 2017), facility management (Mirarchi *et al.*, 2018), urban architectural (Arroyo Ohori *et al.*, 2018) and so on. The separate standards, for instance the two most popular standards of Industrial Foundation Class (IFC) for BIM and City Geography Markup Language (CityGML) for GIS, seem to be widely accepted for exchanging semantic 3D information and geographical for BIM and GIS (Deng *et al.*, 2016). During the integration process, some significant details are lost due to the extraction and simplification of data from one system to another (Gröger and Plümer, 2012; Song *et al.*, 2017).

When it comes to the historic buildings composed of complex elements, the BIM-GIS integration is also the trend and faces the new challenge because both BIM and GIS are originally developed for modern buildings. A typically two stage outline involving HBIM for 3D modelling and GIS for further management and analysis has been defined by Dore and Murphy (2012). But it is critical to minimize the information loss in the conversion process (El-Mekawy *et al.*, 2012; Saygi *et al.*, 2013; Suwardhi *et al.*, 2016) Many studies have been performed to minimize the information loss in integrating BIM and GIS. The common process is to extend the models from BIM to GIS, and a CityGML extension called GeoBIM to get semantic IFC data into the GIS context is developing well (De Laat *et al.*, 2011). BuildingSMART IFC is also extending itself for GIS project application, such as the new entity for spatial zones, geographic elements and external spaces (Przybyla 2010). A united system integrating GIS and BIM concepts on built heritage documentation without information loss is still expected.

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

Connected with ontology for enriched semantics

BIM provided a modelling environment where geometrical information and some intangible data are structured in a coherent database, and GIS provides a management environment where geometrical, attribute and relationship can be queried and analyzed. But they still leave out of the model a large amount of knowledge, not directly relatable to heritage's components but still needed to fully represent the object (Simeone *et al.* 2009). Thus, a knowledge model developed by means of ontologies, are integrated with BIM-based modelling environment to represent all the semantics (its history, physical attributes, function, location, ownership, and preservation process) needed for a comprehensive representation of the historical buildings (Toldo and Carrara, 2014) (Pauwels *et al.*, 2013).

Previous studies show that ontology can overcome many of current IFC data model's limitations. For example, Jung and Joo (2011) emphasized using ontology with reasoning in BIM framework to automate spatial and temporal interrelationship. Abanda *et al.* (2017) combined ontologies with BIM model to facilitate information extraction for cost estimation application, in which ontology is employed to check the semantics and reason the descriptive logic. Ali and Mohammed (2017) encoded a BIM model using Resource Description Framework (RDF) and then grouped the objects into clusters representing different trades. Zhang and Issa (2011) integrated BIM with ontology to generate partial BIM models based on queries.

Specifically, ontologies play increasingly important roles in the connection with HBIM:

- (i) Knowledge modelling: Ontology based knowledge model is combined with HBIM to enrich the semantic information. Ontology serves as a data collector to represent a large amount of semantics possibly independent from the built heritage (for example historical context, social information, environmental resources, other heritage information, etc.) (Simeone *et al.*, 2014 ; Quattrini *et al.*, 2017a; Toldo and Carrara, 2014).

- (ii) Information extraction and querying: The combination of ontology can extend the HBIM model with the capabilities of information extraction and querying. The typical workflow is to use *Autodesk Revit* as HBIM software and *Protégé* for editing ontologies and then to export the project database and query the information by *Revit DBLink* (Simeone & Cursi, 2016; Quattrini *et al.*, 2017a). Besides, based on ontology-based feature modelling, ifcXML is utilized to conduct query processing to extract information relevant to construction practitioners from a given HBIM (Nepal *et al.*, 2013).
- (iii) Connect and transfer the information between HBIM and GIS: Ontological framework can be built for dealing with the interoperability issue between HBIM hierarchy structure and GIS relational database. HBIM model and GIS model are firstly mapped to ontology respectively and then connected and queried using ontology rules. (Karan *et al.*, 2016) (Hor *et al.*, 2016)
- (iv) Help to create the parametric model: HBIM utilized parametric design to generate complex structure based on the rules, which to data is conducted by totally manual-drawing. Lin (2017) mentioned the possibility to applied ontology to computer graphics parametric design which can automate the modelling work to some degree. Actually, this kind of combination could be the basis for automated HBIM parametric design (López *et al.*, 2018), yet few work has paid attention on the ontology-based HBIM modelling.

To fully represent and comprehend a historical/archaeological artefact, an integration (Figure 2.3) with HBIM and ontology can provide both object-oriented information (typically found in BIM software) and semantic information (typically found in ontological modelling systems). Currently, ontology semantics can be connected to HBIM by direct ad-hoc development in HBIM platform, migrating HBIM IFC files to RDF/OWL and developing a unified platform.

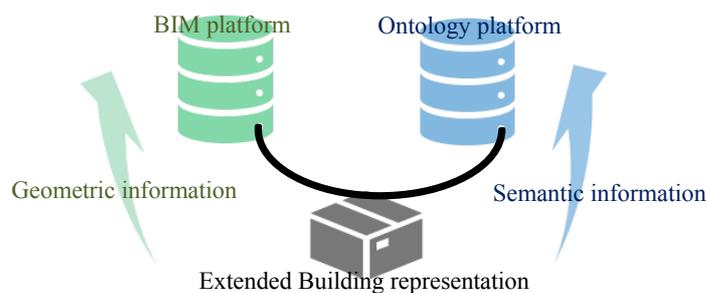


Figure 2.3. A unified system combined with geometric elements and semantic knowledge

- (i) The HBIM environment has been integrated with an ad hoc knowledge base developed by means of ontologies. Such combination enables the end user to query a repository composed of semantically structured data (Quattrini *et al.*, 2017b). The bridge between the HBIM and the ontology-based databases has been generally implemented by means of the *Revit DBLink* plugin. This database comprehensively represents "what is known" of the object and "what is needed to know" for further proceed with the process of investigation, conservation and communication (Simeone *et al.*, 2009).
- (ii) IFC-to-RDF transformation via IfcOWL. IfcOWL is an ontology that can be considered the first step to extending the structured IFC information to the world of semantic ontologies. (Beetz *et al.* 2005) Various research efforts have explored HBIM IFC data for automatic extraction and systematic conversion to OWL, which is referred to as 'IFC to RDF'. Once data enrichment has been done in BIM platform, the standard BIM model export functionality can be straightforwardly used to produce HBIM IFC data compliant with the EXPRESS schema. (Simeone & Cursi, 2017) data enrichment can be captured by the IFC-OWL ontology by mapping HBIM IFC extensible properties. The resulting model has the advantage of being generic and flexible, but the drawback of being complex and requiring long SPARQL queries to extract relevant information. (Quattrini *et al.*, 2017b) (Cursi *et al.*, 2015) The IfcOWL project converts EXPRESS/IFC schemas to ontology. This project is currently embraced by buildingSMART as a future development of the IFC standard (Pauwels *et al.*, 2017).
- (iii) A unified platform can call the HBIM elements and ontology components. Acierno *et al.*, 2017 developed a platform to connect the HBIM *Revit* objects and ontology *Protégé*. When choosing the HBIM element in *Revit*, the same object represents in the ontology editor *Protégé* in terms of data and object properties.

Summary

Many existing techniques, including surveying, photogrammetry, computer vision, computer graphics, Geographic Information System, ontology and the recently developed Building Information Modelling, help built heritage modelling processing from different data sources to the final different levels of detailed information models (Figure 2.4). It focuses on accurate description using software and large-scale areas using procedural modelling. Computer graphics have been used to model heritage and dedicated to virtual reconstruction and enhance visual effects by VR/AR techniques. Surface information is obtained by photogrammetry and laser scanning with non-contact tools, which is accordant with the concept of heritage conservation. Several automated or semi-automated algorithms are available to realize geometric modelling and semantic segmentation. GIS is used to manage the attribute and spatial information, and webGIS provides an available web access tool. Ontology deals with the heterogeneous knowledge describing the heritage. Recently developed BIM techniques provide a more powerful environment that combine the 3D geometric modelling and information management together.

The overall built heritage information modelling should generally involve four phases (Figure 2.4). (i) The first phase is data collection, including documentation and digitization of historic materials, reality-based acquisition using remote sensors, and auxiliary data. (ii) The second phase is accurate geometric modelling and element segmentation in some extension. (iii) The third phase is compiling of the semantically enriched model on the basis of semantic segmentation and recognition. (iv) The last phase is the final products in different level of details for further analysis, management, monitoring and repair.

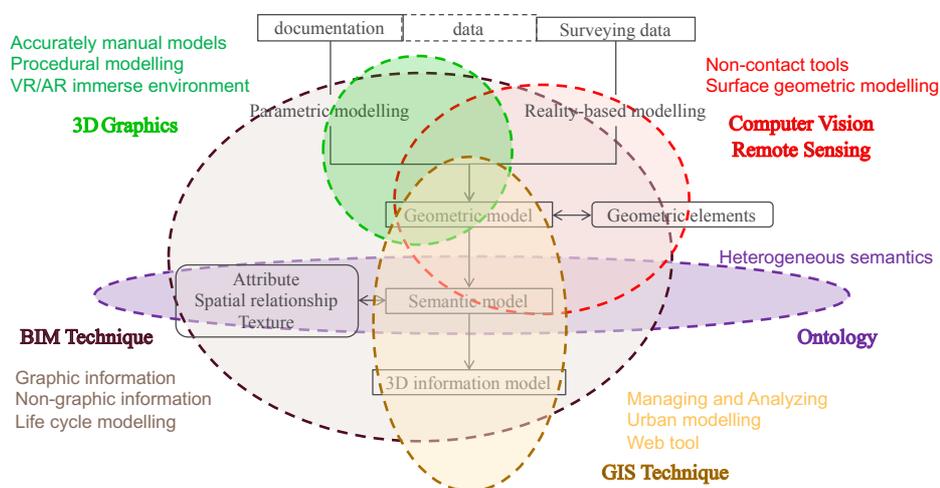


Figure 2.4. The overall scheme of built heritage modelling with combined techniques

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HBIM can utilize the BIM concept to re-create “new” heritage according to the historic material or utilize the “as-built” BIM concept to semantically segment the 3D point clouds based on remote-sensing recording data. This chapter describes the popular HBIM software platform especially the widely utilized *Autodesk Revit* in Section 3.1, the basic concept of level of details (LOD) for the HBIM model (Section 3.2), and two HBIM concepts including documentation based HBIM in Section 3.3 and as-built HBIM in Section 3.4. The overall HBIM should generally involve three phases:

The first phase is data collection, including documentation and digitalization of historic materials, reality-based acquisition using remote sensors, and auxiliary data. In the study, part of INSA Strasbourg building and two lost built heritage (Petit château du Meisenbach and a church of the Abbey of Niedermunster) are chosen to recreate their HBIM models based on the archived documentation. Meanwhile, reality-based point cloud is collected for the façade of Rohan Palace, part of St-Pierre-le-Jeune Church and the beam frame of the Castle of Haut-Kœnigsbourg, Alsace, France.

The second phase is the HBIM modelling according to the collected data materials. This phase is compiling of the accurate geometric modelling and parametric and semantic modelling of the elements. The modelling process can be conducted totally in BIM software (INSA Strasbourg building, façade of Rohan Palace, and the beam frame of the Castle of Haut-Kœnigsbourg). Besides, traditional software platforms can also be adopted to help the modelling process, such as the *SketchUp* (Abbey of Niedermunster), *Autodesk Inventor* (Petit château du Meisenbach), *CloudCompare* and *Rhino 3D* (St-Pierre-le-Jeune Church).

The last phase is the final products for further applications, such as structural analysis based on the material and relationship of the elements, integration with ontology and GIS for semantic and attribute information management, and so on.

3.1. Software platform

There exists a comprehensive list of BIM providers for architectural applications (*Autodesk Revit*, *Graphisoft ArchiCAD*, *Bentley Architecture*, *RhinoBIM*, *CADsoft Envisioneer*, *Nemetschek ALLplan*, *4 MSA IDEA*, and so on) to accomplish this parametric modelling process. The software provides vast numbers of objects describing urban architectures yet lacks specific objects for the different heritage. Historic buildings have specific and complex walls, roofs, openings and structures, which are usually unique to each property. This makes modelling them very challenging with the existing software and approaches.

Thus far, *Autodesk Revit* (Garagnani & Manferdini, 2013; Apollonio et al, 2013; Scianna et al., 2014; Del Giudice & Osello, 2013 ; Barazzetti et al, 2015; Baik et al, 2015 ; Bernardino et al, 2015; Cheng et al, 2015; Li et al, 2015; Ma et al, 2015; Percy et al., 2015; Sun et al, 2015) and *ArchiCAD* (Murphy et al, 2011; Murphy et al, 2013; Oreni et al, 2014; Dore & Murphy, 2013) served as the most popular research platforms to create HBIM. *ArchiCAD* has the priority in its integrated GDL language, which can digitalize the rules and shapes in documentation and reduce the time-consuming manual work. *ArchiCAD* is increasingly adapting to complex and irregular historic structures, such as the connection with *Rhino 3D* and adding NURBS curve into the GDL library to improve the modelling accuracy for any shaped elements. *Revit* provides the friendly API development, *Dynamo* visual programming and extensive plug-in to reduce the human involvement. *Revit* also soundly supports point clouds, which made it appropriate to connect with reality-based modelling. *ArchiCAD* paid more attention to the traditional BIM concept considering its integrated GDL language and the *Rhino-Grasshopper- ArchiCAD* Toolset, while *Revit* goes further in the expansibility via API development and *Dynamo* programming.

3.1.1. *Revit* and *Revit API*

Autodesk Revit is one of the BIM-related computer program to pay attention on the built heritage. HBIM brings additional difficulties compared to traditional BIM modelling, which needs to deal with the irregular structures and soundly support the point clouds to aid the reality-based parametric modelling. In one hand, the irregular structures composing the built heritage make them nonexistent in the IFC element library and *Revit* built-in system. Thus, the heritage modelling utilizing *Revit* generally consists of manual element creation and HBIM model generation, which is conducted by time-consuming manual drawing. In another hand, *Autodesk Revit* has been well supportive of point clouds to aid

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the reality-based parametric modelling process, by direct manual family creation (Garagnani and Manferdini, 2013) or commercial plugins (Klein *et al.*, 2015) such as *Scan-to-BIM* and *Leica CloudWorx*. The good support for 3D point clouds has currently made *Revit* the main reality-based semantic modelling environment. But the plugins are expensive and tend to regular buildings and the manual creation becomes time-consuming with the complex 3D space distribution of the elements.

Revit provides a rich and powerful *.Net Application Program Interface* (API), by which the users can comprehensively utilize the *Revit* parametric modelling and user-specific applications including the heritage modelling. *Revit* API can be developed utilizing *.net* and Python programming, and it also provides some free and friendly tools to the development process, such as *Revit SDK* (<http://www.autodesk.com/revit-sdk>), *RevitLookup* (<https://github.com/jeremytammik/RevitLookup>), and *AddinManager*. *Revit SDK* is the *Revit API* document, which provides the *API* class name and function methods. *RevitLookup* interactively and visually look up the built-in information in *Revit*. The digitalized parameters link the *Revit* and developed plugins together to interactively process the elements. *AddinManager* provide the totally interactive processing between *Revit* and API program in real-time.

The *Revit API* combines the BIM parametric modelling and programming functions (Table 3-1). The interacting programming methods offer designers the ability to interactively design and manipulate *Revit* elements using algorithms and computational logic. *Revit* can provide the UI platform, serves as the basic view platform and database, and parametrically represents the element and builds the relationship automatically. The program can reduce the manual operation, and realize automatic and batch processing aiming at specific functions. Therefore, they can simultaneously automate the element segmentation and parametric representation procedure in BIM environment by specific functions.

In the project, *Autodesk Revit* is utilized as the BIM tool and platform for the modelling process. In the Section of 4.3, a *Revit* API has been developed to build the HBIM model for the beam frame according to the sparse surveying points.

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Table 3-1. *Revit*, *Revit API* development and *Dynamo*

	Merits	Limits
<i>Revit</i> software	UI & 3D view platform Manual modelling tools Information Management and storage Automatic Relationship Supportive of point cloud Available plug-ins	Manual work Rely on the existing functions
<i>API</i> programming functions	Extended functions C# or other .NET programming Reduced manual operation Automatic and batch processing Specific functions Existing algorithms	On the base of <i>Revit</i> platform Boring debugging Difficulty to connect with libraries of (<i>OpenCV</i> , <i>PCL</i> , <i>numpy</i> , etc.)
<i>Dynamo</i> visual programming	<i>Revit</i> tools and extended functions Visual programming & <i>Python</i> Manipulate <i>Revit</i> elements Mainly for the creation of complex geometries Support of conventional geometry Integration of HBIM with database semantic description Structural analysis via <i>Autodesk Robot</i>	On the base of <i>Revit</i> platform Time complexity

3.1.2. *Revit Family*

HBIM consists of a detailed semantic model and a library of parametric components. Parameterization of the architectural elements is the essential characteristic of BIM. The parametric object could be obtained by commercial BIM software (simple and regular shapes) and corresponding plug-in (*Dynamo* in *Revit*), scripting language (*GDL*) or special graphic software (*Rhino 3D*) for irregular elements. The parametric objects are dynamic in some extent and can instantly alter the shape, size and other properties by tuning parameters.

The library of parametric element classes (defined as “*Family*” in *Revit*) needs to be built to define the basic architectural elements of the historic building. A “*Family*” is a group of elements with a standard set of parameters and similar graphical representation, which can be modified by the users.

The modelling of the various architectural heritage objects can be parametrically created in two kinds of “*Families*” in *Revit* platform: “*in-place family*”, directly built-in “*Mode-In-*

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Place” editor of “*architectural*” project environment, is used for the creation of realistic walls; and external component “*Family*”, separately built in *Revit Family* editor, is used for the creation of other parts, such as, columns, roofs and other structures. The “*in-place family*” is grouped and converted into the loadable component “*Family*” outside the project, which can be a “*wall host*” family for openings and loadable family to other projects.

These types of general “*Families*” consist of a set of rules and properties to control the parameters by which element instances can be generated (López *et al.*, 2017). They need to be manually created in the BIM platform according to the prior knowledge (Figure 3.1) and on reference of the point clouds (Figure 3.2). The documentation-based “*Family*” is created by delivering 2D documents and then adding 3D capability; that is, the basic geometric parameters and specific curves are firstly defined and then 3D shape is generated based on rotation and extrusion functions. Although BIM platforms are increasingly supportive of the point cloud, it is still complex to create accurate parametric “*Family*” according to the point cloud. The user’s freeform design is limited when creating complicated geometry and handle large amounts of data in 3D space directly.

Except for these parametric “*Families*”, there also exist a kind of non-editable “*Family*” which presents specific shapes and is transferred from the solid geometry. *Revit* supports several types of 3D geometric formats, such as *AutoCAD* dwg, *SketchUp* skp, and BIM IFC element, which can be loaded in the BIM platform with non-editable geometry.

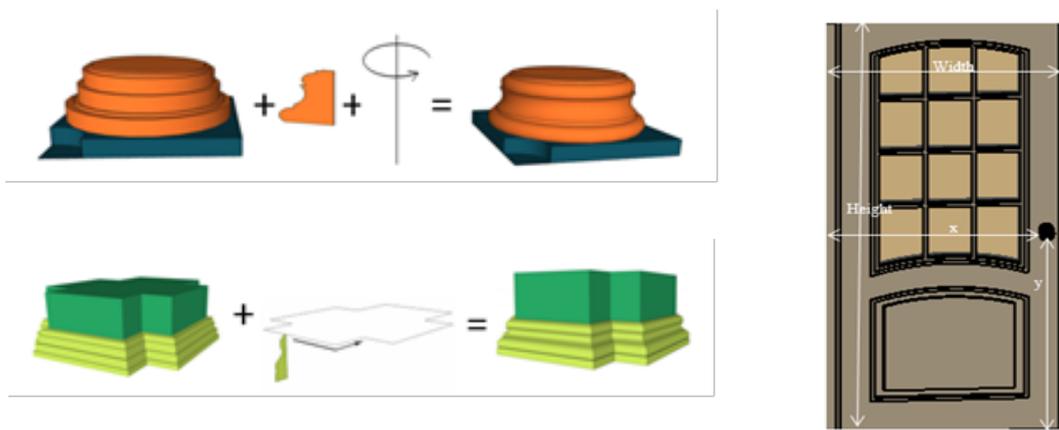


Figure 3.1. The description information about the elements could be obtained from documentation data and then digitized to parametric object library

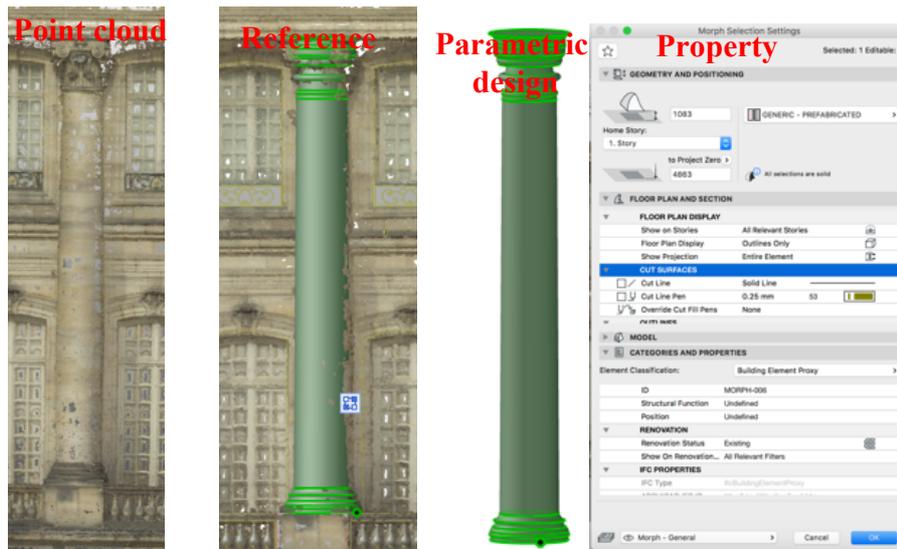


Figure 3.2. The “Family” is created on the reference of the point cloud.

3.1.3. Autodesk Dynamo

Autodesk Dynamo is an open-source visual programming environment which packages the python programming into callable node. Users can directly adopt the developed node and improve and develop the new node. It provides the open-source environment and easy-release of the developed functions as third-party packages to the public.

Dynamo has been a built-in plugin to *Revit* and offers designers the ability to interactively design and manipulate *Revit* elements by programming, which helps in block processing and reduces manual handling (Table 3-1). It can interact with *Revit* to extend its parametric capabilities to the *Revit* project level and provides an environment to create customized packages using *CPython* and its self-defined scripting and through sharing it with other users (Asl *et al.*, 2015).

Dynamo extends *Revit*'s parametric modelling capabilities by adding a level of associativity that does not exist in the off-the-shelf application (Kensek, 2014). Particularly in the field of heritage documentation and HBIM, except for the initial capability to create the complex structures of the built heritage, *Dynamo* is increasingly adopted for various applications:

- (i) *Dynamo* is, in fact, used mainly for the creation of complex geometries, based on mathematical formulas, which can be modified at any time. That is, *Revit Dynamo* works like Grasshopper in *Rhinoceros*.
- (ii) Support of conventional geometric models (such as from *Rhino 3D* and *SketchUp*) and closed mesh and transferring them to *Revit* IFC format.

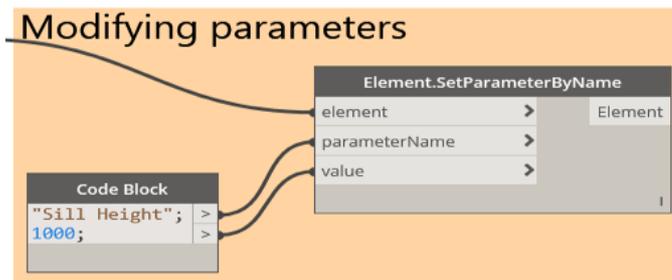
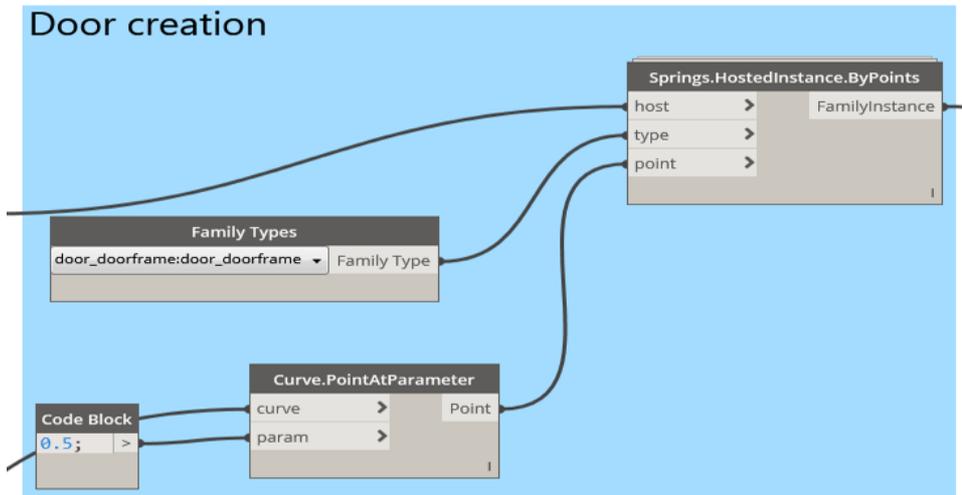
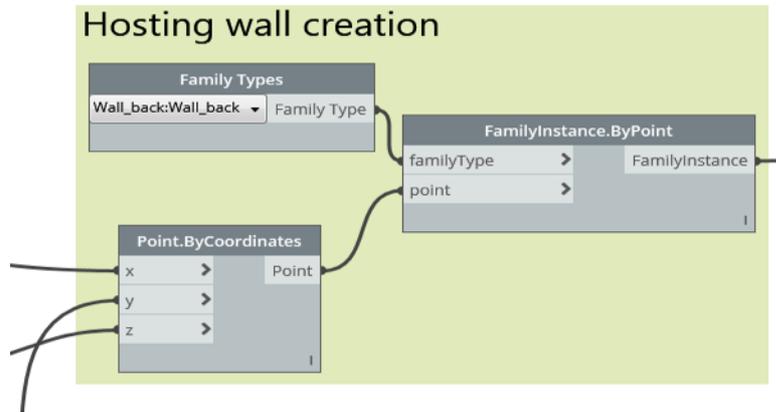
- (iii) Manipulate *Revit* elements by built-in nodes, third-part packages and self-developed Python programs, which benefits for block processing and reducing human involvement.
- (iv) Integration between *Revit* geometric elements and ontology/database semantic description, which is important for the management of the heritage knowledge. It can also interact with the system parameters: extraction of information, composition of strings for communication with the *MySQL* database, recovery and updating of parametric values from the *MySQL* database (Quattrini *et al.*, 2018; Lu *et al.*, 2018);
- (v) Further analysis on the HBIM model, such as material characteristics (Pocobelli *et al.*, 2018) and combining *Autodesk Robot* structural analysis.

In our project, based on the “*Family*” creation, the building modelling process is conducted by *Autodesk Dynamo*. The utilization of *Dynamo* is dedicated to reducing the human involvement during the HBIM modelling from parametric “*Family*” and solid elements. The semantic model composed by the primitives is generated based on the function nodes provided in *Dynamo* and open-source packages, which mainly includes four kinds of modules:

- (i) “Host” elements generation based on coordinates (green part in Figure 3.3). Based on the parametric “*Family*”, the instance can be created in the right position based on the coordinates, including floor, wall, roof, stair, column, etc.
- (ii) “Host Based” elements generation based on the relative relationship with the “Host” elements (blue part in Figure 3.3). The door and window are created based on the relative position in the wall.
- (iii) Parameter modification (orange part in Figure 3.3). The parameters can be modified in either the *Revit* interface or *Dynamo* nodes. The element parameter can be adjusted in *Dynamo* by indicating the parameter name and corresponding value. Arbitrary parameter modification window can be added by the users in the application.
- (iv) “*Family*” generation based on the solid mesh (white part in Figure 3.3). *Spring Nodes*, a custom node package for *Dynamo*'s interaction with *Revit*, are employed to construct the “dead family” and create the elements. Given a conventional geometric component (from *Rhino3D*, *SketchUp*, *AutoCAD* and so on) and a closed mesh, *Spring Nodes* can reorganize them to *Dynamo* geometry. Correspondingly, *Revit* “*Family*” can be created according to existing “*family template*” and defined the dedicated “*family name*”,

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“category”, “material”, and “subcategory”. Considering the unavailability of mesh format in *Revit*, *Dynamo* provides an automated way to transfer the segmented mesh structures to *Revit* “Family” and primitives. But the only requirement is the mesh structure has to be closed to ensure that the mesh surfaces can be joined to solid.



Chapter 3: Conventional HBIM and study areas

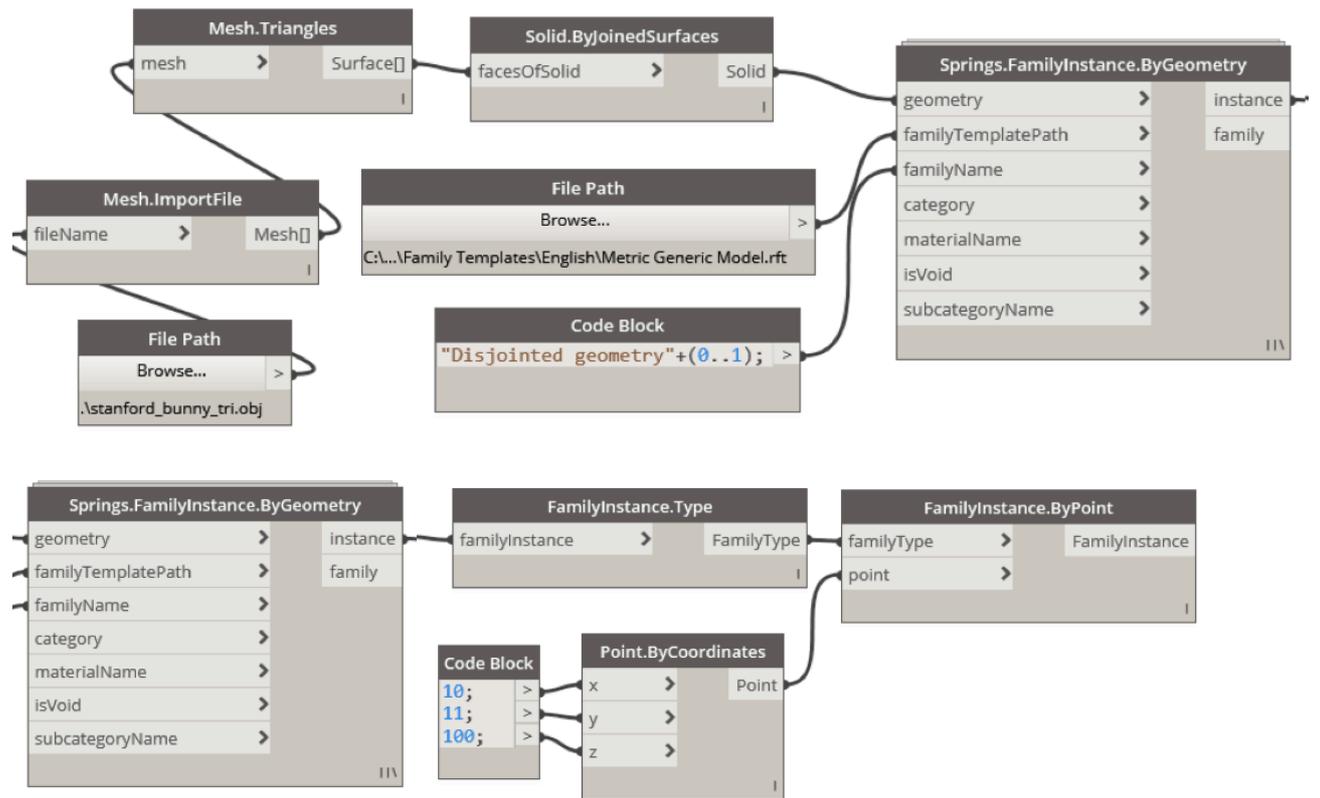


Figure 3.3. *Dynamo* functions for the BIM modelling from primitives

3.2. Level of details (LOD)

One of the most talked about topics regarding enriched 3D modelling is always Level of Detail (LOD). LOD is how deep the detail is in the model element and a measure indicating their grade and scale. Therefore, different 3D modelling techniques focusing on different aims have different definitions of LOD. Originally, the GIS field takes buildings combined with roads, trees, and bridges as basic elements, while the BIM field takes building as the entire entity and takes the compositional structures, such as columns and openings, as the basic elements.

CityGML (Alamouri & Pecchioli, 2010) has defined the LOD as five levels from LOD0 to LOD4 (Figure 3.4), which has been widely accepted in modern building geometric modelling. LOD0 is the cadastral map indicating the footprint of the buildings or a DTM with an ortho-image projected on it. In LOD1, buildings are generalized as rectangular blocks generated by adding the height information. LOD2 provides additional details of the roof and façade with different shapes (multi-polygon, gable roof, camber surface). LOD3 provides the façade sub-structures (windows and doors) and roof superstructures. LOD4 goes further to the indoor scene objects from the surface model. Therefore, CityGML takes buildings as the basic element, and it ignores the details of the micro-structures composing the buildings.



Figure 3.4. Building models in LOD0-LOD4 (image from Biljecki *et al.*, 2016)

In the BIM field, there is no uniform definition of LOD. LOD is also defined as Level Of Development (LODt) in BIM by the American Institute of Architects (2013), which verifies the model information that is required at each stage of development of the project and decides whether to continue to the next stage or not. It focuses on the time scale and development of a new architecture. Similar to the CityGML focusing on the spatial details, PAS 1192-2 defines LODt to consist of LOD (the graphical content) and Level of

Information (the non-graphical content). LOD100 indicates that there is an object, LOD200 adds its size information, LOD300 adds its additional functions and options information, LOD400 describes the object via accurate geometry, and LOD500 defines the object via particular data. The generalized LOD in BIM (Figure 3.5) identifies how much information is known about a building element at a particular stage of the project (Cheng *et al.*, 2015).

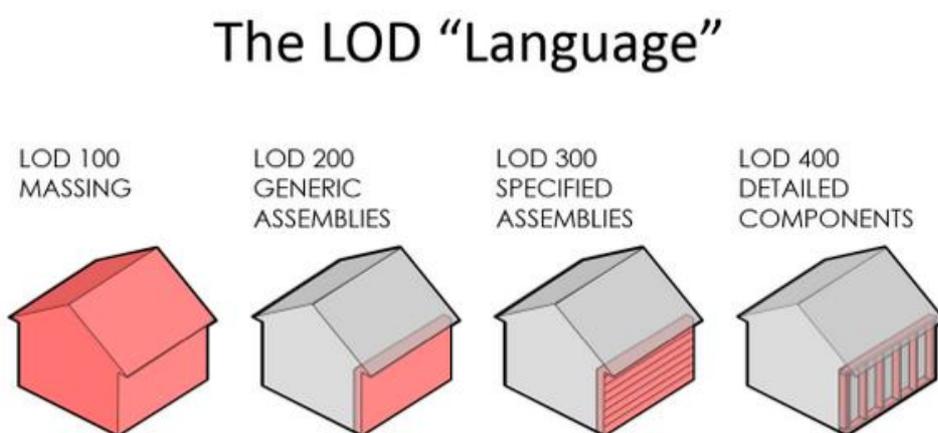


Figure 3.5. Building models in LOD100-LOD400 (image from AIA TAP, 2014)

LOD in both GIS and BIM serves their own applications, which are not totally appropriate for historic models. CityGML is dedicated to modern urban buildings and considers the information details in the stand of buildings, so it contains insufficient description possibilities for the micro-structures. The historic buildings consist of complex elements, mostly of irregular shapes, and various sculptures on the surface or raised structures, all of which need to be accurately modelled. BIM was originally for new buildings. Level of Detail and Level of Development (which may be even more useful) focus on the time dimension for the construction stages. Historic BIM is as-built BIM for the existing heritage. The LOD in BIM or GIS is then not suitable in Heritage BIM where relevant criteria are expected.

The “detail” in historic building information modelling is how complex, accurate and changed the elements are, considering the specific spatial and temporal scale characteristics about the heritage. For the aspect of spatial information, the 3D historic models are being generated at different levels of detail and scales ranging from areal sites to individual buildings and to archaeological complexes using methodologies based on different accurate data acquisition techniques. A historic site firstly may consist of several buildings, which means it is not a mono-building problem. Then, the building in different levels of detail must be considered, from a box to different morphology of the roof/façade and then to the

opening structures and finally to possible indoor structures. Moreover, heritage is used to sculpture many micro-structures around the surface, such as statues or animals, which make it more difficult to reconstruct. Moreover, it is expected to manage the heritage based on the enriched historic models, so it is highly anticipated to cover the change information.

If the heritage has been surveyed and modelled with accurate geometry, semantic segmentation and comprehensive attributes are gathered from several external data sources. It should reach different levels of detail depending on the user's needs. In addition, building a product with different levels of detail may help solve the information loss problem to some extent (Figure 3.6). Generally, the more simplified the structure is, the less possible the information loses. But the simplification goes against the aim of heritage conservation and may result in a non-useful model. The complex elements and non-unified criterion makes it difficult to optimize both aspects simultaneously.

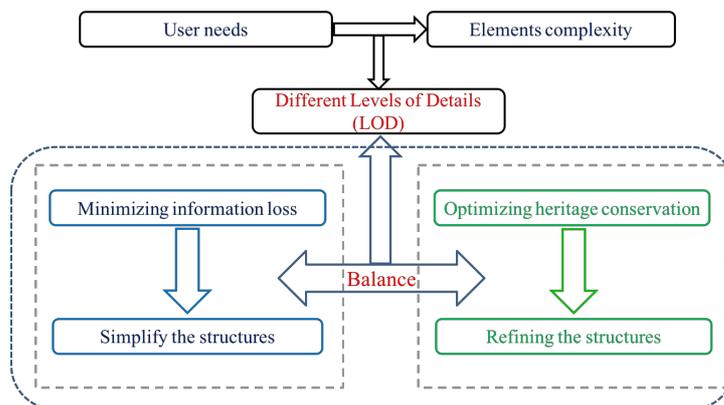


Figure 3.6. LOD to balance the information loss and information accuracy

A LOD definition for built heritage models, considering its characteristics with both the geometric aspect and raw data, could be defined here (Figure 3.7) (we used a parallel numbering, as in BIM):

LOD 100: the 2D cadastral outlines of a different historic building, which means that the building is considered as built heritage to be modelled. The information can be an existing cadastral map, surveying data and remote-sensing mapping.

LOD 200: simple geometric models with sizes and basic shapes. The heritage is an individual object extracted from the background, which can be the image and point cloud segmentation and labelling.

LOD 300: the detailed model with sub-structures, including openings and roof

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superstructures. The heritage is no longer a whole entity, and it consists of façades, roofs, columns, and their sub-elements. The elements can be recognized automatically and parametrically semantically modelled with BIM software.

LOD 400: the accurate model with detailed structures, such as the sculptures in the surface and complex shape about the openings. The accurate geometric model is ideally a replica of heritage, and plenty of attribute, structural and material information realizes the full documentation of the heritage.

LOD 500: the temporal model indicating the changes of historic elements. Representing of the past, considering the procedures needed to restore the heritage, visualization of the present, to enable dissemination and communication of the city as it is, and simulation of the future, with the model being used to visualize and experiment with architectural object, even those at a design stage.

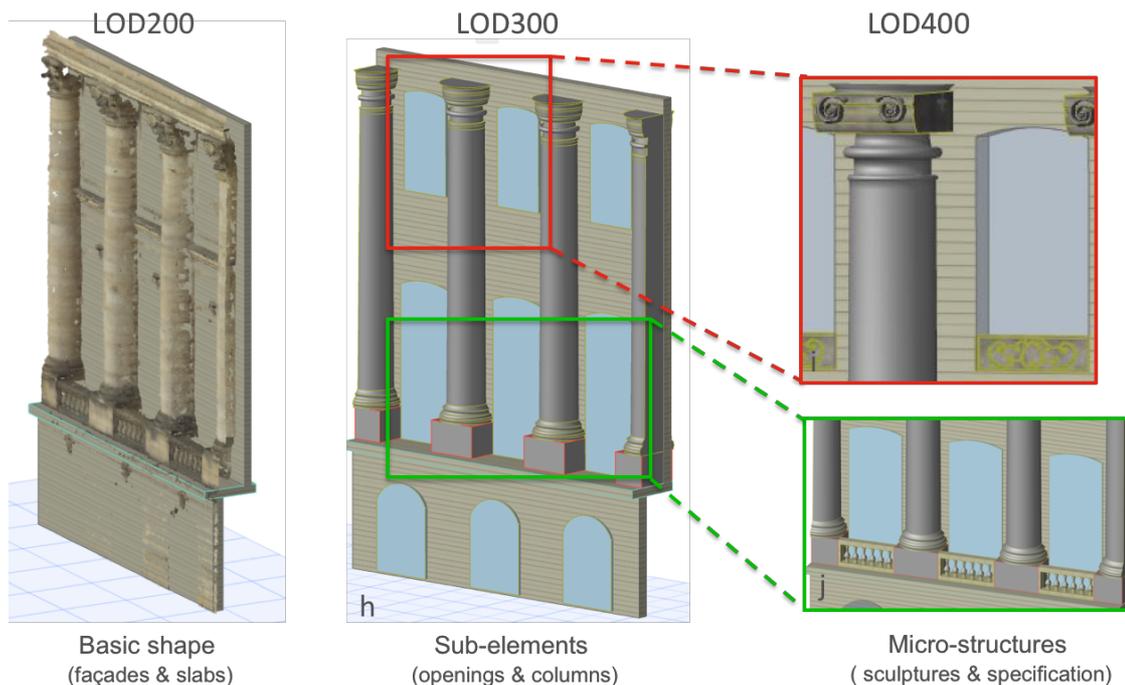


Figure 3.7. The LOD for historic model taking the part of Rohan Palace (Section 3.4.2) as an example. LOD 200 represents the historic building facade with flat planes, which have been segmented and parameterized from point cloud; LOD300 provides the opening, columns and other sub-elements information; LOD400 provides detailed information such as accurate edge, the sculptures in the surface and 3D columns, margins and windows.

3.3. Documentation based HBIM

3.3.1. Workflow

A documentation-based approach recreates the 3D models from the prior knowledge instead of the reality-based data. It is meaningful and feasible to reconstruct ancient landscapes or re-create ruined sites based on the preserved historic documentation and by using document re-interpretation when there are no usable indications in the documentation (Figure 3.8). Traditionally, using historical data to re-create the past has been a hot topic in 3D computer graphics, while the aim is mostly for visualization and to build a 2.5D model. Typical work comes from the “Roma Reborn” project (Dylla *et al.*, 2008), which re-represents the ancient Roma based on historic photos and data records.

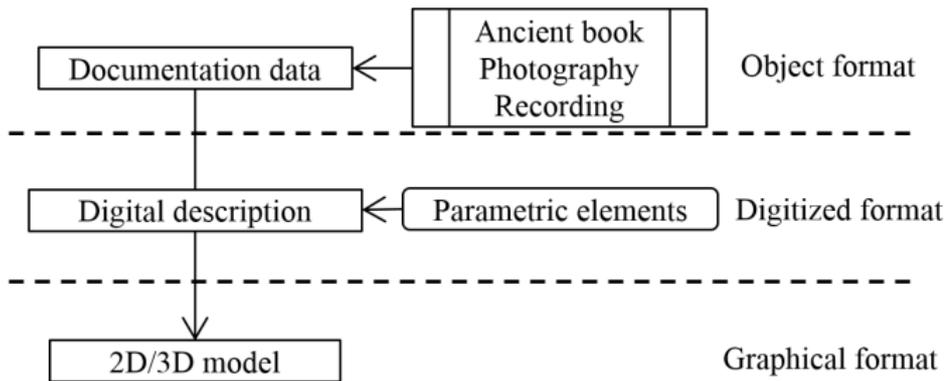


Figure 3.8. The processing of the documentation-based Historic modelling approach

Documentation-based approaches are actually in accordance with the BIM concept, considering that they generate “new” historic buildings from the parametric elements to the whole entity possessing attribute and spatial relationship features. Moreover, the life-cycle characteristic makes BIM software suitable for the temporal and dynamically changing research of historic objects.

In our project, a part of the building of INSA Strasbourg and two lost historic buildings (a Petit château du Meisenbach and a church of the Abbey of Niedermunster) are chosen to explain the documentation-to-HBIM:

- (i) Part of the building of INSA Strasbourg is recreated in BIM platform using the 2D plans and traditional measurement. This case study is dedicated to explain the documentation-based HBIM modelling in detail and the further information query

using the built-in *RevitLookup* and *AddinManage*.

- (ii) The sites of two damaged historic buildings are introduced. Their parametric geometric models have been created using traditional software (*Autodesk Inventor* and *SketchUp*). Moreover, to reduce the human involvement in the conventional HBIM modelling workflow, a *Dynamo*-based geometry-to-HBIM outline is proposed and presented in Section 5.1.

3.3.2. Study areas and materials

Part of INSA Strasbourg building

This project took a portion of INSA Strasbourg building as study area, and created its BIM model according to the site planning drawings (Figure 3.9) and surveying (Figure 3.10). Parameterization of the architectural elements is the essential characteristic of BIM. The parametric object has been provided in BIM built-in system, and can be used to create the real instances according to the defined parameters. It realizes the visualization of 3D geometry and 2D plans (Figure 3.11), parametric modelling of the components, semantic representation of the object's meaning and properties and fixed relationships between the entities (Figure 3.13 and Figure 3.13).

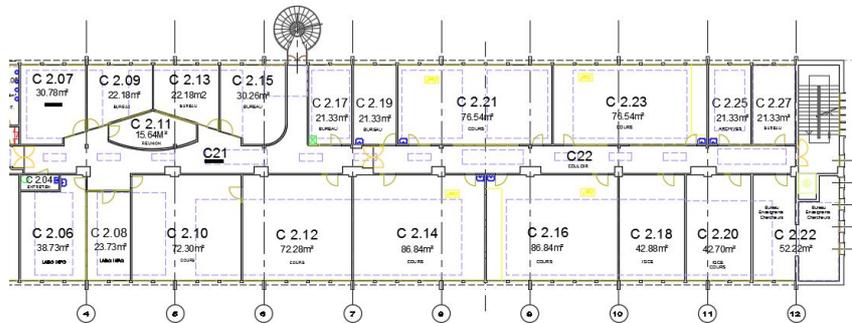


Figure 3.9. 2D planning drawings in *AutoCAD* .dwg format

- Ground plane (cm):**
- ✓ The indoor height is 350 (room) and 418 (aisle) measured by DISTO.
 - ✓ The thickness of the roof is 85 (=418-350+47-30 in room) and 17 (=47-30 in aisle). 47 is the width through the stairs measured by rule. 30 is assumed as the height of the slab arbitrarily.
 - ✓ The size of most columns is 114*50 & 50*78, the height is 350.
- First floor (cm):**
- ✓ The elevation is 435 (=418+17) measured by DISTO and rule.
 - The thickness of the slab is 30.
 - The indoor height is 356 measured by DISTO.
 - ✓ The size of column in the façade is 73*25 (right) and 72*25 (left), the height is 416 (=356+30+30). The column inside is 85*102, 85*147, 85*100, 85*85, 85*103, 85*85, 85*54, 85*85. (Figure 3)
 - ✓ The thickness of the façade is 36 (left), 36 and 30 (right), and 35 (front). The thickness of the vertical wall is 12. The thickness of the walls along the aisle is 8 (left) and 15 (right). (Figure 4)

Figure 3.10. Measurement data using DISTO

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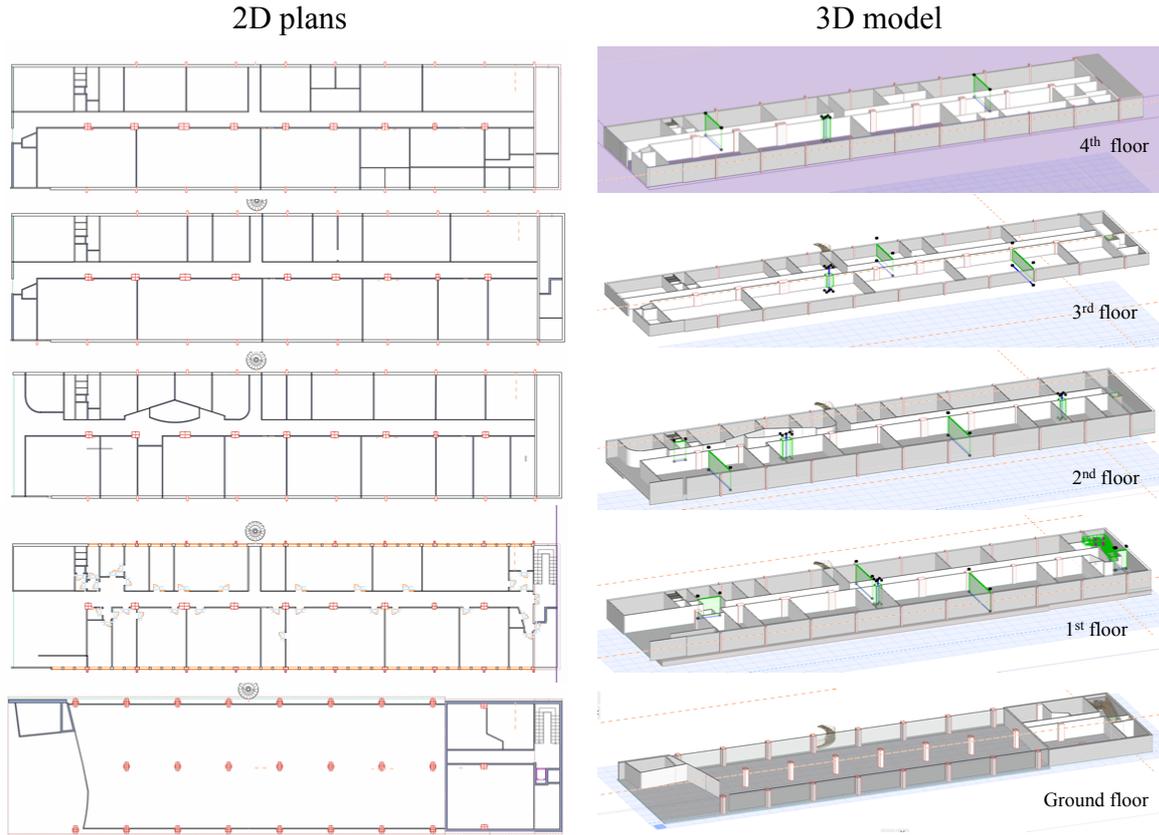


Figure 3.11. The obtained BIM model integrates the 2D plans and 3D model. The black nodes and green primitives in the 3D model (right) indicate the elements are parametric and semantic entities whose shape can be modified and which are classified to certain category.

Wall List							
Wall Type	Volume [m3]	Thickness [cm]	Height [c...]	Area [m2]	Perimeter [m]	Length on Outside Face [m]	Surface Area on Outside Face [...]
Air Space	16.75	25	390	12.99	105.48	51.99	66.81
Air Space	4.57	30	420	3.27	23.55	10.89	15.23
Air Space	25.25	35	420	18.03	105.18	51.54	72.16
Air Space	5.48	36	420	2.62	15.94	7.26	15.23
Air Space	0.37	12	390	0.07	1.42	0.60	2.34
Air Space	0.61	12	386	0.16	2.88	1.32	5.10
Air Space	0.83	12	386	0.21	3.76	1.80	6.95
Air Space	0.95	12	386	0.25	4.36	2.06	7.95
Air Space	1.25	12	386	0.36	6.26	3.05	9.61
Air Space	1.61	12	390	0.41	7.12	3.44	13.42
Air Space	1.67	12	386	0.43	7.43	3.60	13.88
Air Space	5.38	8	386	1.40	35.22	17.44	67.36
Air Space	2.78	8	386	0.72	18.18	9.01	34.77
Air Space	8.70	12	386	2.25	38.34	18.81	72.60
Air Space	2.92	15	390	0.76	10.48	5.09	19.45
Air Space	20.44	12	386	5.32	90.02	44.17	170.52
Air Space	2.93	12	386	0.76	12.91	6.33	24.45
Air Space	2.94	12	386	0.76	12.94	6.35	24.50
Air Space	2.94	12	386	0.76	12.94	6.35	24.52
Air Space	2.96	12	386	0.76	12.85	6.31	24.65
Air Space	2.96	12	386	0.76	12.96	6.31	24.67
Air Space	2.96	12	386	0.76	12.96	6.39	24.67
Air Space	3.11	12	386	0.80	13.65	6.70	25.88
Air Space	3.13	15	386	0.82	11.18	5.44	20.89
Air Space	9.83	15	390	2.52	34.62	16.86	65.54
Air Space	3.70	15	386	0.98	13.60	6.25	24.68
Air Space	3.81	12	386	1.01	17.06	8.41	31.79

Figure 3.12. The parameter and attribute information of some walls

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Door List			
Door Name	Door 20	Door 20	Door with Sidelight ... D
Quantity	9	15	1
Zone Number			
W x H Size	93x203	93x203	160x273
Orientation	L	R	L
Door sill height	0	0	0
Door head height	203	203	273
2D Symbol			
View from Side Opposite to Opening Side			

Figure 3.13. The parameter and attribute information of some doors

The created BIM model can attach the attribute information according to the user's need. But current BIM platform still lacks the effective capability of information query. The built-in *RevitLookup* and *AddinManager* in *Revit* enable the users to look up the built-in parameters (Figure 3.14) and to develop some easy-implementation functions (Figure 3.15). For example, if the users are interested in one type of column and prefer to extract the similar structures in the model. The built-in parameter should be firstly confirmed in the *RevitLookup* (such as the built-in category: *OST_columns*) shown as Figure 3.14. An easy-implementation code and the add-on function is created in the *Revit* (Figure 3.15) and to extract the interested primitives (Figure 3.16).

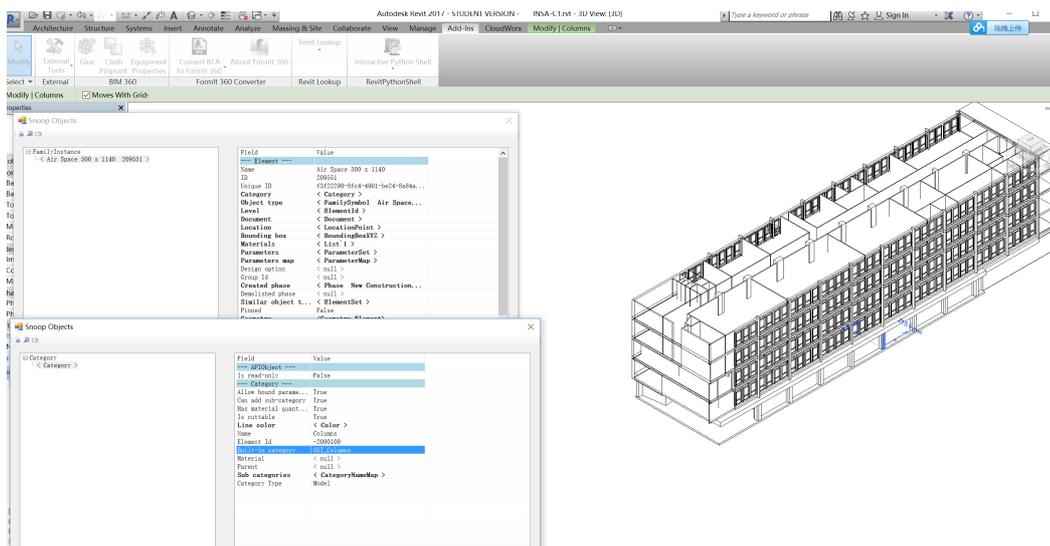


Figure 3.14. To examine the built-in parameters of an element of column

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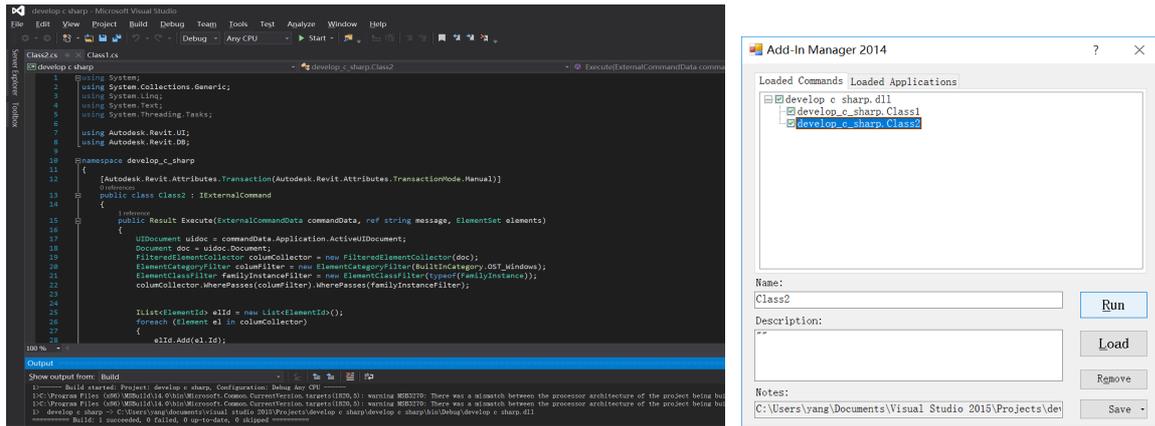


Figure 3.15. The development environment of *Revit* API to generate new functions

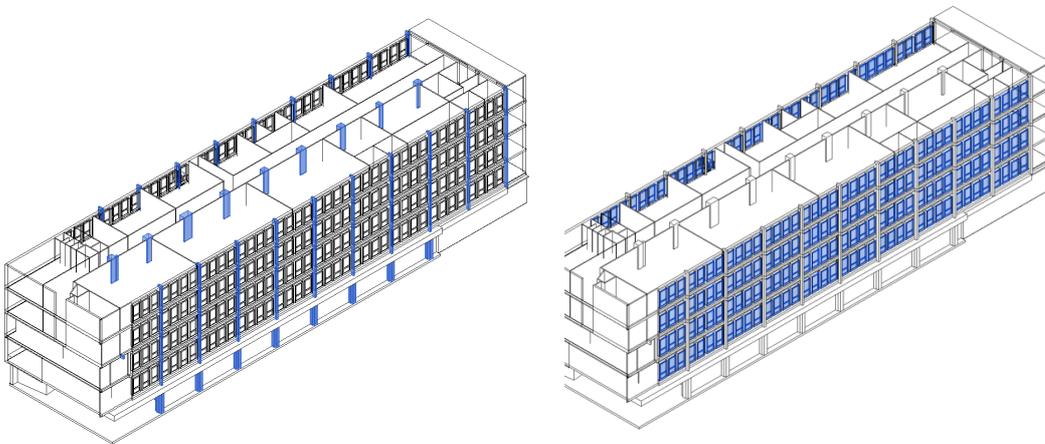


Figure 3.16. The added element extraction function in *Revit* to query the interested instances

Two lost historic buildings

This project utilises BIM technique to recreate two destroyed historic buildings in Alsace, France, an antique monument named Petit château du Meisenbach and a church of the Abbey of Niedermunster. These sites would not remain much more than old stones without works of passionate archaeologists.

A first monument is a ruined old castle constructed of stones dating back to Roman times, and the various excavations which took place allow the discovery of a large number of Roman remains (Diethrich, 2017). On the spot, a paved section indicates its location and no walls exist (Figure 3.17 left). But its composing stones are distributed all around the site (Figure 3.17 Figure 3.18right).



Figure 3.17. The site of the ruins (left) and existing broken structures stored in a Block-Park (right) of Petit château du Meisenbach

The second church (Figure 3.18) is built between 1150 and 1180 AD, the roman style Abbey was devastated during the War of the Peasants (1525) and by two fires, in 1542 and 1572 (Koehl and Grussenmeyer, 2008). Figure 3.18 (left) is an aerial view of the remains of the church, and Figure 3.18 (right) shows the existing parts.



Figure 3.18. The site of the ruins and existing structures of the Abbey of Niedermunster

The geometric model has been obtained according to the documentation in the former works using *Autodesk Inventor* (Diethrich, 2017) and *SketchUp* (Koehl and Grussenmeyer, 2008), respectively. The obtained models are parametrically designed and define the semantic category. BIM platform can directly load these geometric models as a holistic geometry but the semantic category and parametric description are missing. So the challenge comes to the creation of HBIM models on the basis of the existing geometric models, which is described in Section 5.1.

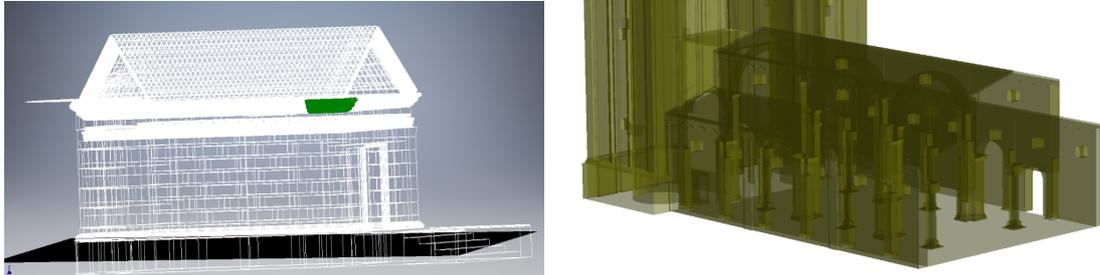


Figure 3.19. *Inventor* model for “Petit château du Meisenbach” (left) and *SketchUp* model for the Abbey of Niedermunster (right).

3.4. HBIM from point cloud

3.4.1. Conventional Scan-to-HBIM by manual drawing

Laser scanning and photogrammetry can rapidly capture the accurate documentation of reality, serving as the data source of as-built BIM. Currently, the geometric model can be accurately created from the point clouds even for the irregular built heritage. Yet the problem is how to convert the geometric model to a semantic model on which additional attribute and relationship information can be attached. As-built BIM software provides such platform to manually create this kind of parametric model with the reference of point cloud. And the friendly support for 3D point clouds has currently made *Revit* the main reality-based parametric modelling environment.

As-built BIM is increasingly used to restore, model and manage existing valuable constructions and historic structures by reality-based remote-sensing recording data acquisition and reverse engineering techniques (Barazzetti *et al.*, 2015). As a 3D information modelling environment, BIM software is increasingly supportive of 3D point clouds representing the entity surface, which is called as a scan-to-BIM process. By importing the point clouds into the BIM software, the solid building components can be created using the existing BIM IFC classes and self-defined structures. Compared with the surface-based geometry model, the obtained BIM parametric model is enhanced with measurements, attributes and strict relationship information.

In our project, three study areas are adopted to build the HBIM models from the point cloud:

- (i) Part of the façade of Rohan Palace is utilized to explain the common scan-to-HBIM process by manual-drawing.
- (ii) Main part of the St-Pierre-le-Jeune church serves as an example for detailed description of the proposed mesh-to-HBIM workflow and the comparison with conventional scan-to-HBIM (Section 5.2).
- (iii) HBIM models of the beam frame structure of “Castle of Haut-Kœnigsbourg” are created to explain the possibility of *Revit* API development and elaborate the improvement of BIM platform compared to traditional geometric modelling (Section 4).

3.4.2. Study areas, materials and HBIM models

Façade of Rohan Palace

The first case is a part of the Rohan Palace façade, Alsace, France (Figure 3.20). The Rohan Palace is a historical landmark of the city of Strasbourg dating to the 18th century. In the former project, the central façade overlooking the River Ill was photographed. The dimension of this façade is approximately 14 x 20 meters (Murtiyoso *et al.*, 2017b). And the Sensefly Albris was used to acquire the images. Using its capability to fix object-to-camera distances, the UAV was flown at a fixed approximate distance of 5 meters from the façade. Overall, 555 images were taken for this dataset using the Albris (Murtiyoso *et al.*, 2017b). Further, taking the point clouds as reference, as-built BIM can manually create the parametric sub-elements with relationship constraints (Figure 3.22-Figure 3.23). That is, BIM technique can help to improve the geometric model to semantic model.



Figure 3.20. Façade of Rohan Palace and the study area (in the central part)

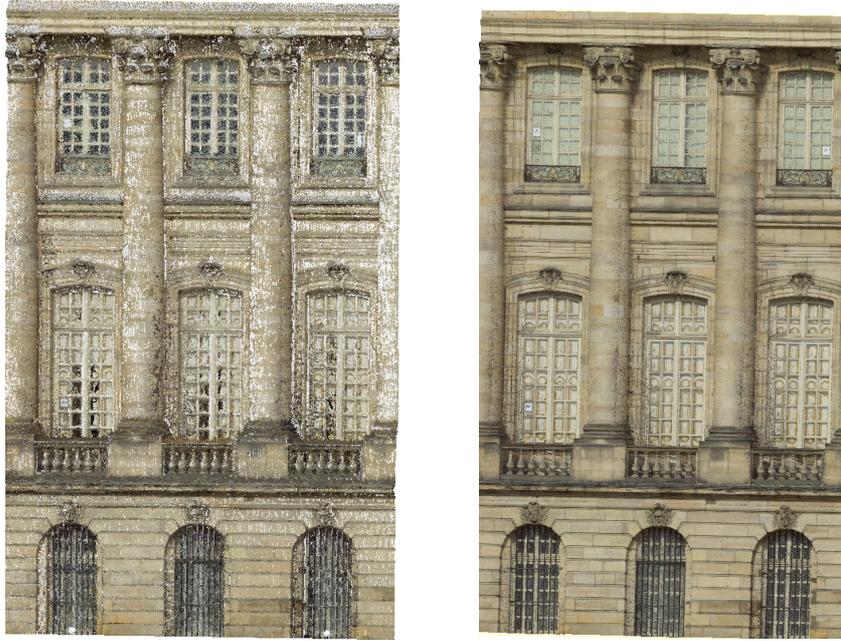


Figure 3.21. The cleaned point clouds (left) and the generated holistic mesh (right)

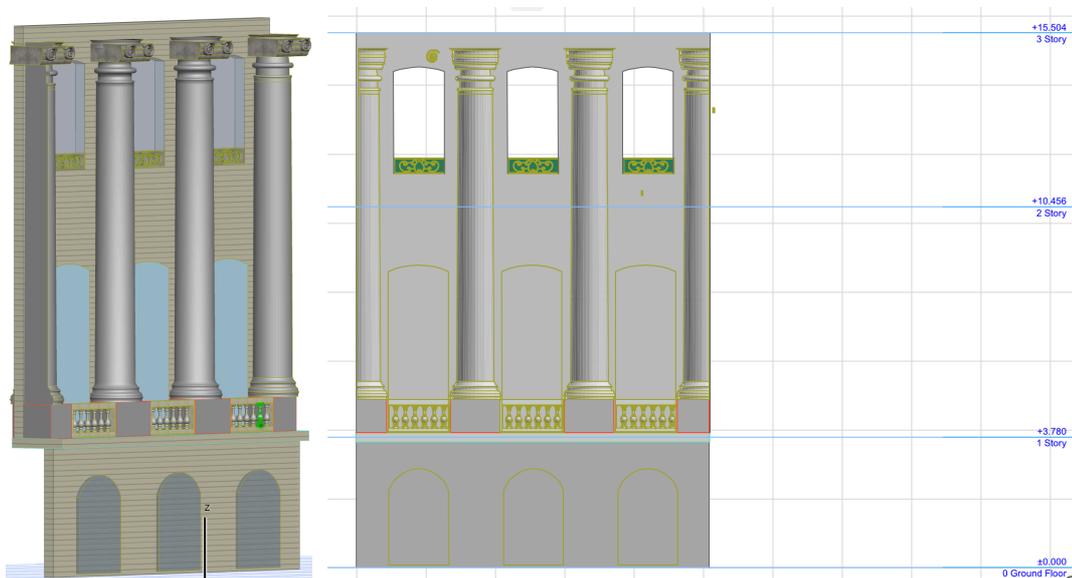


Figure 3.22. The point clouds are manually transferred to parametric model

Type	Column	Morph	Morph	MC
ID	CRE - 003	MORPH-003	MORPH-006	MC
Building Material / Profile	GENERIC - STRUCTURAL	---	---	---
Height	0.960	---	---	---
Core Dimension 1	0.874	---	---	---
Core Dimension 2	1.242	---	---	---
Column Slant Angle	90	---	---	---
Surface Area	---	0.60	39.57	---
Area (by Story)	---	0.00	0.83	---
Volume	---	0.00	9.12	---
Length of				

Figure 3.23. The parametric information about the structures

Case study of St-Pierre-le-Jeune church

The study area is the main façade of the St-Pierre-le-Jeune church, France, built in Strasbourg during the German era between 1889 and 1893. (Fig. 5). In previous project (Murtiyoso *et al.*, 2017b), the Sensefly Albris was used to take high resolution images of the principal façade, and the DJI Phantom 3 was used to complete the rest of the building. In total 2,755 images were taken for this dataset. And the accurate geometric model of the church has been created in the former work, which exists in surface mesh format (Murtiyoso *et al.*, 2017a).

The high accurate geometric model has been obtained using the photogrammetry and point cloud processing approaches. The obtained geometric model is a holistic model without semantic segmentation, parametric description and attached information. In the project, the conventional scan-to-HBIM is described by manual drawing and a newly mesh-to-HBIM workflow is also proposed with reduced human involvement in Section 5.2.

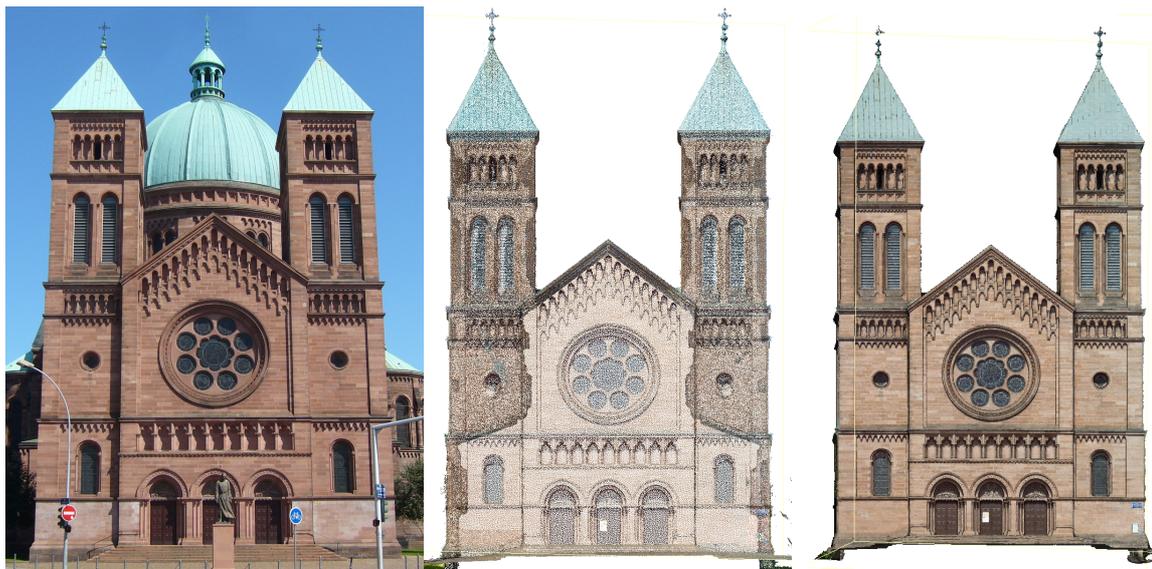


Figure 3.24. The main façade, cleaned point clouds and mesh geometry of the St-Pierre-le-Jeune church and, Strasbourg, France built from typical Alsatian red sandstone.

Case study of beam frame

The case study is a historical building roof with wooden beam framed structure, the so-called “Castle of Haut-Kœnigsbourg”, Alsace, France (Figure 3.26). It is a medieval castle and has been restored (from 1900-1908) following a close study of the remaining walls, archives and other fortified castles built at the same period. It reflects the romantic nationalist ideas of the past and has been officially designated as a national historic site by the French Ministry of Culture.

The timber roof is supported by a beam frame and truss structure (Figure 3.26). The beams are normally leaning and oblique distributed in the 3D space. The beams are of very regular shape and not broken, which makes a total station based approach feasible.

The laser scanning directly captures the 3D geometric information of the object, which provides a highly detailed and accurate representation of the shapes. Laser scanning is one of the intense developments in geomatics, and has been established as a standard tool for built heritage reconstruction. The pipeline of accurate geometric modelling derived from laser scanning generally consists of data acquisition, point cloud registration, segmentation, mesh generation and texture mapping. In this project, point clouds are the data source for further parametric modelling in BIM platform. So just point cloud registration and segmentation is needed for the acquired data. The obtained point clouds are shown in Figure 3.25.

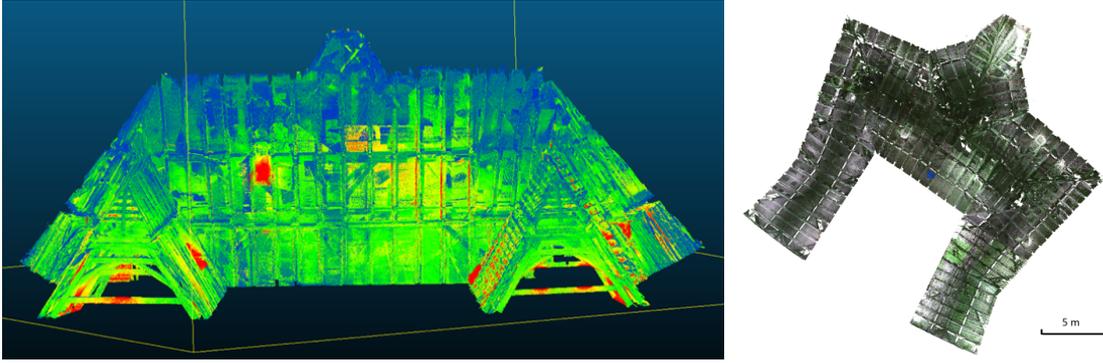


Figure 3.25. Terrestrial laser scanning data (left) serves as spatial reference in *Revit* (right).

In this project, conventional manual measurement surveying data were utilized. The beams were identified through a total station recording (Leica TS02), taking measurements on the edges of them. The project was georeferenced using GNSS reference points around the site in order to define a consolidated geodetic network (Figure 3.27). For this manual survey, we needed 18 surveying stations. The field operation lasted six days. Totally, 1,710 XYZ points (Figure 3.28) were collected in order to obtain the 3D model. At least six points were acquired on each beam, located in the three or four parallel edges of this beam.



Figure 3.26. Castle of Haut-Kœnigsbourg (top left) and details of its truss structure (top right and bottom).

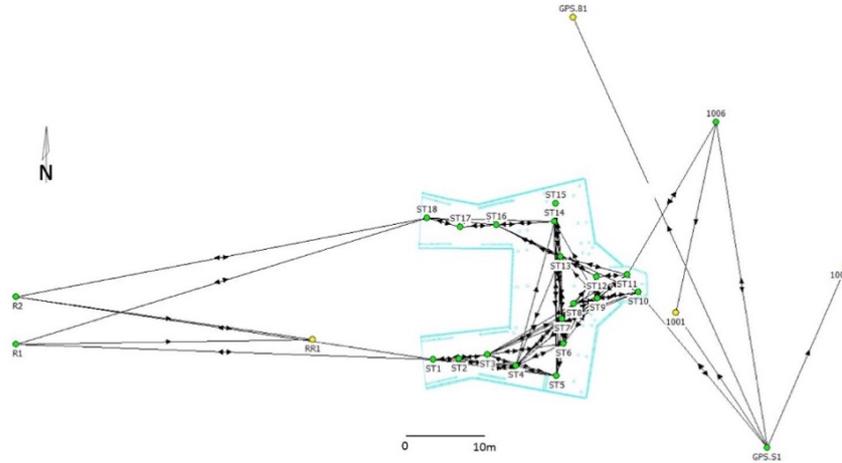


Figure 3.27 Geodetic network of the total station recording

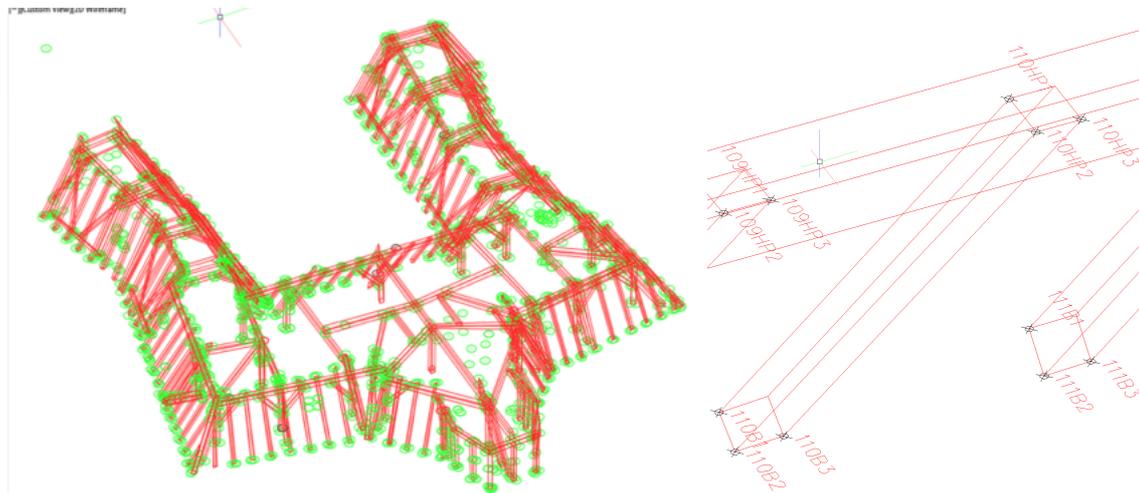


Figure 3.28. The total station data recording of the beams (*AutoCAD*). Each beam collects at least six total station points (the green circles and blank “X” marks).

For the detail, the position recorded whether the collected point was the corner of the beam. In horizontal beams, the points are labelled with "n" (north), "s" (south), "e" (east) or "o" (ouest, means “west” in French) to display its position in the cardinal oriented beam edge. For vertical beams, the points are labelled with "h" (haut means top) or "b" (bottom). The oblique beams are labelled with the combination of "h" or "b" and "n", "s", "e", "o". Some typical points are also marked with additional “p” to identify it as points to be prolonged on the edge (Figure 3.29). Anyway, when collecting the total station points, it is difficult for the operator to identify correctly the end of the beams, which can be a source of error, therefore a strict codification has been used during the recording. The collected data such as point IDs and *XYZ* coordinates were saved in ASCII text formats. The ID indicates the

Chapter 3: Conventional HBIM and study areas

selected beam, the point position and edge number.

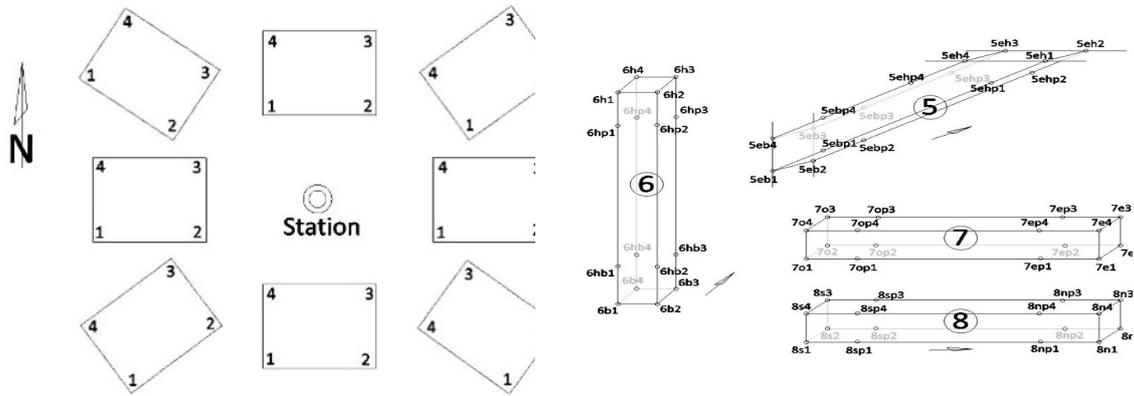


Figure 3.29. Point numbering and codification used by total station survey.

Station	ST2	HI = 1.42100 , VO = 60.56904			
Reference	ST1	HP = 0.20000 , AH = 238.14300 , AV = 125.87150 , DI = 3.07	Point	97BP3	X = 2022563.28227 , Y = 8125781.70909 , Z = 72:
Reference	ST3	HP = 0.20000 , AH = 29.61425 , AV = 124.45525 , DI = 3.32	Point	97HP3	X = 2022563.32509 , Y = 8125781.29952 , Z = 72:
Reference	ST4	HP = 0.20000 , AH = 46.94000 , AV = 112.58400 , DI = 6.31	Point	98BP1	X = 2022565.60649 , Y = 8125782.35013 , Z = 72:
Reference	ST5	HP = 0.20000 , AH = 50.38400 , AV = 107.30650 , DI = 10.83	Point	98BP2	X = 2022565.73330 , Y = 8125782.40914 , Z = 71:
Reference	ST6	HP = 0.20000 , AH = 30.04675 , AV = 106.86900 , DI = 11.51	Point	98BP3	X = 2022565.70230 , Y = 8125782.63147 , Z = 71:
Mesure	97BP3	HP = 0.00000 , AH = 272.50600 , AV = 103.47350 , DI = 3.51	Point	98HP1	X = 2022565.80797 , Y = 8125780.67812 , Z = 72:
Mesure	97HP3	HP = 0.00000 , AH = 266.01850 , AV = 89.90850 , DI = 3.32	Point	98HP2	X = 2022565.94008 , Y = 8125780.71565 , Z = 72:
Mesure	98BP1	HP = 0.00000 , AH = 320.70350 , AV = 128.59950 , DI = 2.76	Point	98HP3	X = 2022565.87013 , Y = 8125781.29049 , Z = 72:
Mesure	98BP2	HP = 0.00000 , AH = 324.21200 , AV = 128.74500 , DI = 2.81			
Mesure	98BP3	HP = 0.00000 , AH = 324.73600 , AV = 128.93600 , DI = 3.04			
Mesure	98HP1	HP = 0.00000 , AH = 299.21150 , AV = 28.47950 , DI = 2.03			
Mesure	98HP2	HP = 0.00000 , AH = 308.96700 , AV = 27.78500 , DI = 1.99			
Mesure	98HP3	HP = 0.00000 , AH = 318.20700 , AV = 56.65750 , DI = 1.80			

Figure 3.30. Collected data and point codification (ID).

Summary

According to the data source representing the historic object, the current methods can be divided into documentation-based approaches and reality-based approaches. The geometric model can be accurately created from either reality-based approaches or documentation-based computer graphic methods. Yet the problem is how to convert the geometric model to a semantic model on which additional attribute information can be attached. BIM platform provides a solution which can directly deal with the historic materials and point clouds (Figure 3.31).

BIM platform is originally developed for new buildings, it is therefore also appropriate to recreate lost heritage according to rules and parameters. Generally, BIM software (including *Revit*) is not a 3D-centric and freeform geometry modeller. They mostly create the 3D model based on the rotation and extrusion of prior defined position in 2D plane. Thus the manual drawing of scan-to-HBIM is time-consuming and difficult to ensure geometric accuracy to some degrees.

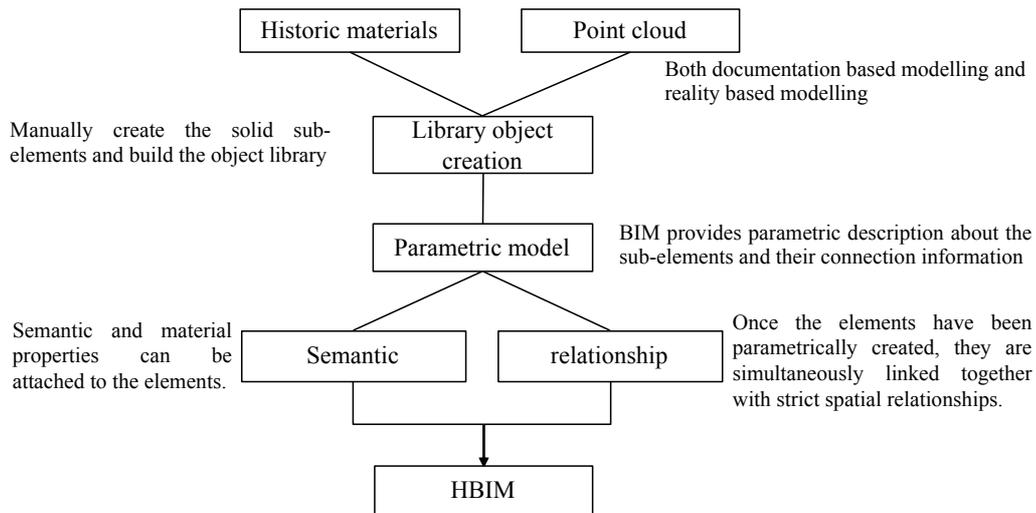


Figure 3.31. Workflow of BIM to Heritage modelling

4 | Comparing geometric model and HBIM model

This chapter considers the modelling of as-built timber beam frame structure from surveying points data (Section 4.1). Traditional geometric models are created by automated Python programming and manual drawing in *AutoCAD*, respectively (Section 4.2). A HBIM model is created by our developed *Revit* plugin instead of the conventional manual drawing (Section 4.3).

The main objectives of this chapter include two aspects:

- (i) the first is to explore the advantage of HBIM modelling compared to conventional geometric model. Reality-based data has been widely accepted to realize the heritage geometric modelling, and current challenge comes to the element segmentation and information management aiming at the heritage conservation. Recently developed as-built BIM software, an integrated platform for modelling, visualization, spatial database, and management, can directly build the HBIM model from the reality-based data. The created HBIM model is a parametric model with semantic and relationship information.
- (ii) the second is to develop a *Revit* API plugin to replace the human drawing works in the conventional HBIM modelling procedure. The parametric model from the reality-based data in HBIM environment is manually created in a time-consuming way. A *Revit* API plugin is dedicated to automating the semantic segmentation and parametric modelling process.

4.1. Geometric model and HBIM model

Currently, it is no longer a problem to obtain an accurate 3D geometric model, either by terrestrial laser scanner or dense matching imagery approaches, which focuses on the outline structures and measurement information for the real object. However, it is still highly anticipated to realize semantic segmentation of sub-elements and build their connection information (Díaz-Vilariño *et al.*, 2015).

BIM technique provides the uniform platform for geometric and parametric modelling, connection information management and structural analysis of the beam framed roof structure (Park, 2011; Oreni *et al.*, 2013; Chi *et al.*, 2015). The new model offers us uniform platform for the whole information representing the heritage and further structural and material analysis (Barazzetti *et al.* 2015; Murphy *et al.* 2013; Saygi and Remondino, 2013). Bassier *et al.* (2016) have noted the important role of BIM from scan data to structural analysis model for heritage timber roof structures. They utilized BIM technique to connect the geometry model (*SolidWorks ScanTO3D*) and structural analysis (*ANSYS*) (Figure 1). But BIM platform is just utilized to store the parametric information about the beams and build their relationship, while the geometric modelling need to be conducted in other environments. And the semantic modelling process in the BIM platform is conducted by totally manual drawing.

When it comes to timber beam frame structure, a detailed model of the beam frame should provide the material information and spatial relationships as joints, which is important for further analysis and heritage conservation. Beam frame system, which is widely existing in the timber roof structure of the historic buildings, is adopted as case study in this chapter to explicitly realize the above objectives. Timber roof structure is the typical architectural style in the historic buildings, and it is generally supported by beam frame system. The connected and joint beams are organized as a structural system to sustain the load bearing of the roofs. However, for the wooden beam frame supporting the building roofs, the bearing mechanisms still have not received the due attention and consideration they certainly deserve. Semplici and Tampone (2006) explored the historic timber architectures and load bearing structures in the UNESCO World Heritage List. They reported that timber beam structures were not the object of conservation and appropriate repair in many countries and were suffering from neglect and alteration.

In this project, the case study is a historical building roof with wooden beam framed structure, the so-called “Castle of Haut-Kœnigsbourg”, Alsace, France (Section 3.4.2: Case

study of beam frame). The timber roof is supported by a beam frame and truss structure. The beams are of very regular shape and not broken, which makes a total station based approach feasible. The data source in this chapter is the sparse surveying points.

4.2. Wireframe geometric model

Compared to datasets based on point clouds acquired by terrestrial laser scanning, the number of points recorded by total station is very low but each point is significant. Total stations deliver highly accurate single-points, often used as 3D surface reconstruction reference points or control points for other techniques. Although limited number of measured points do not allow a detailed study of the structure, it is still easy to rebuild wireframe rectangular beams.

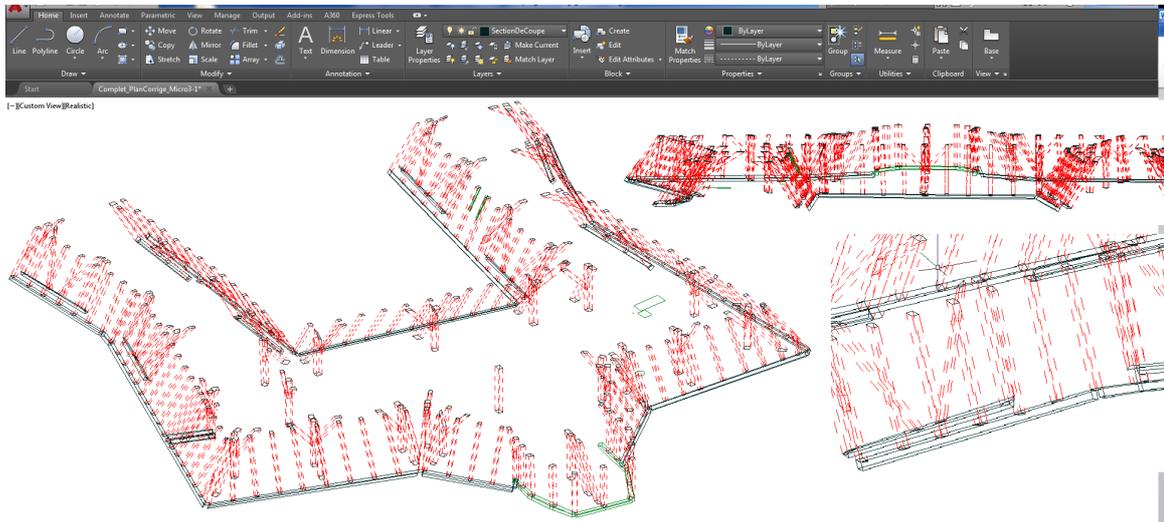


Figure 4.1. Wireframe model in *AutoCAD*

Despite of the increasing support of reality-based as-built data, BIM platform cannot directly support the ASCII format file with total station points. Thus, *AutoCAD* is employed to build the parametric model by manually connecting the beam edges. This modelling was very time consuming. About 400 beams were reconstructed (Figure 4.1). The obtained beam system is a linear wire-frame model. The wireframe model cannot define relationship and variable parameters describing the beam elements. The obtained wireframe model is supported for further BIM application and structural analysis in BIM platform and computational software.

4.3. HBIM modelling of beam frame

4.3.1. Conventional Scan-to-HBIM

Revit Structure, as one of its typical workspace, is also a specialized software with the necessary theoretical model to analyse the global structure of the frame. The point clouds can be directly loaded in *Revit Structure* environment and three reference levels are created to confirm the location (Figure 4.2). The final parametric model is created based on the BIM beam “family” on the reference of point clouds (Figure 4.3). Compared to the wire-frame model (Figure 4.1), the BIM solid model provides not only definite relationship and variable parameters describing the beam elements (Figure 4.4), but also more reality results in terms of geometry and structure behavior (Bassier, 2016).

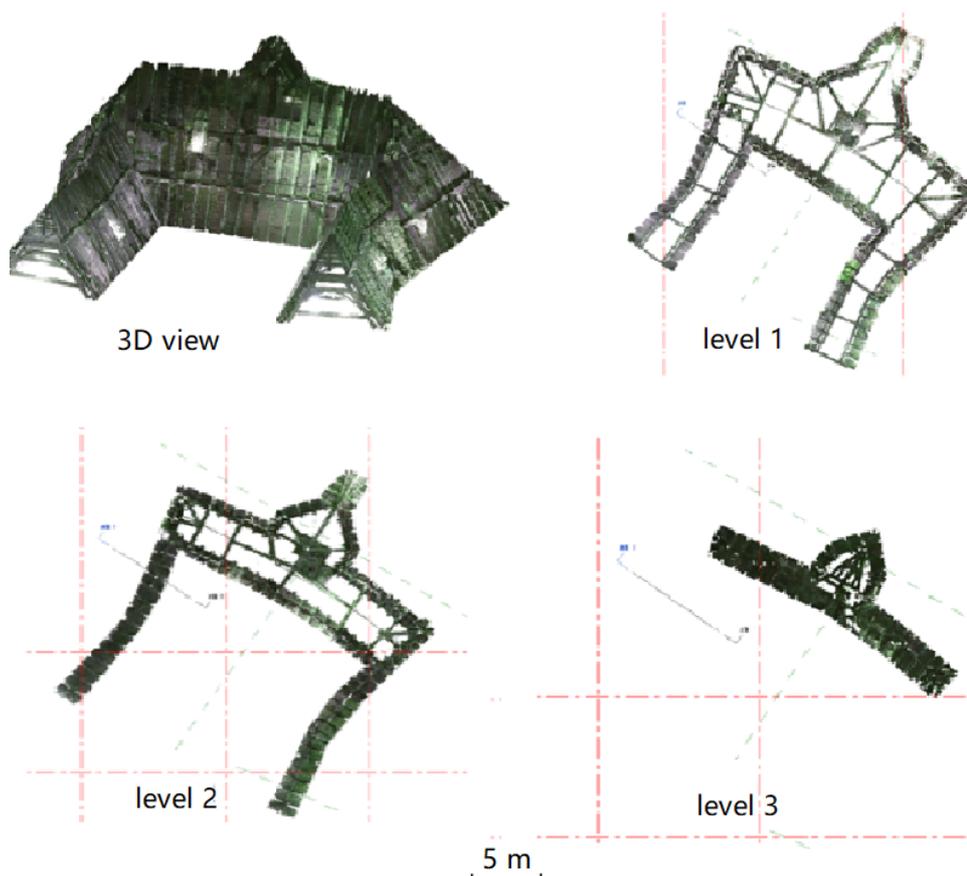


Figure 4.2. Different reference levels to model the beams.

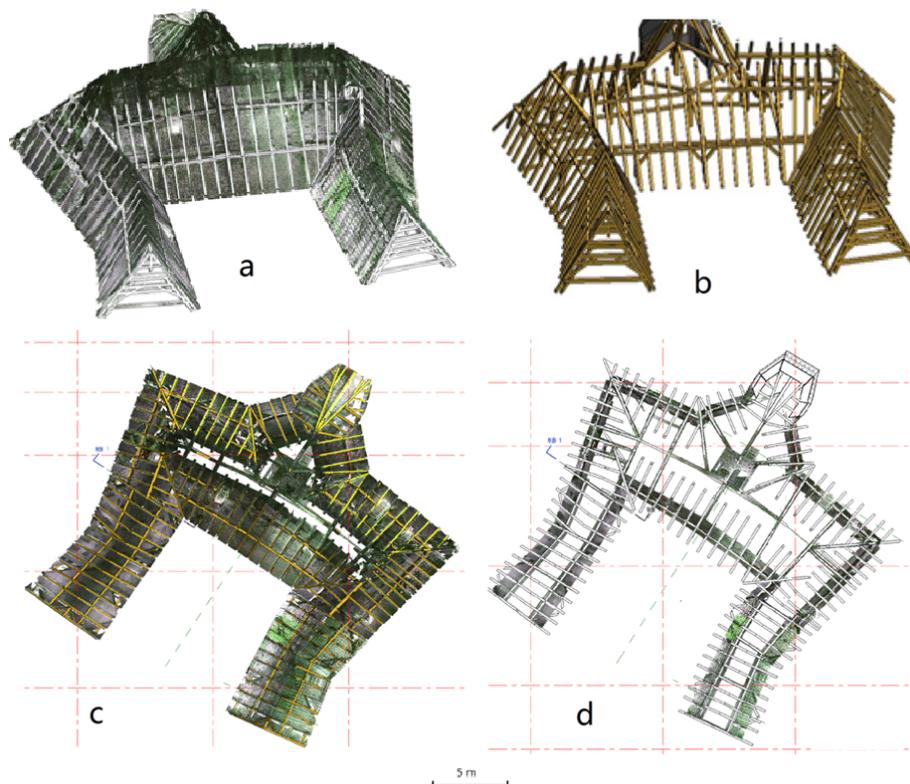


Figure 4.3. Parametric beam frame model from point cloud. (a) 3D viewer with reference point clouds (b) 3D frame (c) 2D viewer with reference point clouds (d) 2D frame.

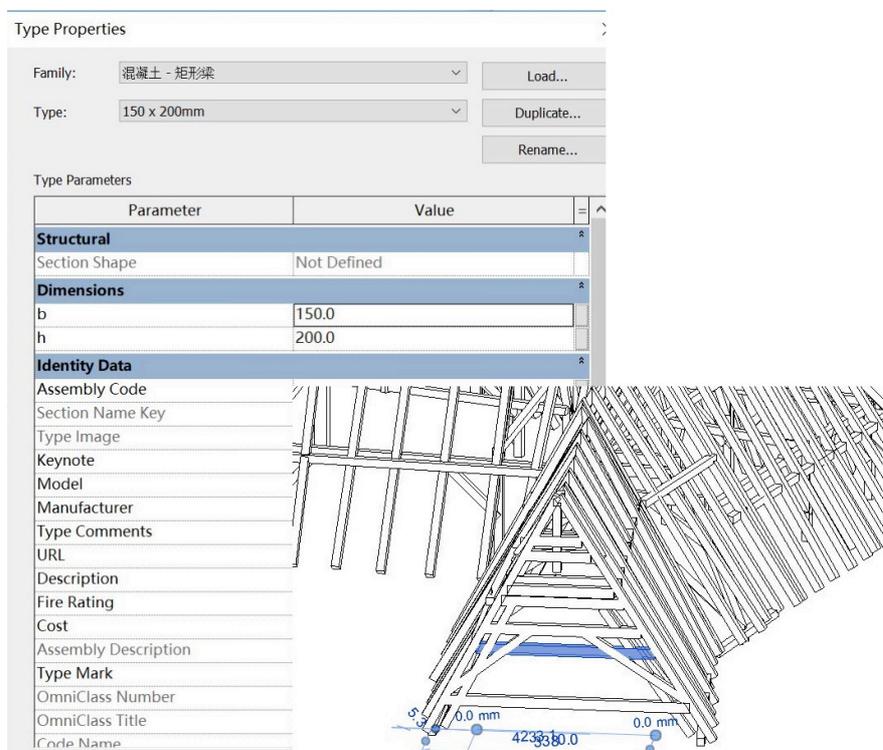


Figure 4.4. The parametric geometry and the type properties defined by users.

Chapter 4: Comparing geometric model and HBIM model

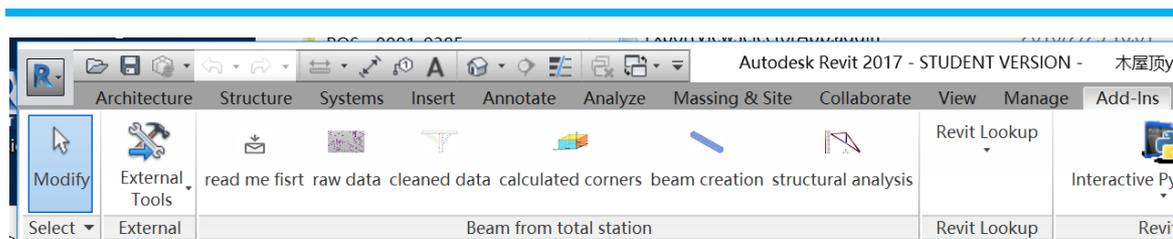


Figure 4.6. The loaded interface of the developed plugin in the *Revit*

4.3.3. Parametric beam generation from the points

The current version realizes the total station related functions (Figure 4.6): displaying total station data, cleaning point data, parameter and corner calculation, and parametric beam generation. If a timber roof structure is studied, the plugin allows the geometry reconstruction of the beam frame from ASCII text files, and outputs the IFC format data.

Although the field work based on the total station points was time consuming, the beam construction process could be finished fast with a limited number of accurate points. It is expected to transfer the disordered points to parameters describing the cuboid beams. A cuboid beam can be described by a central point, three directions and extensions (Figure 4.7 (d)), which is the basis to create the beam element in BIM platform. As the points are not always the corners, two parameters of the beam are not totally confirmed: one is the circle point and another is the height.

Specifically, the plugin mainly involves the following functions:

Displaying total station data. This plugin is able to conveniently parse ASCII text files containing *XYZ* coordinates derived from real beam frame total station data capture, translating them into native reference points *Revit*'s mass modelling environment. Despite of the increasing supporting of reality-based as-built data, *Revit* cannot directly support the ASCII format file with total station points.

Cleaning point data. Some total station data are redundant and mistaken, which need to be eliminated before the beam parameter calculating. Inputting total station points is shown in Figure 4.7 (a), which are disordered and difficult to transfer to *Revit* beam structure directly.

Parameter and corner calculation. The parameters and corners are calculated by the proposed workflow in Figure 4.7. It can automatically transfer the disordered points to the corners of beam structures (Figure 4.7 (b)). The algorithm is also a built-in function in the developed plugin, whose construction procedures are displayed as follows:

- (i) Firstly, we can obtain the direction of height (h), considering that collected total station

points are located in a set of parallel edges.

- (ii) Then mapping the points to the vertical plane along with the height direction, we can obtain three (if the points are located in the three out of four edges) or four corners (if the points are situated in the whole four edges). In the former case, we can calculate the fourth point under the rectangular assumption of the beam shape. The other two directions (l & w) are thus confirmed. The three obtained directions are further refined because they may be not vertical to each other owing to the error of total station points.
- (iii) Finally, the extension can be calculated by vector computing. And the circle point is confirmed by the minimum bounding box of the total station points.

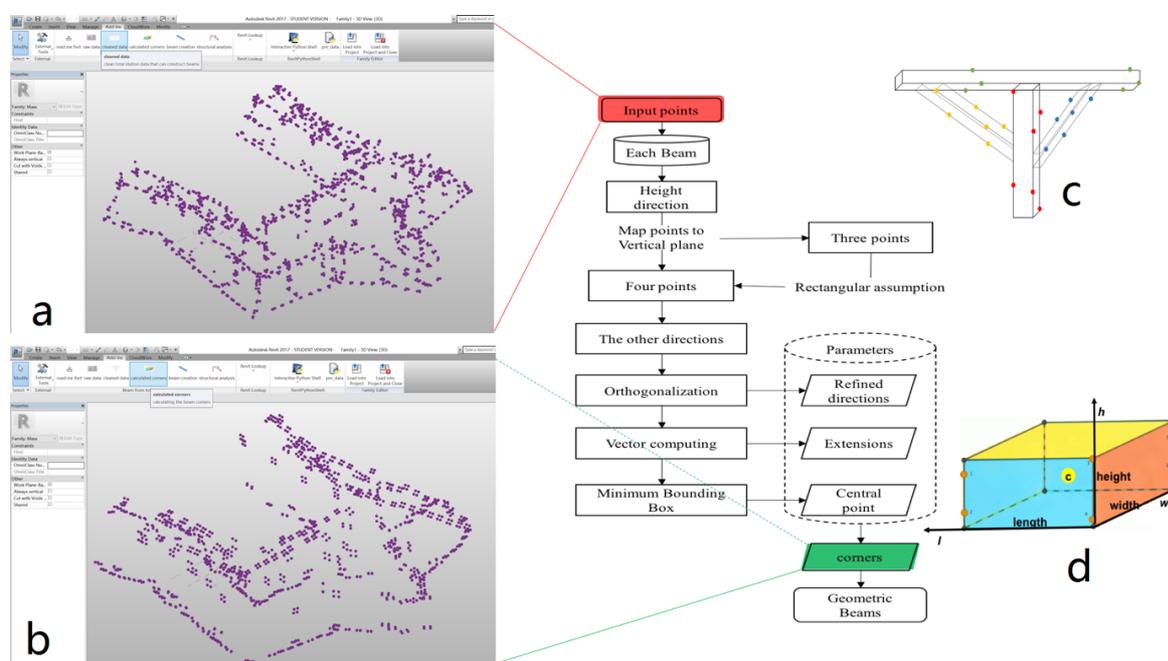


Figure 4.7. Beam reconstruction workflow (a) Initial total station points displayed in *Revit* after data cleaning; (b) Beam corners calculated by the algorithm in workflow; (c) Simplified description of the distribution of the initial points; (d) Rectangular beam description by central point, extensions, and directions.

Parametric beam generation. A *Revit* “*Beam family*” is created firstly, which is in the regular rectangular shape and basic wooden materials. Then the family instances can be created in the central position (based on the calculated parameters) along the direction confirmed by the corners. The beam elements (Figure 4.8) are in standard BIM parametric type, which can be modified and exchanged either by the API or users.

After constructing the blocks, the relationship and additional information can be added and

Chapter 4: Comparing geometric model and HBIM model

managed, which is the advantage of BIM technique. The results show the potential of automating the parametric modelling by interactive API development in BIM environment. It also integrates the separate data processing and different platforms into the uniform BIM platform. BIM environment provides the attributional material and construction information management and structural analysis based on the obtained model.

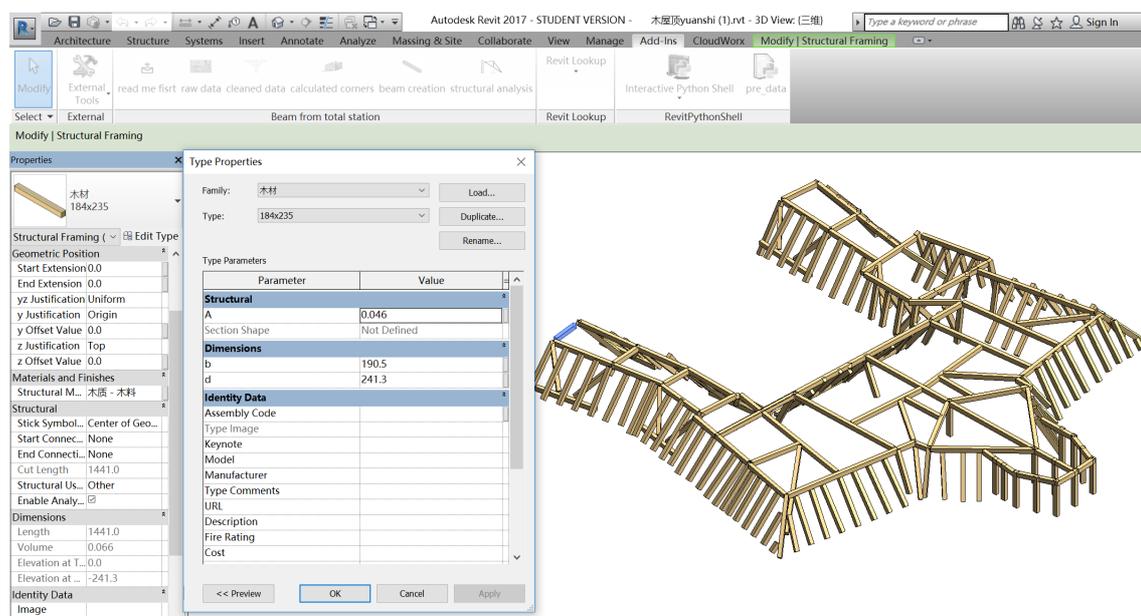


Figure 4.8. Display of the Parametric Beam frame system in *Revit*.

The parametric model from total station is the pseudo solid model from wireframe model. Although the total station points provide the highest single point positioning accuracy, it is difficult to accurately describe the surface and geometry of the beam element. And it can hardly monitor the dynamic change of the beam frame, considering the huge time cost. The scan-to-BIM plugin for timber beam frame parametric modelling from point clouds is expected and currently in preparation. Some point cloud segmentation algorithms have been proposed for regular steel beam frame (Laefer *et al.*, 2017) and columns (Díaz-Vilariño *et al.*, 2015). Our developing plugin is expected to realize the semantic segmentation and parametric modelling from the point clouds in BIM environment for sloped timber beam frame by combining the typical Point Cloud Library (PCL).

Summary

This chapter presented the potential of a parametric modelling tool in as-built BIM environment for a rectangular roof structure whose elements are leaning and crossing beam frame. The material feature (wooden in the study) can be modified and analyzed in the HBIM platform. The developed plugin tool does not only automate the semantic and parametric modelling, but also integrate together the geometry modelling and parametric elements management. The final frame consists of parametric beam elements, which can be applied to structural analysis.

The traditional approaches (Section 4.2) obtain the geometric models without semantic and relationship information, and they are difficult to further add and manage the attribute and material information. For example, beam elements are traditionally constructed firstly, and their joint and interconnected relationship need to be judged and analyzed further. In contrast, the relationship and parametric description is the core for BIM technique. BIM technique obtain the semantic model simultaneously during the geometric modelling process, and the relationship and additional information can be attached and analyzed.

The BIM based parametric modelling of a timber roof structure can provide: (i) an accurate complete survey on the geometry aspect; (ii) material and relationship information of the sub-elements; and (iii) possible deformations and changes over time. Generally, it can provide the conservation professionals decision support with spatial, temporal and multi-criteria analysis.

Moreover, the current HBIM parametric modelling process is generally manual, as the obtained models for the timber beam frame in Section 3.4.2. BIM 3D modelling tools focus primarily on delivering 2D documents with the added 3D capability. When creating complicated geometry and handle large amounts of data in 3D space directly, the user's freeform design is limited. This dramatically reduces project productivity and accuracy of arbitrary tip-tilted distribution of beam frame. The *API* development really maintain the need of beam construction in two ways: the first one is obviously the automation, and the other is the possible improvement of accuracy. The *API* directly calculate the parameters of parametric beam and then manipulate the BIM beam element with obtained parameters, which can return more accurate spatial location than manual drawing. Moreover, the regular geometric shape of the beam element makes the automatic segmentation feasible.

5 | Geometric model to HBIM

This chapter presents the transformation of geometric models to HBIM models with reduced human involvement instead of the conventional manual drawing. Accordingly, a solid-to-HBIM for damaged built heritage (Section 5.1) and a mesh-to-HBIM for as-built heritage (Section 5.2) are proposed by utilizing *Revit Dynamo* visual programming. The proposed mesh-to-HBIM outline is also compared with the current scan-to-HBIM workflow.

There have been lots of works to recreate the built heritage in computer graphics software (such as *SketchUp*, *Rhino 3D*, and *Inventor*). These geometric models can be loaded in the BIM software, but their semantic information is lost and they exist as a non-editable holistic geometry without parameters. To utilize the BIM functions, the geometric models need to be re-built to HBIM models by manual drawing of the composing elements in the BIM environment.

Moreover, BIM software is increasingly supportive of 3D point clouds representing the entity surface, which is called as a scan-to-BIM process. By importing the point clouds into the BIM software, the solid building components can be created using the existing BIM IFC classes and self-defined structures (as the HBIM models of the façade of Rohan Palace, St-Pierre-le-Jeune Church, and the beam frame of Castle of Haut-Kœnigsbourg in Section 3.4.2). Unfortunately, such scan-to-BIM process remains mostly a manual process, and a key challenge today is thus to automate the process leading to as-built BIM from point clouds (Macher *et al.*, 2017).

In the project, *Dynamo* is used to develop a semi-automated function to build the HBIM models with reduced human involvement. The *Dynamo*-based HBIM modelling transfers the parametric family for the lost built heritage (the Petit château du Meisenbach and the Abbey of Niedermunster in Section 5.1) and geometric structures for the existing heritage (St-Pierre-le-Jeune Church in Section 5.2) to HBIM model via *Revit Dynamo* visual programming.

5.1. Geometric model to HBIM for lost heritage

Built heritage suffers from human caused damage and natural disaster. When a particular building no longer exists, the point clouds may be unavailable. The accessible data source is limited to the archived materials (such as historical documents, bibliographic references, photographs, drawings, etc.) and remaining damaged sites (ruins and partly existing structures). The current virtual reconstruction to unveil the existence of the ruined and damaged historic buildings is mostly conducted by shape-grammar of computer graphics technique (Quattrini and Baleani, 2015; Dylla *et al.*, 2008).

Recent works using BIM technique on demolished historic buildings focused on the comparison of semantic HBIM model with traditional CAD modelling (Boeykens *et al.*, 2012; Apollonio *et al.*, 2013; Ludwig *et al.*, 2013). Such processing is conducted entirely by manual processing, which is accordant with the original BIM bottom-up process: parametric modelling of the specific parts for the studied heritage, and then integrating the elements into the BIM model (Casu and Pisu, 2016). Anyway, it is expected to generate BIM models using an automatic/semi-automatic method (López *et al.*, 2017).

As far as my knowledge, there are few works to reduce the human involvement during the BIM modelling process from existing geometric primitives. This research focuses on the 3D parametric modelling of lost architectural heritage from the archived documentation and ruins.

The proposed approach has been implemented onto two damaged historic buildings (in Section 3.3.2) through the practical BIM tools, *Autodesk Revit* platform and *Dynamo* visual programming plugin (Figure 5.1). The BIM parametric elements (i.e., columns, roof, slabs, and walls) are manually created according to the historical archive of the dimensional shape and the scanning of remaining structures, and then a semi-automatic modelling procedure is developed by *Dynamo* visual programming to build the geometric primitives to the semantic HBIM model.

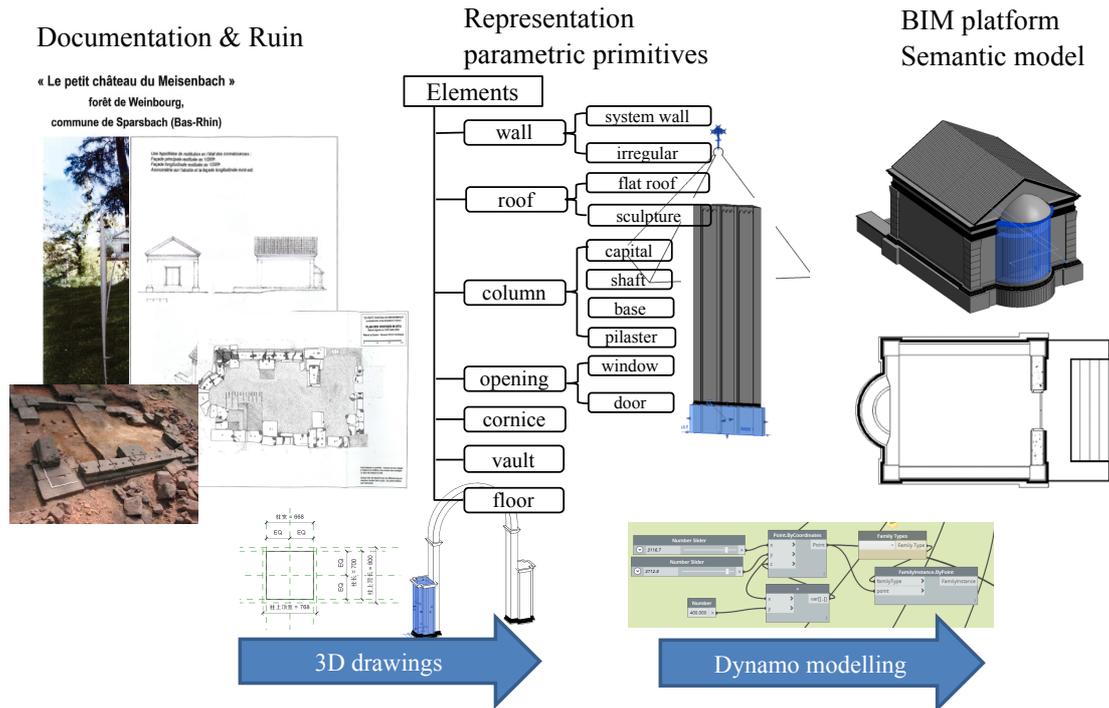


Figure 5.1. Workflow from documentation recording to parametric elements and BIM model

5.1.1. Existing geometric models

The first step concerns the collection of historical data, including the bibliographic knowledge and the reality-based data of ruins. The documentation records the prototype of the building, including the compositing structure by different shapes of structures. And the parametric model has been obtained in the former works using *Autodesk Inventor* (Diethrich, 2017) and *SketchUp* (Koehl and Grussenmeyer, 2008), respectively (3.3.2: Two lost historic buildings). The obtained parametric models can be loaded in the BIM platform, but the parametric and category information are missing and the loaded structures are holistic geometry (Figure 5.2) which are only visible yet not editable and cannot attach additional information (Figure 5.3). Thus, all of them still need to be converted into BIM components which at present needs to be carried out manually.

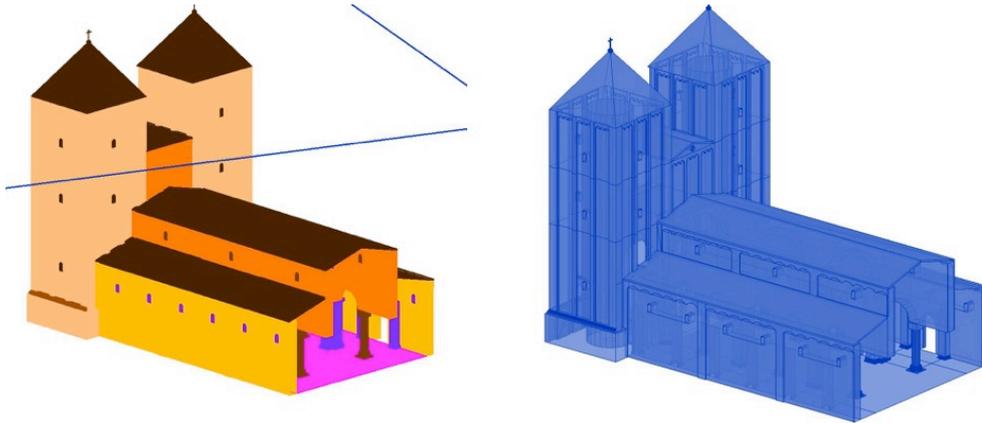


Figure 5.2. The loaded entity is only visible and becomes a holistic geometry (the Abbey of Niedermunster)

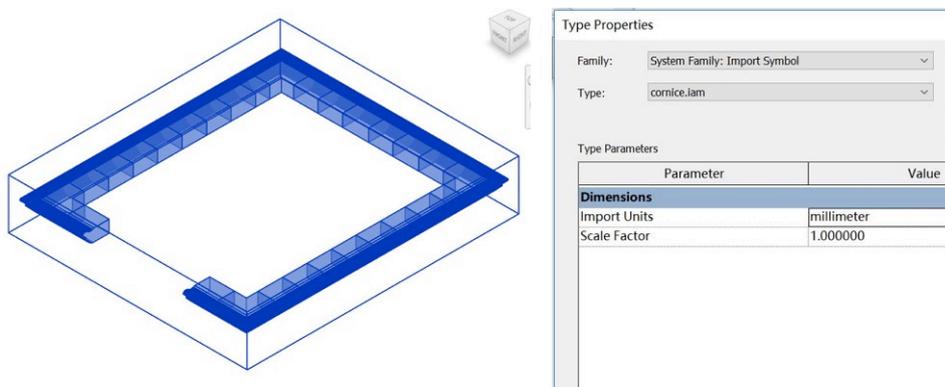


Figure 5.3. The parametric component becomes a non-editable geometry and cannot attach additional attribute in *Revit* (an eave of the Petit château du Meisenbach)

5.1.2. Parametric elements by manual drawing

HBIM consists of a detailed semantic model and a library of parametric “*Families*”. A “*Family*” is a group of elements with a standard set of parameters and similar graphic representation. The library of parametric element classes is first built to define the basic elements of the historic architecture (Figure 5.4 and Figure 5.5). The modelling of the various architectural heritage objects was done in two kinds of “*Families*” in *Revit* platform: “in-place family”, directly built-in “Mode-In-Place” editor of “architectural” project environment, is used for the creation of realistic walls; and external component “*Family*”, separately built in *Revit* Family editor, is used for the creation of other parts, such as, columns, roofs and other structures. The “in-place family” is grouped and converted into the loadable component “*Family*” outside the project, which can be a “wall

host” family for openings and loadable family to other projects.

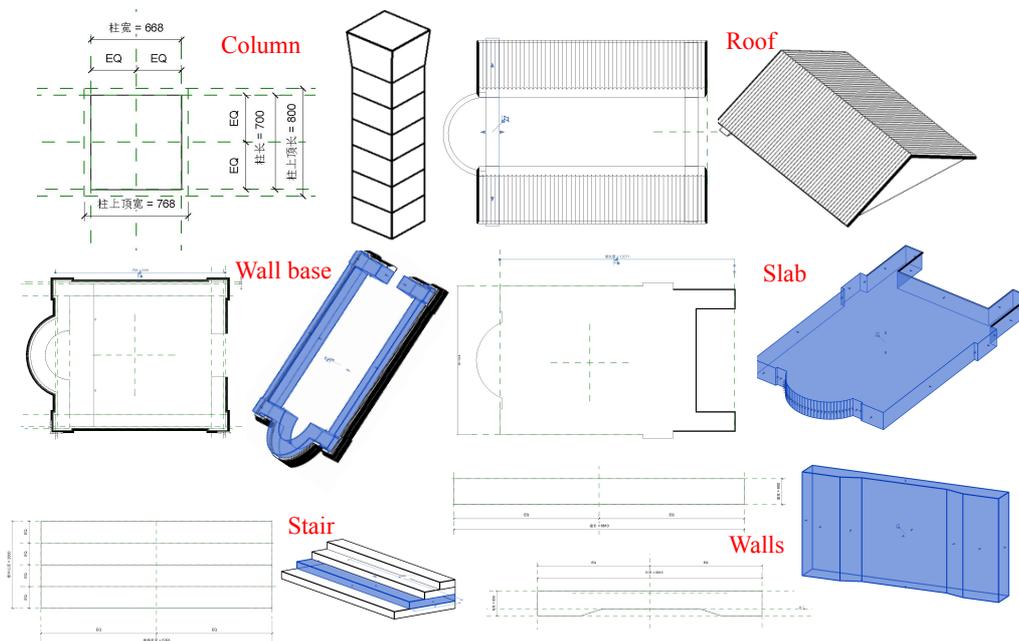


Figure 5.4. The parametric “Families” for the “Petit château du Meisenbach”

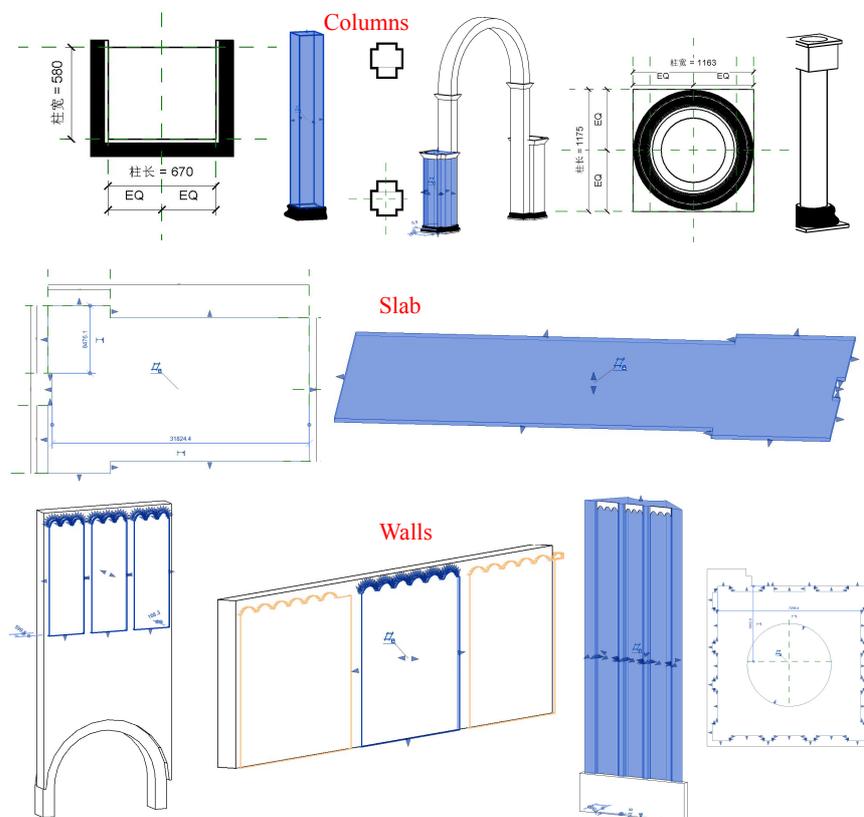


Figure 5.5. The parametric “Families” for the Abbey of Niedermunster

5.1.3. HBIM (LoD3) by *Dynamo*

On the base of “*Family*” creation, the building modelling process is conducted by *Autodesk Dynamo*. The obtained model is a geometric model with parameters and semantics. The parameters can be changed in *Revit* interface and *Dynamo* nodes. The *Dynamo* based modelling is conducted based on the relative relationship and coordinate values (Figure 5.6), and this project takes the slab element as the reference plane.

Figure 5.7 to Figure 5.10 show the final model in 2D and 3D views. As for the geometric aspect, the obtained model is an architecturally detailed model with considerably complex shape about the object’s parts.

The created model is accordant with LOD300 in IFC, which contains the full exterior of an architectural model with detailed wall and roof structures, doors and windows. Compared with the most LOD300 models currently available which have been constructed by tedious and time-consuming manual works (Donkers *et al.*, 2015), the choice of *Dynamo* visual programming maintains the need to reduce human involvement during the modelling process. The current work automates the semantic modelling from parametric “*Families*” elements aiming at lost historic buildings, while the creation of “*Families*” is still in a manual way.

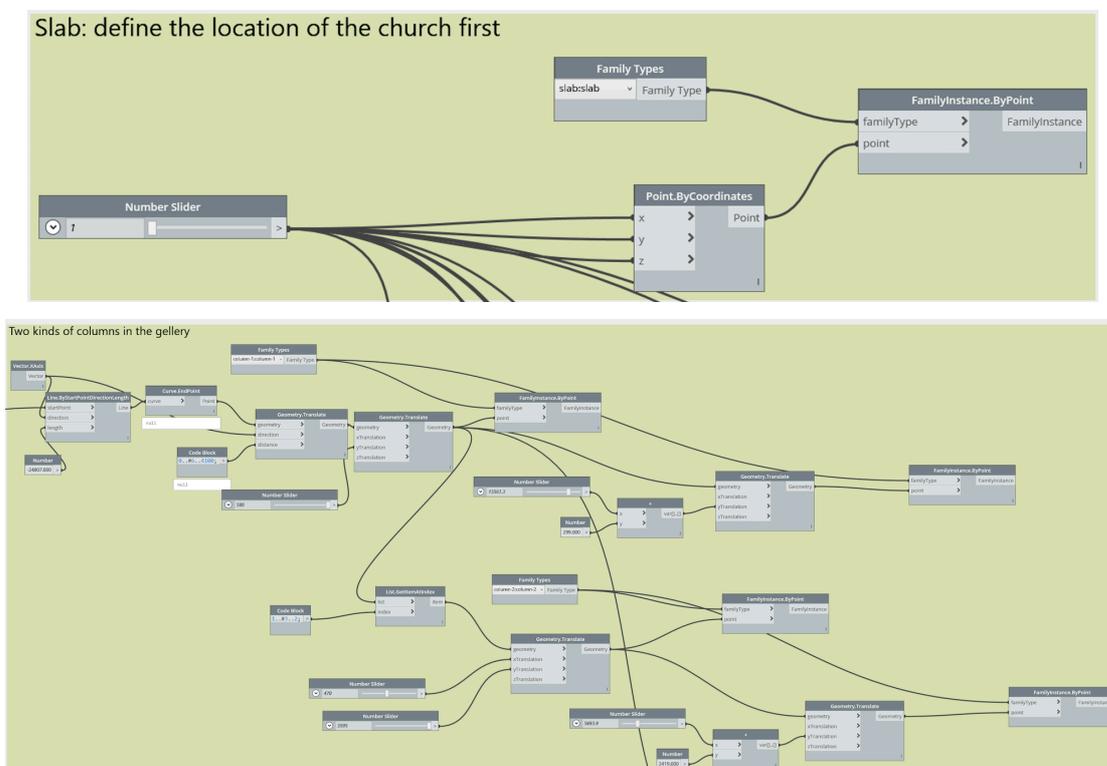


Figure 5.6. Some *Dynamo* nodes to generate HBIM elements

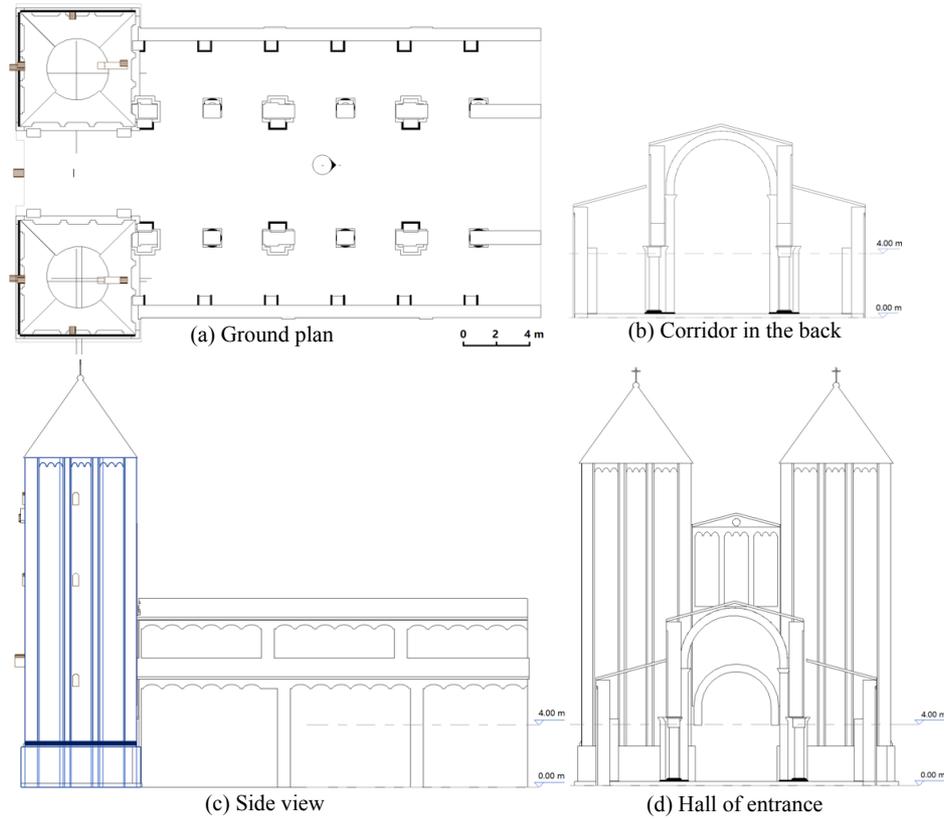


Figure 5.7. 2D views of the Abbey of Niedermunster

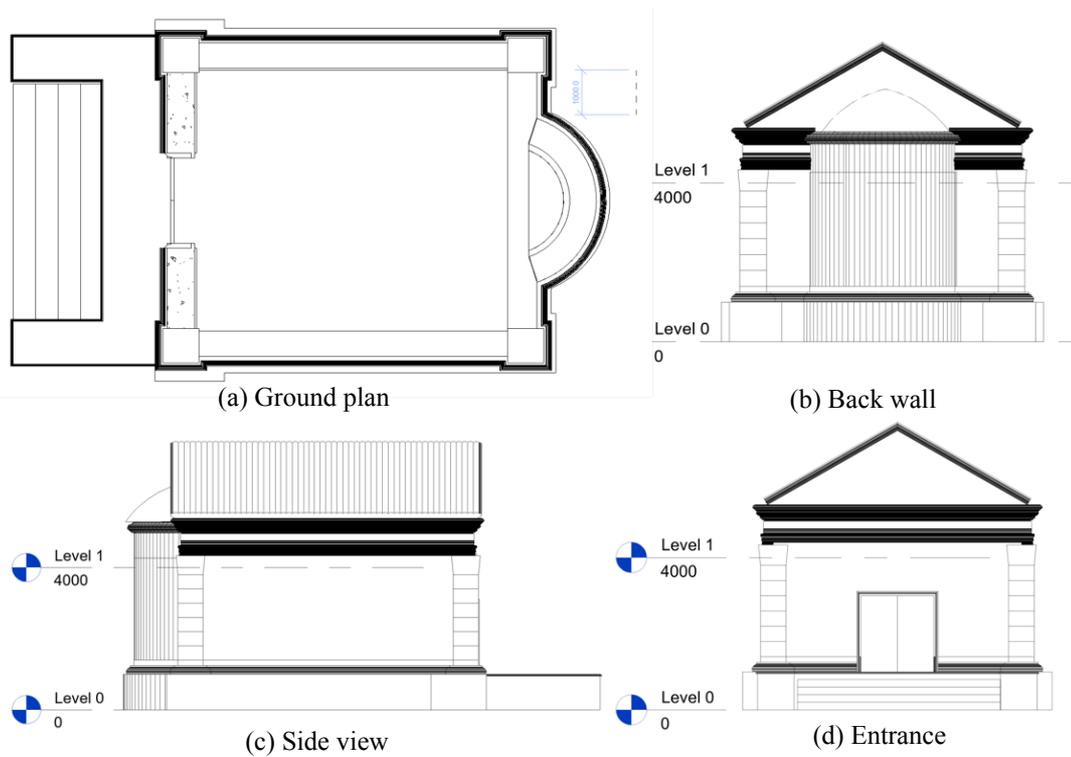


Figure 5.8. 2D views of the Petit château du Meisenbach

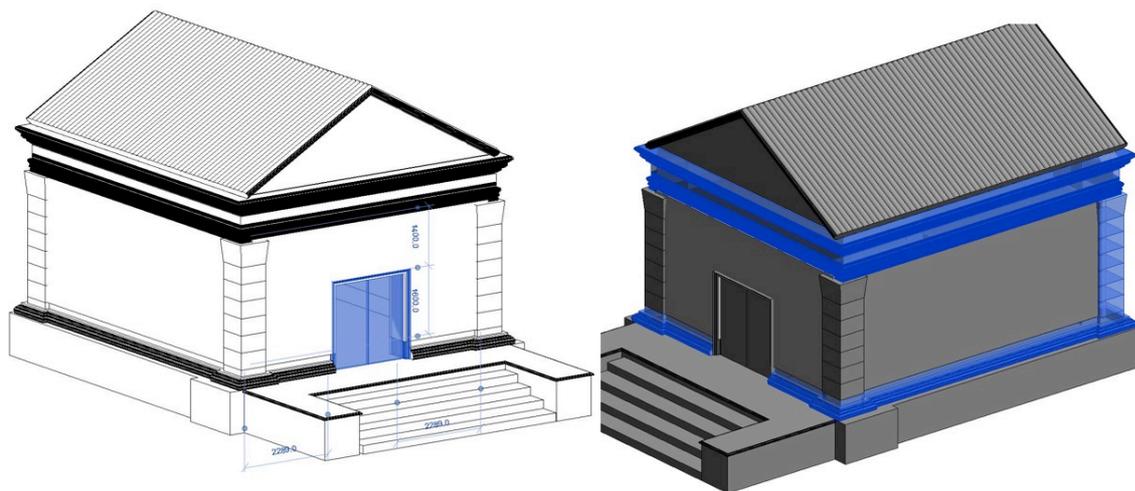


Figure 5.9. The final parametric HBIM model of the Petit château du Meisenbach in 3D views, whose parameter and semantic information can be modified further

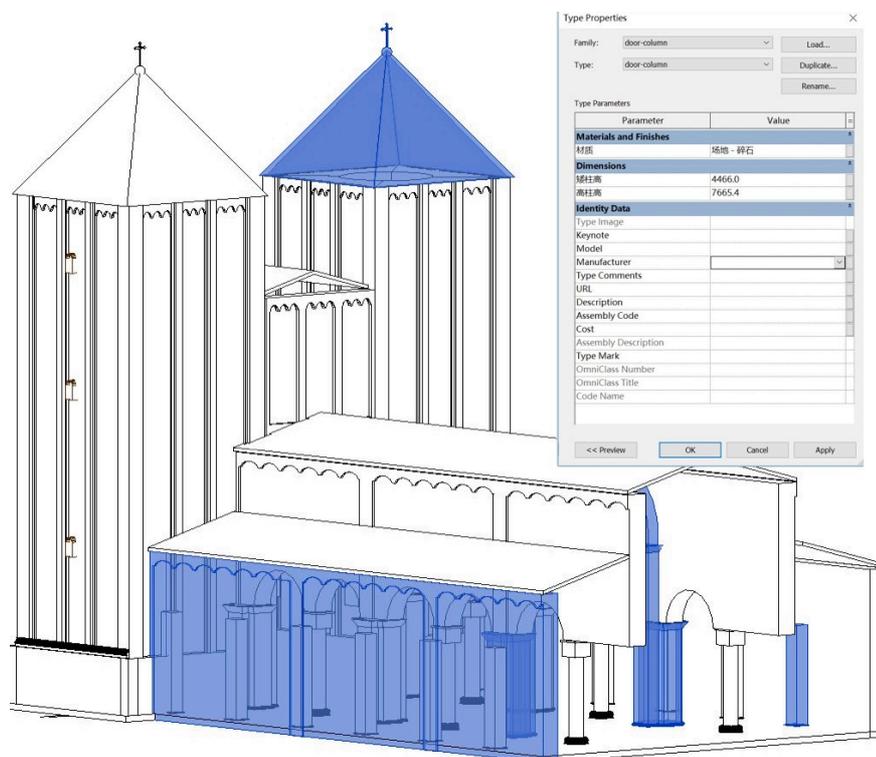


Figure 5.10. The final parametric HBIM model of the Abbey of Niedermunster in 3D views with parametric geometry and extensible properties

5.2. Scan-to-HBIM and Mesh-to-HBIM for existing heritage

5.2.1. Conventional Scan-to-HBIM

The point cloud data have been pre-processed (Figure 3.24) before feeding it into the BIM environment. BIM technique can be used to help to improve the geometric model into the parametric model. As-built BIM has provided a platform for direct semantic modelling using the surface of a point cloud. The first is the creation of the “*Families*” that are not included in the built-in system (Figure 5.11).

The obtained HBIM model using point clouds is a geometric model with parameters and semantics. The parameters can be changed in *Revit* interface and *Dynamo* nodes. Figure 5.12 shows the final model in 2D and 3D views. As for the geometric aspect, the obtained model is an architecturally detailed model with the considerably complex shape on the object’s parts. The LOD of the HBIM model is based on the “*Family*” elements, in which the more parameters and higher accurate geometry are manually created, the higher LOD is obtained. The created model corresponds to the LOD300 in IFC, which contains the full exterior of an architectural model with detailed wall and roof structures, doors and windows (Biljecki *et al.*, 2016).

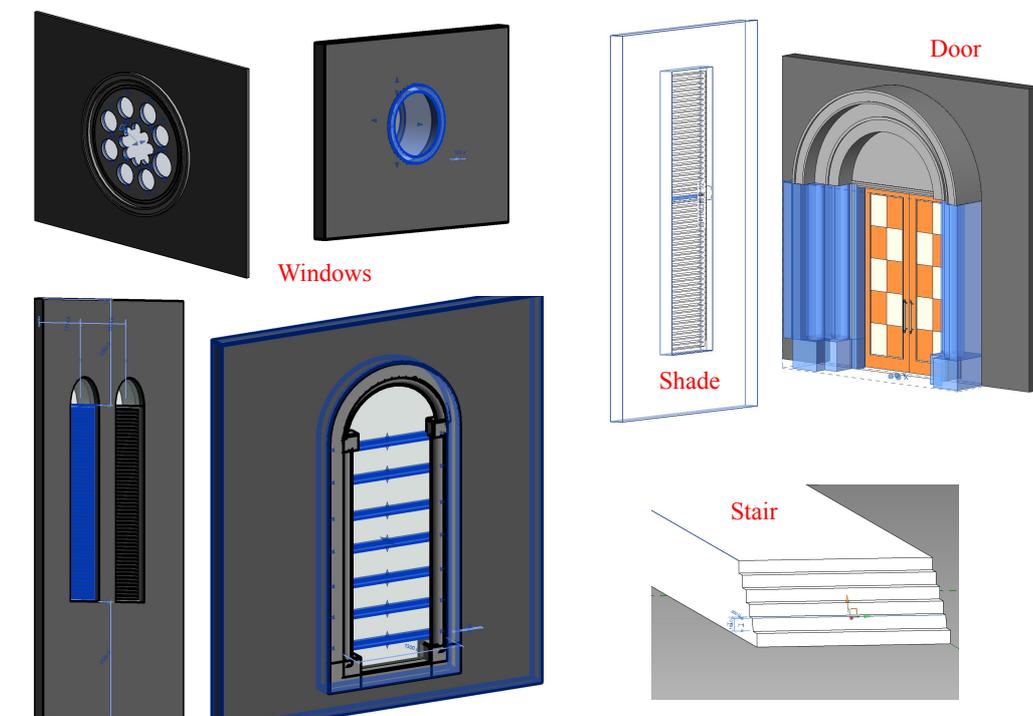


Figure 5.11. Typical “*Families*” composing the church

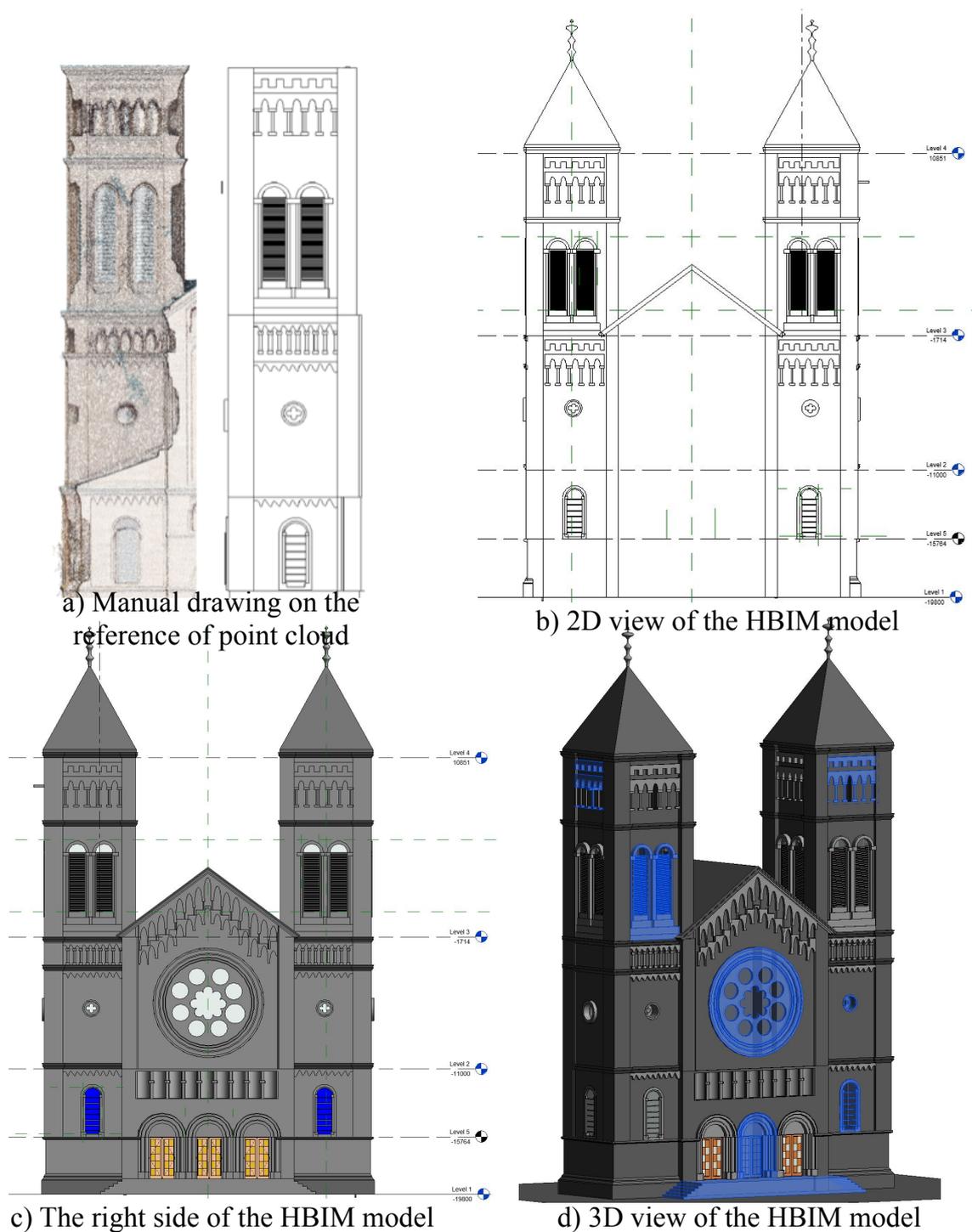


Figure 5.12. The 3D manual drawing in *Revit* using point clouds as a reference, and the final HBIM models from manual scan-to-HBIM in 2D and 3D view.

5.2.2. Mesh-to-HBIM

The proposed approach in this chapter is dedicated to reducing the human involvement in the as-built HBIM reconstruction period. It builds the HBIM models through the practical BIM tool, *Autodesk Revit* platform and its built-in *Dynamo* visual programming.

For the mesh-to-BIM process, the segmented solid primitives are semi-automated created in *Rhino 3D* from the surface mesh geometry and transferred to *Revit* elements via *Dynamo*.

Two HBIM models were obtained from the point clouds and scan-to-BIM process, and mesh geometry and mesh-to-BIM process, respectively.

The final HBIM models are generated from parametric elements in a manual way and from solid primitives by *Dynamo* programming with reduced human involvement, respectively.

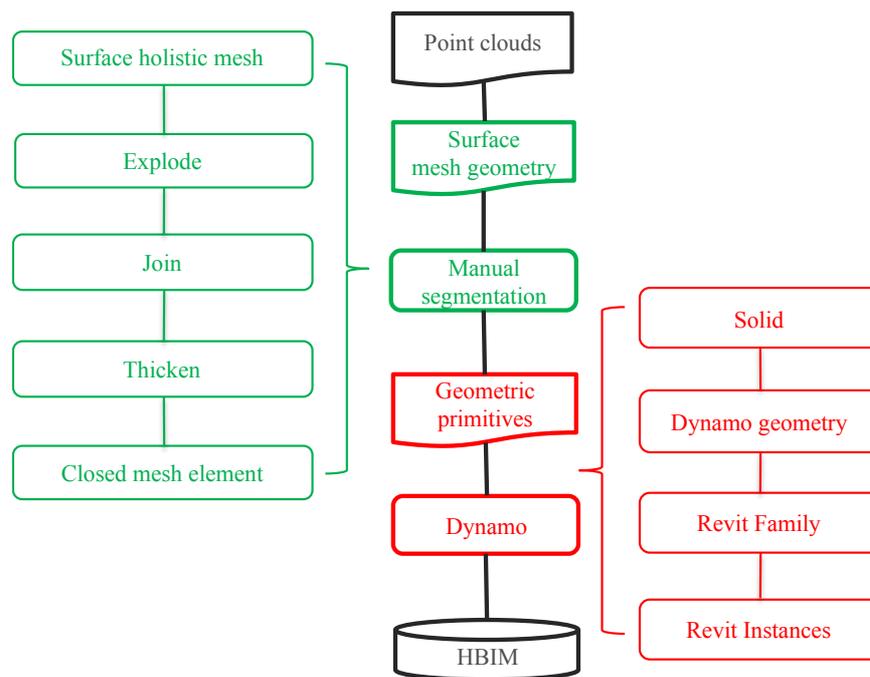


Figure 5.13. The proposed mesh-to-HBIM processing outline for existing historic buildings from mesh structure using *Rhino 3D*, *Revit* and *Dynamo*

5.2.3. Primitives generation

The accurate geometric model of the church has been created in previous work, which exists in surface mesh format (Murtiyoso *et al.*, 2017). The mesh-to-HBIM process transfers the surface geometric model to solid HBIM model and preserves the geometric shape as accurate as possible. It consists of primitive extraction, surface to solid transformation, and BIM component generation (Figure 5.13). The holistic mesh is fundamentally segmented into primitives representing the church's basic components (i.e., walls, roofs, columns, slabs). By visual programming in *Dynamo* environment, the solid mesh geometry can be transferred into *Revit Family* elements, which makes it necessary to transfer the surface mesh to closed solid mesh.

The *Rhino 3D* software is utilized to segment the mesh geometry and generate solid primitives. The holistic mesh geometry is divided into small blocks by multilayered explosion. Take the roof structure as an example (Figure 5.14); the roof consists of several blocks (yellow parts), and the block needs further explosion if it involves non-roof structures. The blocks are then joined together to obtain the basic elements of the church and transferred to solid geometry by adding thickness (Figure 5.15). The solid elements are closed mesh geometry, which is necessary for further modelling in *Revit* and *Dynamo*.

With the closed solid geometry, we can easily import them into *Dynamo* geometry and generate the corresponding *Revit "Family"*. However, the family element has limited parameters, which is the non-editable "*dead family*". So it depends on the users' need. If the user prefers parametric geometry, manual drawing of the "*Family*" is necessary; on the other hand, if the user prefers the original mesh geometry, the "*dead family*" is a time-saving way.

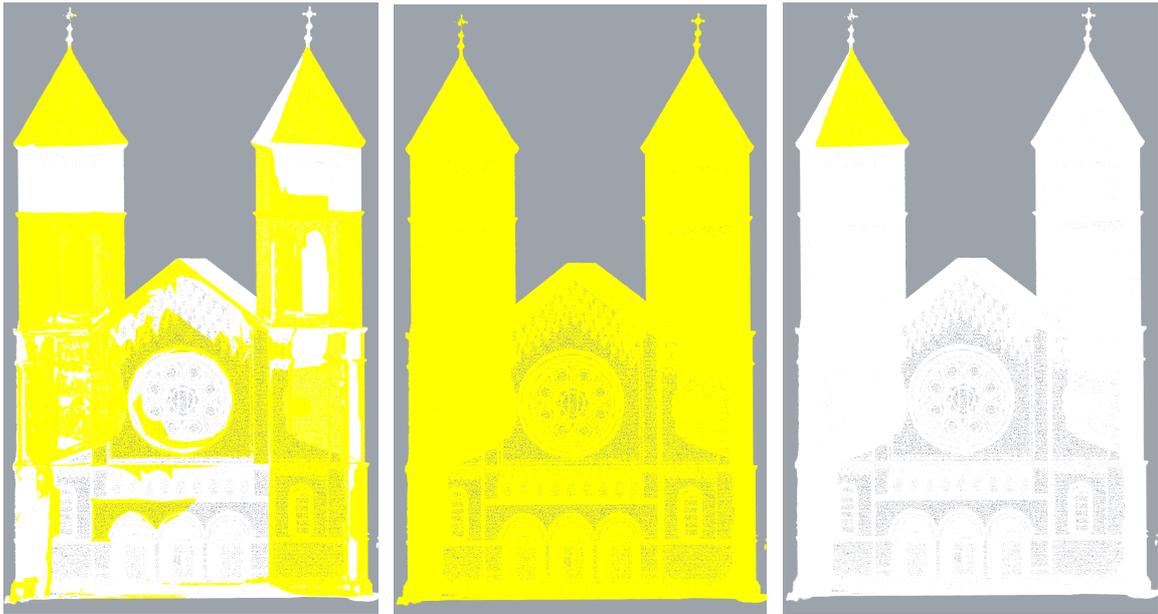


Figure 5.14. The explosion processing to segment the holistic mesh into small blocks by multilayered explosion.

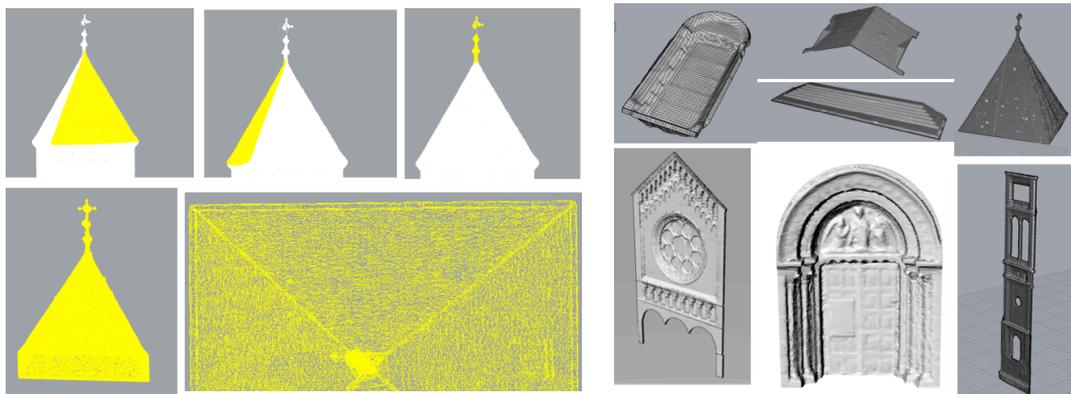


Figure 5.15. The segmentation, combination and thickness process to transfer the holistic surface mesh into individual parts (left) and the solid elements of the closed mesh (right)

5.2.4. Semantic HBIM from mesh by *Dynamo*

The obtained HBIM model using surface mesh is a geometric model with semantics and non-editable geometric instances. The model has potentials to attach attribute, material and temporal information in the BIM platform (Figure 5.16), yet its geometric aspect information is limited to non-editable and no changeable parameters available. Figure 5.17 shows the final model in 3D view and the semantic elements. The geometric information of the model is directly transferred from the surface mesh without human modification. The

Chapter 5: Geometric model to HBIM

accuracy is extremely affected by computer performance because the huge meshes and large scale of the building may go beyond the capabilities of the software.

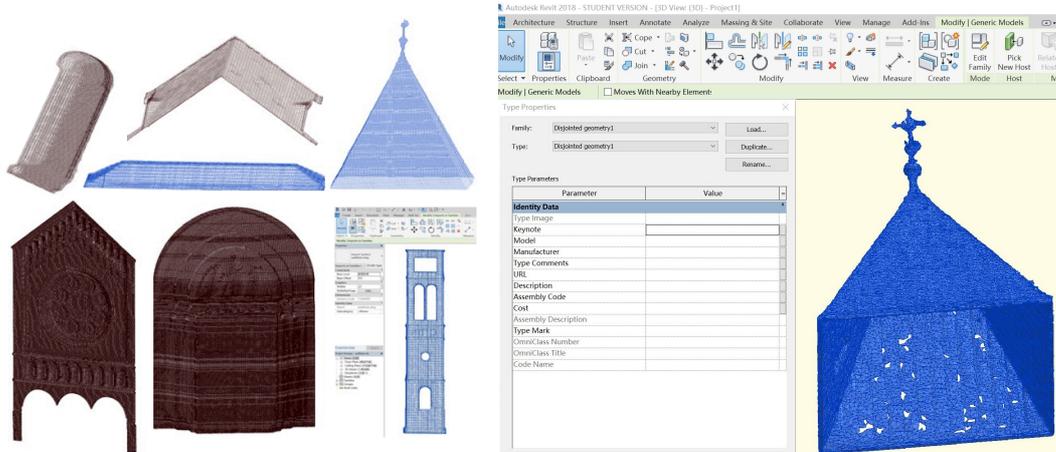


Figure 5.16. Converted “*dead Family*” in Revit from closed mesh in *Rhino 3D* using *Dynamo*

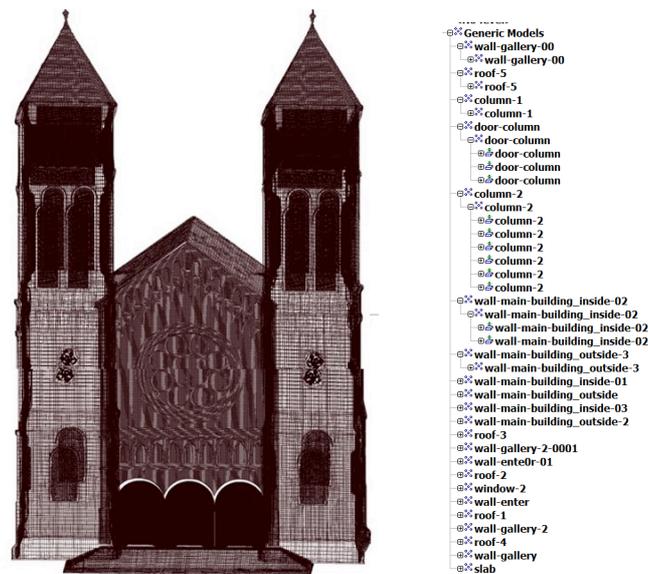


Figure 5.17. HBIM model from mesh geometry by *Dynamo*

5.2.5. Comparison between scan-to-HBIM and mesh-to-HBIM

Reality-based data has been widely accepted for the creation of heritage geometric modelling, and one current challenge includes heritage information modelling using the recently developed BIM technique. As a 3D information modelling environment, BIM software is increasingly supportive of 3D point clouds representing the entity surface and

Chapter 5: Geometric model to HBIM

generates a popular scan-to-BIM process.

Considering the complex structure of the built heritage, the scan-to-HBIM is mostly conducted in a manual drawing way on the reference of the point cloud. Although BIM is supportive of point cloud, it is still not friendly enough to process the point clouds as the specific point cloud processing software. *Revit* provides the API development based on .Net programming, yet it is still difficult to connect with the point cloud library (PCL) to extend the point cloud processing capabilities.

In the project, three geometric models are obtained, including the holistic surface mesh model, parametric HBIM model from point cloud, and semantic HBIM model from the mesh. Table 5-1 compared their merits and limitations.

Table 5-1. Comparison of three types of geometric models

Aspects	Mesh	Scan to HBIM	Mesh-to-HBIM
Manual work	low	high	middle
Time complexity	Accuracy	level of proficiency	Depending on the computer performance
Geometry	Surface	Volume	Volume
Parameter description	Non-parametric	parametric	Non-parametric
Semantic	Global and holistic	Local	Local
Description	Non-attribute	Attribute	Attribute
Relationship	No	Strict	Possess
LOD	Depending on the accuracy of point cloud	Manual drawing	Based on mesh structure
Main limitation	Only geometry available	Time-consuming, professional training	Huge size

Summary

This chapter presented a possibility for the generation of HBIM from the surface mesh and solid geometry with reduced human involvement. In the HBIM project, the modelling process consists of parametric “*Family*” creation and semi-automated building reconstruction. Two types of HBIM models from different formats of “*Families*” are created. In one hand, starting from the collection of the point clouds and the documentation, related parametric “*Family*” classes are manually created in HBIM environment. On the other hand, the utilization of *Dynamo* enables the element-to-BIM process, which directly transfers the segmented solid geometry to BIM environment with reduced manual processing. The obtained BIM “*Family*”, however, has limited parameters and lacks explicit geometric description because the automatic generation from geometry returns to non-editable solid elements.

Currently, various kinds of geometric models are available for the heritage documentation, including the virtual reconstruction according to the documentation (Petit château du Meisenbach and the Abbey of Niedermunster in Section 3.3.2) and the surface mesh geometry from the point clouds (St-Pierre-le-Jeune Church in Section 3.4.2). Compared with the traditional geometric models, the obtained HBIM parametric model is enhanced with measurements, attributes and strict relationship information.

The *Dynamo*-based HBIM modelling transfers the parametric family and geometric structures to HBIM model via *Revit Dynamo* visual programming. The fundamental work is to manually create the parametric “*Family*” or to segment the surface mesh into closed solid geometry representing building components (i.e., walls, roofs, columns, slabs). Then, by visual programming in *Dynamo* environment, the element-to-BIM process can be conducted to convert the segmented solid geometry to BIM environment with reduced manual processing. The relationships among building objects were also subsequently defined.

For the lost heritage, the modelling process consists of manual parametric “*Family*” creation and semi-automated building reconstruction (Figure 5.18 (left)). Starting from the collection of historical materials, related parametric “*Family*” classes are firstly created in HBIM environment. Then, the semantic model composed by the parametric elements is generated in an automated way by *Dynamo* visual programming package.

For the existing built heritage, this chapter compares two HBIM workflows, conventional

scan-to-HBIM from the point clouds and newly proposed mesh-to-HBIM from the surface mesh, respectively. Consequently, a parametric HBIM model is manually created on the reference of the point clouds (Section 5.2.1); and a semantic HBIM model is created from the solid mesh components using *Dynamo* visual programming (Section 5.2.4).

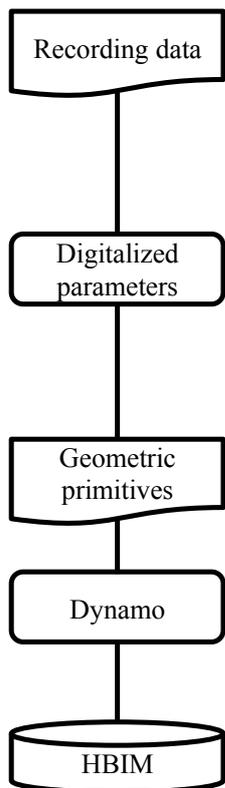
The manual parametric HBIM modelling converts the point clouds to the solid model (Figure 5.18 (right)). It not only reserves the geometric aspect of information but also parametrically describes the attribute, material and relationship information of the sub-elements. The scan-to-HBIM process creates the BIM solid components from point clouds, which remains a time-consuming manual process and thus it is expected to reduce the human involvement as much as possible.

The semi-automated mesh-to-HBIM modelling reduced lots of human works (Figure 5.18 (middle)). The HBIM model composed of the solid elements is generated in a semi-automated way by the *Dynamo* visual programming package. The segmented elements can be stored and managed in the BIM environment with attached attributes information and relationship established among the elements. The obtained BIM model, however, possess no geometric aspect parameters because the automatic *Revit* “*Family*” generation from mesh geometry returns non-editable solid elements.

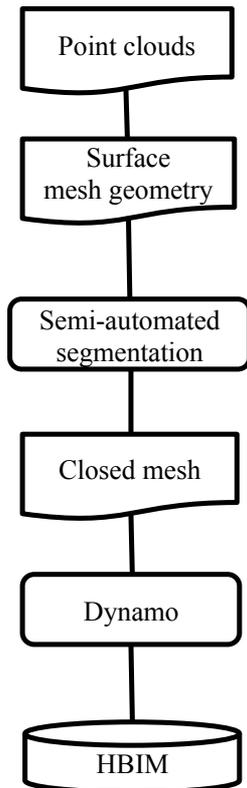
These results show the feasibility of utilization of *Dynamo* to reduce the human involvement in the process of HBIM modelling from parametric family, segmented solid elements and mesh geometry. And the complexity of the human involvement depends on the users’ need. The two workflows provide the users with different options for HBIM modelling. So it depends on the users’ need. If the user prefers parametric geometry, manual drawing of the “*Family*” is necessary; on the other hand, if the user prefers the original mesh geometry, the dead family is a time-saving way.

Moreover, this chapter presents the potential to utilize *Dynamo* to conduct the HBIM modelling from the parametric “*Families*” and “*dead Families*”, which are applied on lost heritage and existing heritage. The mesh-to-HBIM for the existing historic buildings is more important, because the manual-drawing of scan-to-HBIM faces lots of challenges and current reality-based modelling easily achieves the high-accurate mesh geometry. By contrast, the manual-drawing of parametric HBIM modelling for the lost historic buildings are more appropriate because it is accordant with the original BIM concept to build the information model according to the defined parameters.

Dynamo modelling for lost heritage



Mesh-to-HBIM



Traditional Scan-to-HBIM

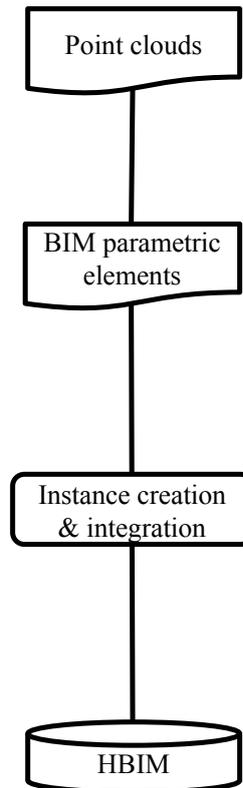


Figure 5.18. Different HBIM modelling workflows: Solid-to-HBIM (left), mesh-to-HBIM (middle) and scan-to-HBIM (right)

6 | Applications of the HBIM

HBIM can potentially allow for effective integration of information with other platforms for further applications, such as the connection with ontology (Lu *et al.*, 2018) and the structural analysis (Bassier *et al.*, 2016).

In the field of built heritage, the knowledge base has been created by means of the ontology editor *Protégé*, representing each entity through the Meaning-Properties-Rules structure. HBIM model is integrated with such ontology semantic relational system to enhance the representation of heritage knowledge and semantic reasoning. The current IfcOWL project converts EXPRESS/IFC schemas to ontology, which has been embraced by buildingSMART as future development of the IFC standard (Pauwels *et al.*, 2017). The obtained BIM model can be straightforwardly converted to ontology OWL format and integrated with interested semantics.

ICOMOS (2003) has recommended the need of further structural analysis and management of the architectural heritage on the basis of geometric documentation. Current structural analysis is conducted in civil engineering software to assess the heritage conditions once the HBIM model has been generated.

These integrations face the challenge of information loss, and *Revit Dynamo* increasingly provide a possible tool to extend the HBIM capabilities in the unified *Revit* environment.

6.1. HBIM with enriched ontology semantics

Both BIM and ontology utilize object oriented approach consisting of a primitive system to describe the characteristics of the built heritage elements as well as their relationships (Figure 6.1). An ontology entity is represented through a synthesis of three main features to define the concepts that belong to a particular knowledge domain: ‘classes’, ‘properties’ and ‘rules/relationships’. Generally, ‘class’ is defined by assigning different meanings; “properties”, instead, are necessary to represent all the descriptive aspects related to the concerned element such as geometrical, physical and behavioral features; and “rules” denote how the classes or entities are associated with others. The relationship in ontology pays more attention on semantics, while the relationship in BIM emphasize the spatial and geometry. The relationship in ontology is defined between classes or entities. The relationship rules can link lower level entities and higher complexity ones as results of multiple entities’ assembly, (‘Part-Of’, ‘Whole-Of’) or define hierarchical relationships ruling entity generality stratifications in terms of Father/Son, Prototype/ Instance (‘Is-A’, ‘Instance-Of’) (Cursi *et al.*, 2015). The HBIM elements are linked together with strict spatial relationships once they have been parametrically created. The spatial relationships are fixed, even if the sizes or shapes of the elements change.

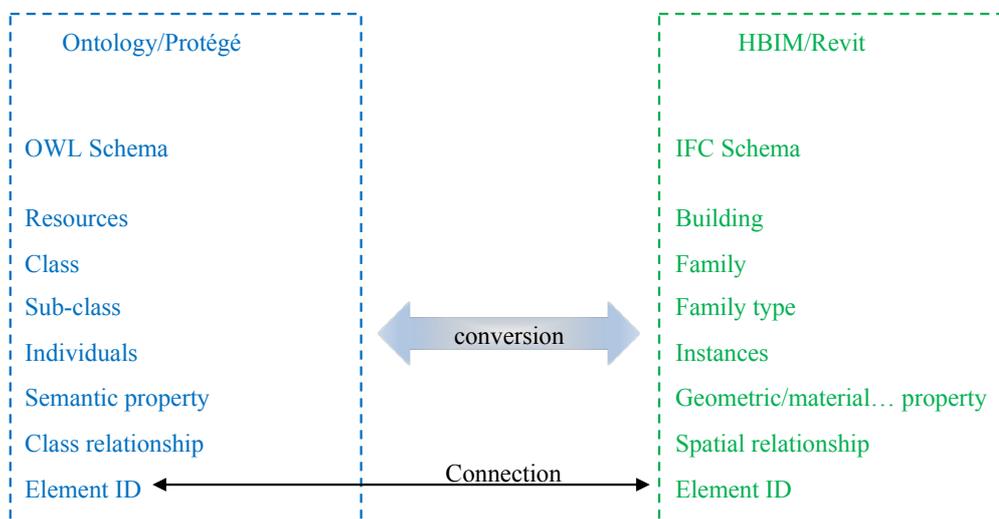


Figure 6.1. The conceptual schema of BIM and ontology

Thus, both of them rely on a component-based approach oriented to depiction of the single entities that compose the built heritage assigning to them a set of properties according to the specifications of their class/“Families”. The similar object-oriented fashion to the modelling of the architectural object makes it possible to connect between the database of

Chapter 6: Applications of the HBIM

the ontology-based system and the BIM database (Cursi *et al.*, 2015). Consequently, this connection was established by assigning the same label to both the representations of the corresponding entity in the two modelling environments (Figure 6.2). Ontology builds the knowledge model for the heritage, and HBIM builds the parametric model for the heritage. The different kinds of properties and relationships can be acquired separately.

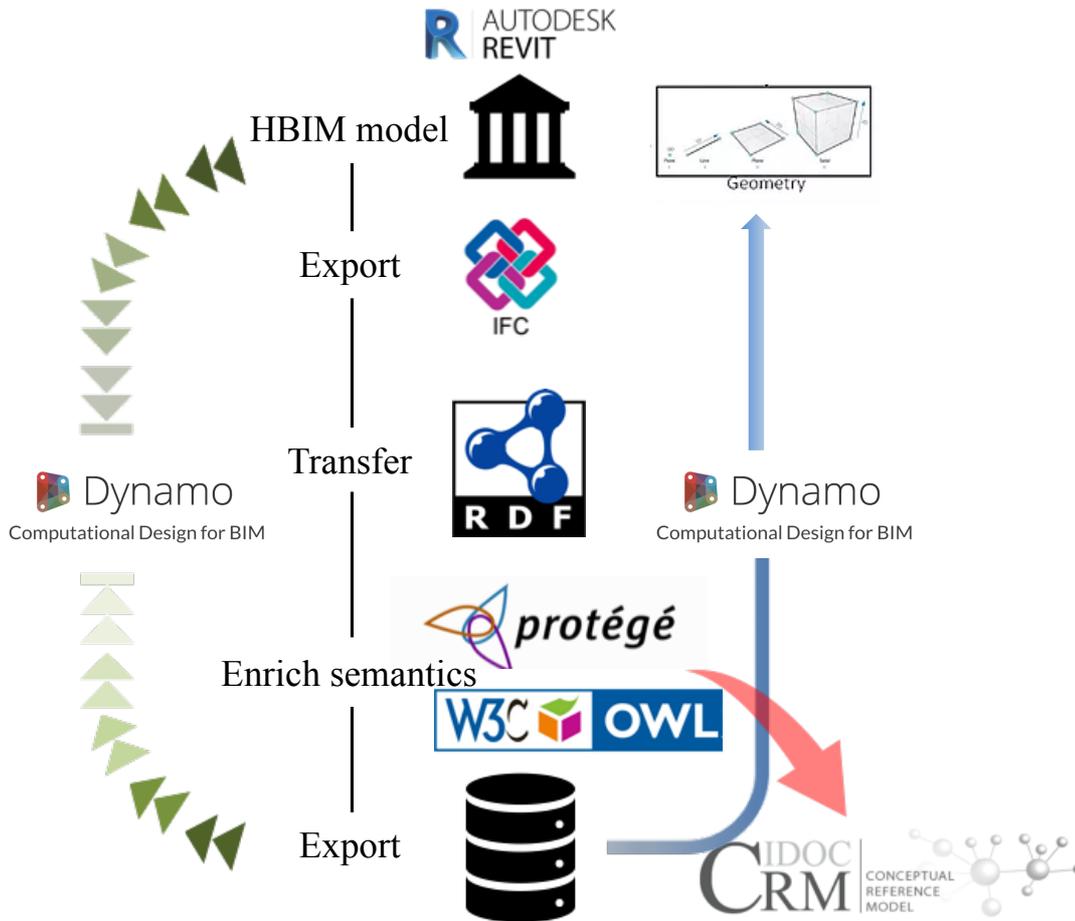


Figure 6.2. The connection of HBIM IFC model and ontology OWL model

In line with the research trend, there are two schema, RDF and OWL, to present standards for implementing ontologies. RDF is XML-based language to describe resources, process information on the web, designed to be interpreted by computers not for being read by people. OWL is built on top of RDF and adds richness of semantics to RDF, which is designed to provide a common way to be read by computer applications instead of humans and to process the content of information. OWL is a way of adding meaning / semantic richness to RDF. The main difference between RDF and OWL comes to the relationship. RDF just links concepts together (instances in class) and just has the parent-children relationship among the same class the relationship is defined by subClassOf,

subPropertyOf, range-domain. OWL adds more restrictions: Relationships between classes, Richer Properties (i.e. Transitive). OWL allows automated reasoning / inference and can be reasoning the properties according to defined knowledge.

On the other hand, there are two schema related to BIM models. EXPRESS define the data standard for information models about entities and attributes. Accordingly, the information model involves BIM IFC schema. That is, BIM model is under the Express schema. *Revit* can import the IFC file format, yet cannot import the express format data.

The integration can be a two-step modelling process by migrating IFC files to ontology environment for semantics richness (Quattrini *et al.*, 2017a; Pauwels *et al.*, 2017). Currently, a number of EXPRESS to OWL conversion procedures have been proposed based on IfcOWL, which provides an OWL representation of IFC EXPRESS schema (Pauwels *et al.*, 2016). Figure 6.3 is the ontology classes and properties defined in IfcOWL.

Once data enrichment has been done in BIM platform, the standard BIM data export functionality can be straightforwardly used to produce IFC data compliant with the EXPRESS schema. We then used the IFC-to-RDF conversion tool realized by Pauwels' software to obtain RDF data by mapping IFC extensible properties according to the IfcOWL ontology.

Protégé, an open resource platform used to construct domain models and knowledge-based applications with ontologies (Lin 2017), is adopted to enrich the properties and relationships for the HBIM entities. Specifically, we rely on the IfcOWL ontology to model the additional domain data.

Here, we explained the transformation taking the HBIM of the façade of Rohan Palace as an example (Figure 6.4). The model consists of IFC pre-defined structures and self-defined families by users. After the transfer, we can notice the families are totally transferred to classes in ontology. The individuals are obtained from the BIM instances with the consistent IDs and material property is also reserved. The only relationship available is the “subClassOf”, because the RDF only supports of this kind of relationship. Whereas, the geometry information and the spatial relationship are lost.

Chapter 6: Applications of the HBIM

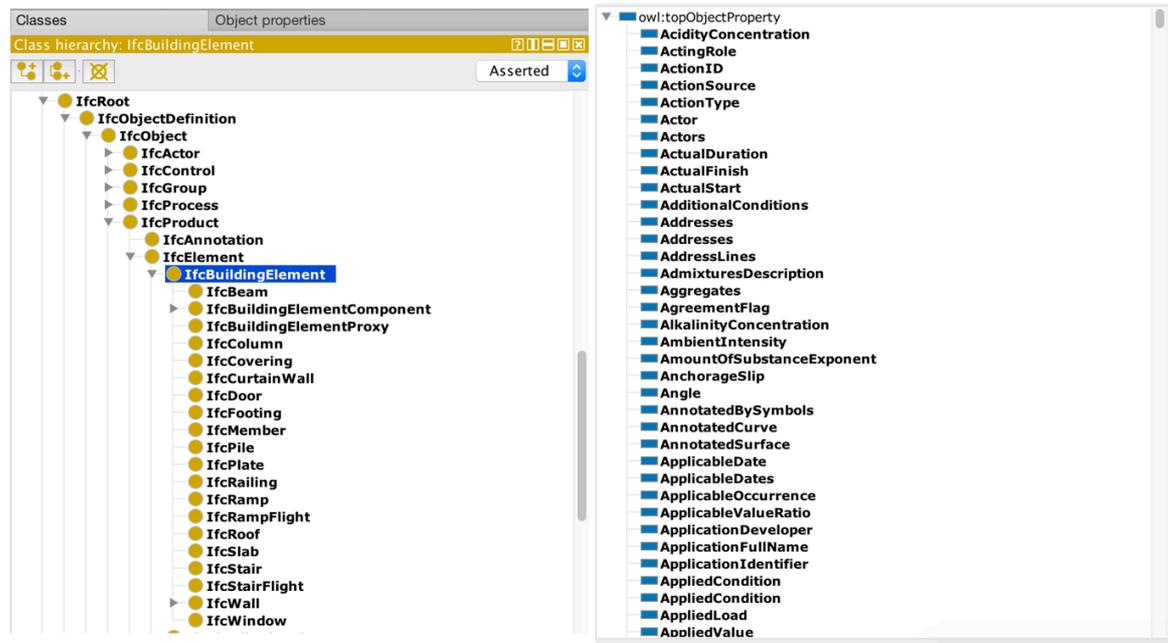


Figure 6.3. IfcOWL properties in *Protégé*

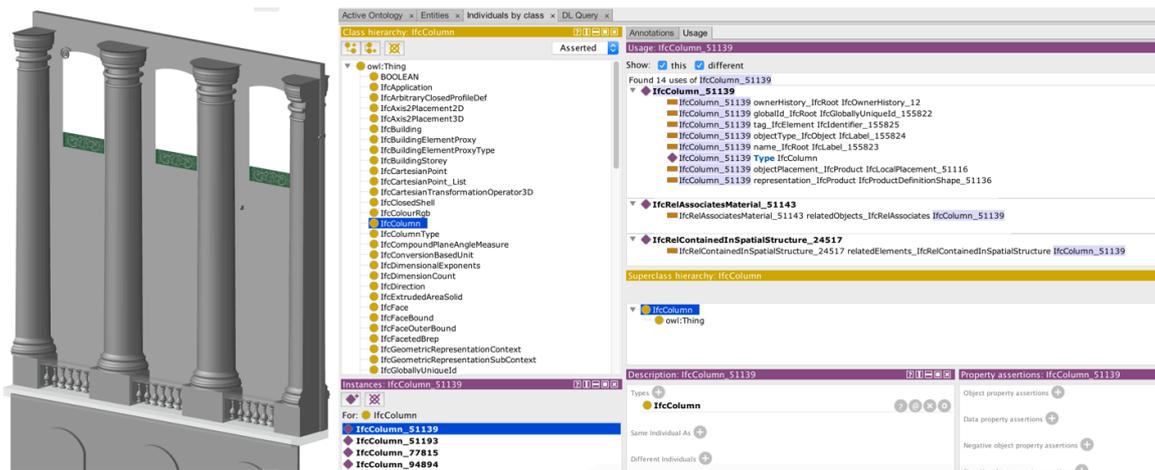


Figure 6.4. IFC-to-RDF for the HBIM model of Palais Rohan (including IFC structures and self-defined families)

6.2. Integration of structural analysis and HBIM

The HBIM model is composed of semantic elements with material information and relationship information, which is the base for the structural analysis and management. In the project, we conducted the structural analysis of the wooden beam frame structure of the Castle of Haut-Kœnigsbourg (in Section 3.5.2), whose HBIM models have been created by manual-drawing from the point clouds (in Section 3.5.2) and by *Revit* API plugin from the surveying points (in Section 4.4).

Timber roof structure is the typical architectural style in the historic buildings, and it is generally supported by a beam frame system. The connected and joint beams are organized as a structural system to sustain the load bearing of the roofs. However, for the wooden beam frame supporting the building roofs, the bearing mechanisms still have not received the due attention and consideration they certainly deserve. Semplici and Tampone (2006) explored the widely existing historic timber architectures and load bearing structures in the UNESCO World Heritage List. They reported that timber beam structures were not the object of conservation and appropriate repair in many countries and were suffering from neglect and alteration.

Structural analysis is the only way to assess the structural condition and load-bearing capacity of the beam structure (Chapman *et al.*, 2006; Sanchez-Aparicio *et al.*, 2015; Sanchez-Aparicio *et al.*, 2016), which is extremely important to the building roof conservation. The structural analysis depends highly on how the as-built model is close to the real situation, including various aspects of input parameters (geometry, materials and joint relationship). That is, both reality-based geometry modelling and structural analysis of the beam frame system need to be addressed for the conservation of historic timber roof, both of which have been well studied.

On the one hand, the reality-based data can model the accurate geometry model of the current condition of the heritage and monitor the subsequent changes. The typical beam frames have been geometrically modelled from reality-based data, such as the roof of historical castle (Arias *et al.*, 2007; Koehl *et al.*, 2015; Bertolini-Cestari *et al.*, 2016) and towers (Leonov *et al.* 2015). On the other hand, Finite Element Method (FEM) based computational software can conduct structural analysis by introducing 3D geometry files obtained by reality-based modelling (Armesto *et al.*, 2009, 2015), provided that the beam connection has been built.

The current problem for further analysis and heritage conservation is to segment the beams, build their connection information and attach the material character based on the 3D geometric model (Díaz-Vilariño *et al.*, 2015). All of these necessary information have been generated and stored in the HBIM model. In our project, the HBIM model is transferred to structural analysis software *COMSOL*, yet the connection and material information needs to be recreated in the *COMSOL* environment (Figure 6.5). That is, the solid geometry model consisting of elements are manually created in the software. Secondly, tetrahedron element is employed to free meshing, and totally the number of dividing elements comes to 14092 (Figure 6.6). And *FEM* is utilized by evenly distributed load method at the top (1e6 Pa) and

fix component at the bottom and calculated under the steady status (convergence factor 0.001). Von Mises stress distribution and displacement distribution is finally calculated.

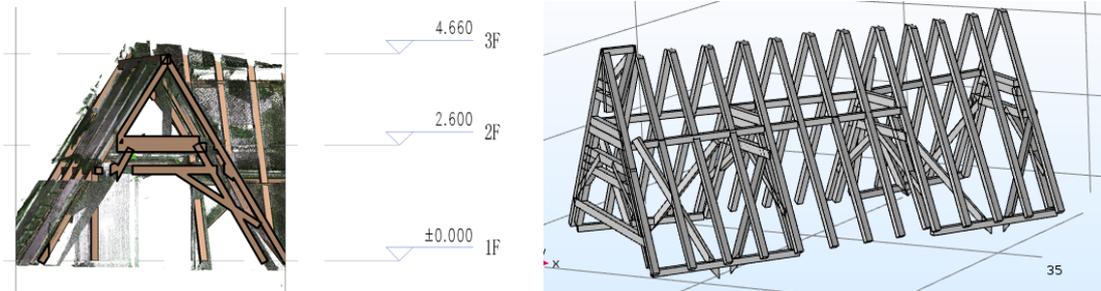


Figure 6.5. The difference between the segmented elements in *Revit* (left) and *COMSOL* (right). The segmented elements with connection information in *Revit* are re-segmented in the *COMSOL* platform.

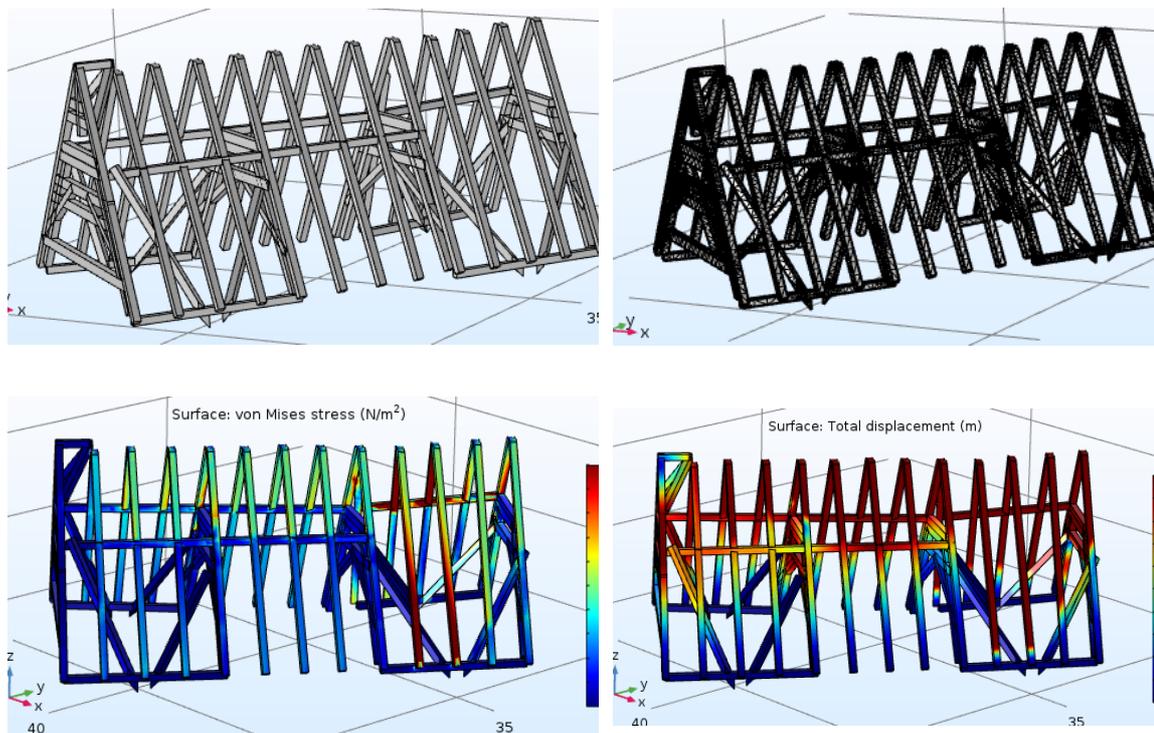


Figure 6.6. The re-segmented geometry model in *COMSOL* (up left), free meshing with the tetrahedron element (up right), the final von Mises stress distribution (down left) and displacement distribution (down right).

Although the computational software can conduct the structural analysis, the different environment not only needs the data exchange especially considering the irregular structures, but also reduces some inefficient and repetitive work as the element

segmentation. The parametric elements and the relationship information of the HBIM model cannot be recognized by the computational software, which results in the repetitive elements extraction processing during the structural analysis (Figure 6.5).

Although the structural analysis can be conducted utilizing the computational software, the obtained parametric model actually cannot directly be supported by the software. The parametric HBIM components cannot be recognized by computational software (such as *COMSOL*, *ANSYS*, etc.) and remerge to the holistic geometry. Such kind of losing of the semantic information implies the frame system needs to be segmented to separate beams again.

Although current works on HBIM and structural analysis are mostly conducted separately (Bassier *et al.*, 2016), BIM environment has potential to serve as the uniform platform for heritage documentation from scan data and management by structural analysis (Figure 2). *Revit* currently adds the extended capability on structural analysis by integrating with the *Autodesk Robot* Structural Analysis. The integration allows bidirectional data exchange¹: (i) transferring a structure model from *Revit* to *Robot* or from *Robot* to *Revit*, (ii) updating a structure model in one program after making changes in the model in another program, and (iii) returning the results of static analysis and required reinforcement calculated in *Robot* to the *Revit* model.

The HBIM provides the possibility to combine the separate processing, the software incompatibility and data homogeneity to the uniform platform. The BIM platform serves as the platform for visualization, 3D modelling, semantic segmentation and structural analysis, which is important for verifying the actual load-bearing capacity and structural safety of historic timber roof structures.

¹ *Revit - Robot Integration*. <https://knowledge.autodesk.com/support/robot-structural-analysis-products>

Summary

HBIM is increasingly integrated with other techniques as described in Section 2.4.2. It can potentially allow for an effective exchange of information between different domains and platforms and for the creation of enriched models (Cuisi *et al.*, 2015). But current heritage projects are still struggling with information exchange especially for the complex structures (Figure 6.7), and lots of works are dedicated to optimizing the information loss in the transformation process.

We are working on extending the HBIM capability by *Revit Dynamo* packages instead. The proposed mesh/solid-to-HBIM by *Dynamo* (in Chapter 5) indicate the segmented components from computer vision and computer graphics can be transferred to semantic HBIM models directly. *Revit Dynamo* provides the integration platform, where users can browse the semantic information reserved in ontology database and the 3D model in *Revit* at the same time. *Dynamo* can also conduct *Robot* structural analysis in the *Revit* environment. Therefore, the available of open-source packages and self-developed nodes in *Dynamo* can dramatically extend the HBIM capacities in the unified BIM platform.

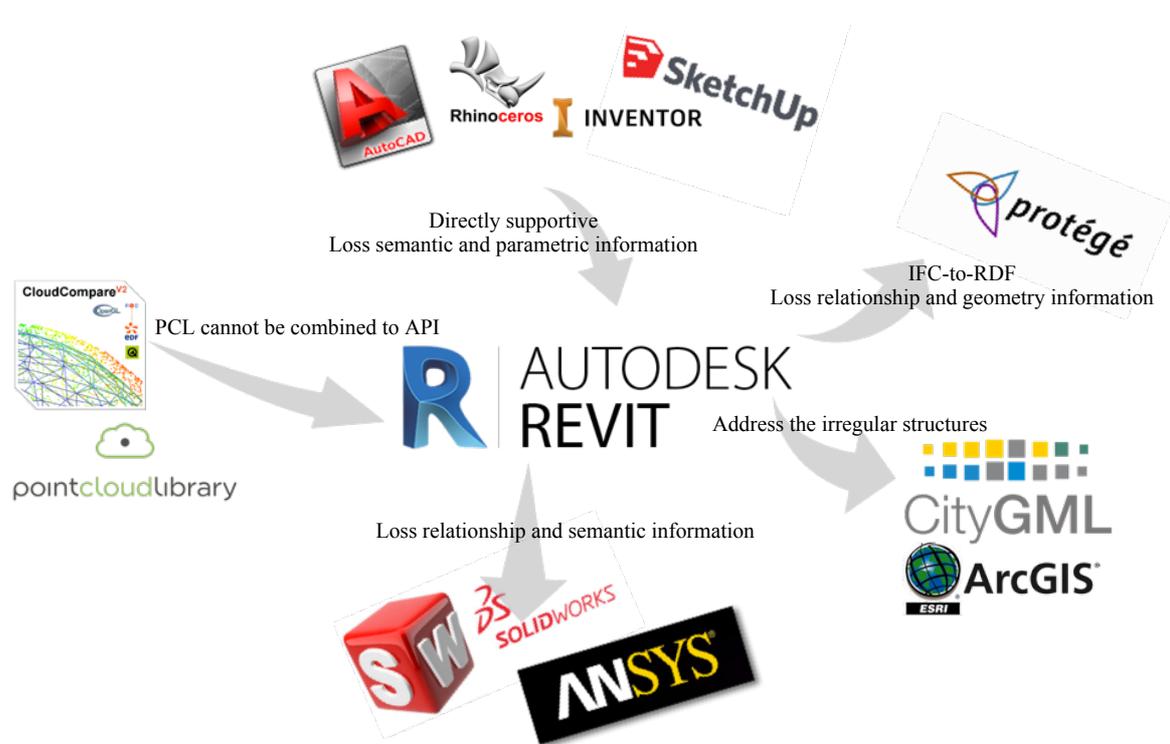


Figure 6.7. The integration of HBIM and other techniques facing different types of difficulties

Conclusion and perspectives



Conclusion

The main objective of the thesis is to explore the potential of transferring the traditional geometric modelling of the built heritage to HBIM. Both the original BIM concept and as-built BIM concept have been widely applied on the built heritage documentation and from generic modelling outlines.

The original BIM concept is consistent with the documentation-based HBIM, which exploits the historic materials to parametrically design the lost and damaged heritage. In our project, HBIM models of two damaged built heritage are created according to the spots and the historical records.

Moreover, BIM software is increasingly supportive of reality-based data and causes a new concept called Scan-to-BIM. Correspondingly, HBIM modelling for the existing built heritage can be created based on the point cloud. In the project, HBIM models of the historic structures, including the St-Pierre-le-Jeune church, façade of the Rohan Palace, and the timber beam frame of Castle of Haut-Kœnigsbourg, are created from the point cloud.

Recent HBIM provide an unified platform for semantic/parametric modelling, 2D/3D visualization, and spatial/attribute database and management of the built heritage. The created HBIM model is a parametric model with semantic and relationship information. It also provides a platform to store, manage and analyze the various attributes, spatial relationships and geometric information. Thus, HBIM can maintain the demand of built heritage reconstruction, management and conservation. Moreover, the HBIM can attach the irregular structure created in computer graphics, the semantic information enriched in ontology, the semantic segmented component using the algorithms in computer science and point cloud processing, and the further structural analysis.

The drawback of the conventional HBIM modelling lies in their time-consuming manual-drawing. The project presented a possibility for the generation of HBIM from the point cloud, surface mesh and solid geometry with reduced human involvement. HBIM modelling process consists of “*Family*” primitive creation and information model

generation. In the project, two types of HBIM models, parametric HBIM and semantic HBIM, from different formats of “*Families*” are created.

The possibility of the proposed concepts of solid-to-HBIM and mesh-to-HBIM to reduce the human involvement benefits from the *Autodesk Dynamo*. *Dynamo*, as an open source graphical programming software, offers designers the ability to interactively design and manipulate BIM elements by programming. The *Dynamo*-based HBIM modelling transfers the parametric “*Family*” and geometric structures to parametric HBIM and semantic HBIM model respectively via *Revit Dynamo* visual programming.

(i) The parametric HBIM modelling process involves manual parametric “*Family*” creation and semi-automated building reconstruction. Starting from the collection of the point clouds and the documentation, related parametric “*Family*” classes are manually created in HBIM environment. Then, the semantic model composed by the parametric elements is generated in an automated way by *Dynamo* visual programming package.

(ii) The utilization of *Dynamo* enables the solid/mesh-to-HBIM process, which directly transfers the segmented solid geometry and closed mesh to BIM environment with reduced manual processing. The obtained BIM “*Family*” and semantic HBIM model, however, has limited parameters and lacks explicit geometric description because the automatic generation from geometry returns to non-editable solid elements. The semi-automated solid/mesh-to-HBIM modelling reduced lots of human works. And the segmented elements can be stored and managed in the BIM environment with attached attributes information and relationship established among the elements.

Generally, for the lost built heritage, there possibly have been built parametric model using the traditional graphic software; for the existing built heritage, current reality-based technique have acquired accurate mesh geometry and pay attention on the automated/semi-automated semantic segmentation. Meanwhile, the HBIM semantic element connected with attribute, material and spatial relationship information provides the base for heritage management, and the parametric geometric description is not always necessary. The solid/mesh-to-HBIM show the feasibility of utilization of *Dynamo* to reduce the human involvement in the process of HBIM modelling from solid elements and mesh geometry.

So it depends on the users’ need. If the user prefers parametric geometry, a complete and personified “*Family*” has to be drawn manually; on the other hand, if the user prefers the original geometry, a semi-automated generation of dead “*Families*” will be a time-saving way.

Future work

Taking the HBIM platform as the core, the integration of other techniques can extend its capabilities dramatically: computer graphics for parametric modelling of complex structures, photogrammetry and computer science for automated semantic segmentation, GIS for spatial information analysis and ontology for heterogeneous semantics management. Although these integrations face the problem of information loss, and *Revit Dynamo* increasingly provide a possible tool to extend the HBIM capabilities in the unified BIM environment.

The future work will be dedicated to the information communication between the HBIM and ontology, improvement of the proposed mesh-to-BIM workflow and the introduction of popular deep learning on the BIM modelling.

Integration of HBIM geometry and ontology semantics

In order to connect the HBIM environment with the knowledge base, particular attention has to be given in creating a correspondence between the ontologies structure and the entities network in the HBIM environment. The combined entity of HBIM and ontology includes both object-oriented information, geometric information, typically found in BIM platform, and semantic information, usually found in ontology modelling systems (Kalay *et al.*, 2014). They are connected via the same labelling of the entity in the two modelling environments. Currently, there are still three ongoing aspects of work that need to be done (Figure 6.2):

(1) Information extraction of semantics and geometry

It is important to conduct the information extraction and query utilizing the semantic ontology. The drawbacks of the ontology analysis come to the requiring of long SPARQL queries to extract relevant information (Quattrini *et al.*, 2017b) and the accessing of the HBIM element. *Revit Dynamo* provides the integration platform, where users can browse the semantic information reserved in ontology database and the 3D model in BIM platform at the same time. The browsing result can be exported as a text file for further application (Lu *et al.*, 2018).

(2) Mapping to the CIDOC-CRM formal structure

The CIDOC-CRM provides ISO standardized definitions as well as a formal structure for describing the implicit and explicit concepts and relationships used in Cultural Heritage

Documentation (Messaoudi *et al.*, 2018). In order to align our work with a wider research community effort, we are dedicated to mapping some classes of our ontology with this standard.

(3) Semi-automated HBIM parametric modelling

Parametric design is applied to complex building form generation, and the current parametric HBIM elements are created in manual-drawing way. *Revit Dynamo* is originally utilized to conduct parametric design and generate complex shapes. The knowledge about the geometric shape and coordinates can be digitalized to ontology formalized format, and there exists the possibility to support the geometric primitive generation and location definition using *Dynamo*.

Automated mesh-to-BIM

The current mesh-to-HBIM process relies on the segmentation in the *Rhino 3D* platform. And then the components can be stored and managed in the BIM environment with *Revit Dynamo* modelling. Therefore, the future work is how to detect the semantic elements based on the point cloud segmentation algorithms, which is expected to replace the processing in *Rhino 3D*.

Considering the complex shapes of built heritage, the ongoing work will first focus on the regular buildings of the 3D city modelling. Semantic segmentation will be firstly applied on point clouds and generate components in mesh format. And then *Dynamo* is utilized to build the BIM models from the mesh geometry. The obtained semantic model will lack of the parametric description of the geometry, but it possess the other properties of BIM.

Combination of deep learning and BIM modelling

The current HBIM modelling is unidirectional procedural rules and few works have adapted the supervised machine learning technique. The similarity between the BIM modelling and machine learning is to classify the similar elements by rule-based description. The developments of machine learning, especially deep learning (Sinha *et al.*, 2016), brings breakthroughs to various information applications. Currently, deep description for volumetric shapes is increasingly developing aiming at point clouds (Qi *et al.*, 2017) and CAD object (Wu *et al.*, 2015) dataset. Under the same architectural style, such as ancient China and Roma, the historic buildings show similar composing elements. That is, a training set is expected if structures of the same style are collected, and it can be used to recognize and even model the heritage. The historic buildings under the same architectural

style present similar features. Once some buildings have been modelled, they could serve as training data and build the corresponding feature library to model similar objects automatically. And this is really accordant with the element “*Family*” based BIM parametric modelling.

Contributions

Publication in the book chapter

Yang, X., Koehl, M., Grussenmeyer, P., Automating Parametric Modelling From Reality Based Data by Revit API Development. *Book Chapter “Latest Developments in Reality-Based 3D Surveying and Modelling”*, 307–325, 2017. doi:10.3390/books978-3-03842-685-1/15

Publications in the international conferences with oral presentations, abstract reviewed proceedings published in the *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*

Yang, X., Koehl, M., Grussenmeyer, P., Mesh-to-BIM: from segmented mesh elements to BIM model with limited parameters, *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2, 1213-1218, 2018. doi: [10.5194/isprs-archives-XLII-2-1213-2018](https://doi.org/10.5194/isprs-archives-XLII-2-1213-2018)

Yang, X., Koehl, M., Grussenmeyer, P., Parametric Modelling of As-built Beam Framed Structure in BIM Environment. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W3, 651-657, 2017. doi: [10.5194/isprs-archives-XLII-2-W3-651-2017](https://doi.org/10.5194/isprs-archives-XLII-2-W3-651-2017)

Yang, X., Koehl, M., Grussenmeyer, P., & Macher, H., Complementarity of Historic Building Information Modelling and Geographic Information Systems. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI/B5, 437-443, 2016. doi: [10.5194/isprsarchives-XLI-B5-437-2016](https://doi.org/10.5194/isprsarchives-XLI-B5-437-2016)

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Modélisation 3D du patrimoine bâti ancien : intégration de modèles géométriques dans un BIM patrimonial

Résumé des travaux en français

1. Introduction

Dans le domaine du relevé et de la représentation, celui du patrimoine bâti a bien évolué au cours de ces dernières années : alors que les supports papiers étaient la règle, les supports numériques prennent aujourd'hui largement le dessus, les dessins 2D sont remplacés par des modèles 3D, la modélisation géométrique s'est enrichie d'informations supplémentaires et a ainsi évolué en modélisation de l'information. Parallèlement à la révolution des technologies de l'information, incluant de nouvelles techniques de modélisation globale de l'information, le BIM (*Building Information Modelling*) s'est développé : il permet de gérer les informations géométriques sous forme de modèles paramétriques, mais également les informations sémantiques en complément d'autres attributs. L'une des applications récentes du BIM se tourne vers la documentation et la conservation du patrimoine. L'utilisation du BIM dans la modélisation du patrimoine correspond à l'un des enjeux et représente l'une des problématiques majeures dans la gestion des bâtiments anciens ce qui a permis de développer le concept de *Heritage-BIM* ou HBIM soit encore la maquette numérique de bâtiments historiques. Les domaines principaux d'application du HBIM concernent la reconstruction du patrimoine tel que construit (TQC) ou encore la reconstitution du patrimoine perdu.

Avec les méthodes traditionnelles nous obtenons des modèles géométriques, dépourvus d'informations sémantiques ou de structures d'informations descriptives, et il est souvent difficile d'y rajouter ou d'y gérer davantage d'informations comme, par exemple, des caractéristiques de construction ou des matériaux. Les relations entre les composants, leurs descriptions paramétriques, leur nature ou encore leurs dimensions constituent, par contre, le cœur du concept BIM. Le BIM permet de constituer un modèle sémantique simultanément au processus de modélisation géométrique. Une structuration d'information reposant sur des relations géométriques et comportant des informations supplémentaires

permettra d'étendre les possibilités de connaissance et d'analyse.

Cette recherche est dédiée à la documentation numérique du patrimoine bâti en utilisant la technique BIM en plein essor. Considérant que le HBIM repose encore fortement sur des méthodes de dessin et de modélisation manuels très chronophages, l'un des objectifs scientifiques de cette thèse consiste à explorer et développer de nouveaux processus de transformation de modèles géométriques en modèles HBIM.

De manière plus précise, les objectifs de cette thèse comprennent (Figure 1) :

- (i) L'exploration des processus généraux du HBIM, y compris du concept de HBIM pour le patrimoine bâti disparu (restitution) et du concept de HBIM-TQC pour le patrimoine bâti encore existant ;
- (ii) La comparaison du modèle géométrique traditionnel au modèle HBIM du point de vue de la modélisation paramétrique et sémantique, des relations et des traitements possibles comme, par exemple, l'analyse structurelle, l'intégration dans un système d'information géographique (SIG) ou encore l'utilisation d'ontologies ;
- (iii) Le passage du modèle géométrique traditionnel vers un modèle HBIM avec comme objectif la réduction de l'implication humaine par le développement d'API et l'utilisation d'une programmation visuelle, par exemple, le langage *Dynamo*.

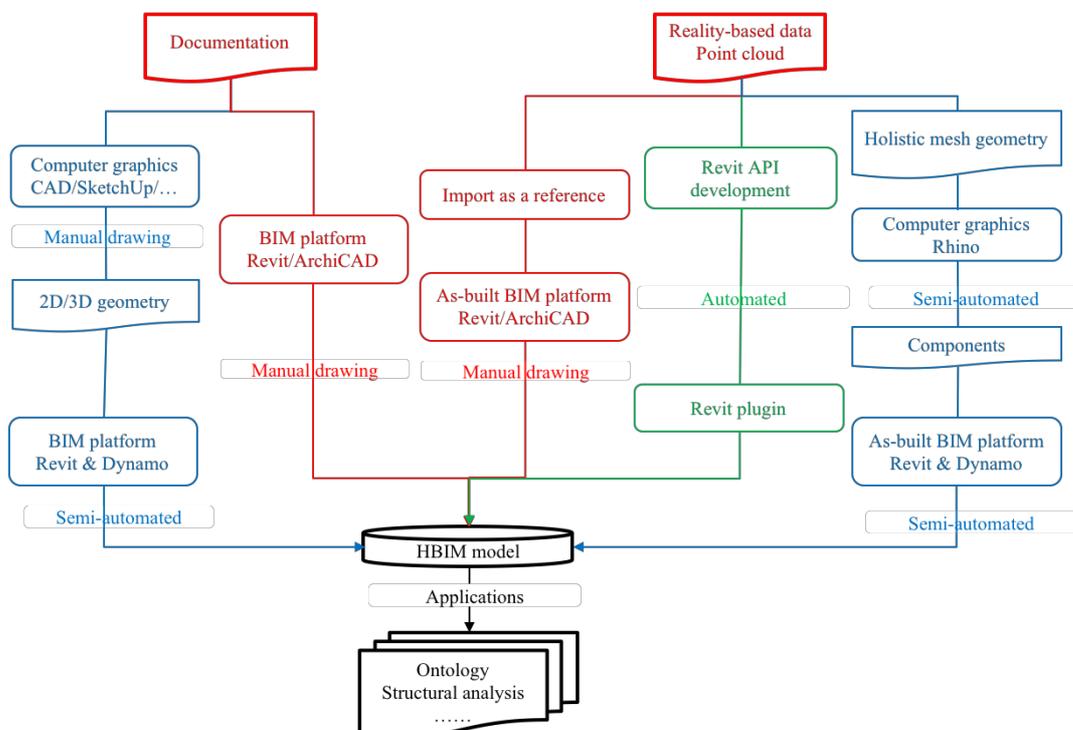


Figure 1. Processus de modélisation HBIM en utilisant des méthodes différentes

2. Méthodologie

L'intégration et la gestion de nuages de points 3D a fait d'*Autodesk Revit* l'un des principaux environnements de modélisation TQC. L'API (interface de programmation applicative) d'*Autodesk Revit* combine les fonctions de programmation et de modélisation paramétrique BIM et offre aux utilisateurs la possibilité de concevoir et de manipuler de manière interactive des éléments *Revit* (familles d'objets constructifs) à l'aide d'algorithmes. *Dynamo* est un *plugin* (module d'extension) intégrable à *Revit*, basé sur l'API *Revit* et proposant un environnement de programmation visuelle. Il est conçu pour étendre les capacités de modélisation paramétrique de *Revit* en y rajoutant un niveau de mise en relation qui n'existe pas dans le logiciel standard, en plus des paramètres de pilotage basés sur des entrées externes issues, par exemple, de données extraites d'une analyse.

Revit et *Dynamo* visent tous deux à créer des bâtiments et structures constructives sous forme de modèles BIM et sont donc également utilisables en HBIM. *Revit* devient une plateforme commune pour la modélisation et la gestion du patrimoine bâti. *Dynamo* est de plus en plus utilisé pour la mise en place de la documentation patrimoniale pour diverses applications comme : (1) la création de géométries complexes, (2) la prise en charge de géométrie volumique, de maillages fermés et le transfert au format *Revit* IFC (*Industry Foundation Class*), (3) la manipulation d'éléments *Revit* par des nœuds intégrés, (4) l'intégration d'éléments géométriques de *Revit* à partir de leur description sémantique basée sur des ontologies, et (5) l'analyse détaillée du modèle HBIM.

Le processus de modélisation paramétrique HBIM repose généralement sur un processus majoritairement manuel. Le développement d'API et la mise en œuvre de la programmation visuelle *Dynamo* peuvent étendre les processus de modélisation HBIM de deux manières : la première est évidemment l'automatisation et l'autre est l'amélioration de la précision. Ainsi, dans cette recherche, nous avons exploré la modélisation HBIM en utilisant le logiciel *Revit*, le développement de l'API *Revit* et la programmation *Revit* *Dynamo* pour :

- (i) Initier les processus HBIM. Les zones d'étude comprennent du patrimoine bâti existant (bâtiment de l'INSA de Strasbourg, façade du palais des Rohan, l'église St-Pierre-le-Jeune à Strasbourg, une partie de charpente historique du Château du Haut-Kœnigsbourg) et deux bâtiments en ruine (Petit Château du Meisenbach et l'église abbatiale de Niedermunster).
- (ii) Expliquer les améliorations apportées par une plateforme de modélisation BIM par rapport à une modélisation géométrique traditionnelle et introduire un plugin développé pour la modélisation HBIM d'une charpente historique à partir d'un nuage clairsemé de

points topographiques.

(iii) Proposer un nouveau processus de passage d'un modèle géométrique (modèle 3D solide et maillage surfacique) vers un modèle HBIM en utilisant le langage *Dynamo*. Le processus maillage-vers-HBIM proposé permet de créer le modèle HBIM en réduisant l'implication humaine.

3. Expérimentations

Nous présentons un cas d'étude pour la production de HBIM à partir du maillage de surface et de géométrie volumique sous forme semi-automatique. Dans le projet HBIM, le processus de modélisation consiste en une création de *Familles Revit* paramétriques et une reconstruction de bâtiment semi-automatisée. Deux types de modèles HBIM impliquant différents formats de *Familles Revit* sont créés. D'une part, à partir de la collecte de nuages de points (acquisition par scanner-laser 3D ou par photogrammétrie) et de la documentation descriptive complémentaire, les classes paramétriques de *Familles Revit* associées sont créées manuellement dans l'environnement HBIM. D'autre part, l'utilisation de *Dynamo* permet la mise en place d'un processus d'entité-vers-BIM qui permet un passage directement d'une géométrie de surface ou de solide vers une structure BIM, le tout de manière semi-automatique. Cependant, les *Familles Revit* obtenues ne comportent qu'un jeu de paramètres limités et manquent de description géométrique explicite car la production automatique à partir de la géométrie ne génère que des éléments complexes fermés non modifiables.

HBIM du patrimoine perdu par *Revit Dynamo* :

La méthode proposée a été mise en œuvre sur deux bâtiments historiques ruinés, un monument antique nommé "Petit château du Meisenbach" (Figure 2) et "l'église abbatiale de Niedermunster" (Figure 3), en Alsace, France. Les éléments paramétriques de structure BIM (colonnes, toits, dalles et murs) sont créés manuellement à partir d'archives historiques complétées d'une numérisation au scanner-laser 3D des structures restantes des ruines (Figure 4 & Figure 5). Une procédure de modélisation semi-automatique a ensuite été conduite sous *Dynamo* pour construire les primitives géométriques associées au modèle sémantique HBIM (Figure 6 - Figure 8).



Figure 2. Le site des ruines (à gauche) et le parc à blocs (à droite) du Petit Château du Meisenbach

Sur le site de Meisenbach il ne subsiste plus que qu'un niveau de blocs de base. Les blocs significatifs ont été inventoriés et rangés dans un parc à blocs pour être ré-enfouis sous terre afin d'en assurer leur conservation. Les différents blocs ont été relevés par voie photogrammétrique pour être modélisés sous forme de nuages de points denses. La transformation des modèles sous forme de nuages de points en modèles géométriques a ensuite été réalisée pour obtenir un modèle 3D exploitable.



Figure 3. Le site des ruines (gauche) et des structures détruites existantes (droite) de l'Abbaye de Niedermunster

Sur le site de Niedermunster il ne reste plus qu'une élévation d'un niveau du massif occidental. Pour tout le reste du site, seuls des éléments du niveau de base sont encore accessibles. Le site a été relevé par un scanner-laser terrestre 3D. Certaines parties aux formes géométriques ont été modélisées sous formes d'objets eux-mêmes géométriques. Les parties ruinées ont été modélisées sous la forme de maillages issus des nuages de points initiaux. Les objets ont été classés sémantiquement selon leur rôle dans la structure de l'édifice.

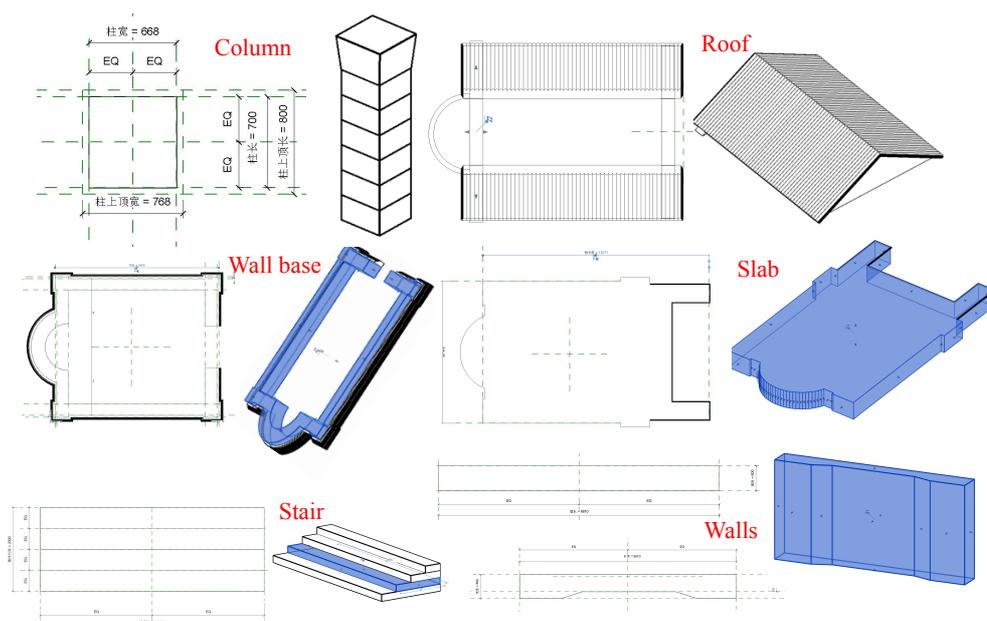


Figure 4. Les primitives paramétriques créées en tant que "Familles" Revit du "Petit Château du Meisenbach"

Les blocs de base ont été modélisés initialement sous *Autodesk Inventor* à partir des relevés effectués dans le parc à blocs. Près de 200 blocs ont été ainsi modélisés. La reconstruction géométrique de l'ensemble de l'édifice a été réalisée selon un schéma de construction paramétrique et comporte finalement plus de 1100 objets individuels. Les différentes contraintes entre les objets ont permis une reconstruction guidée par un archéologue et sa connaissance du site. Pour le transfert sous *Revit*, les objets particuliers ont tout d'abord été transformés en "Familles" de constituants paramétriques (Figure 4). Cette constitution de "Familles" d'objets paramétriques est réalisée manuellement et est nécessaire dans le cas d'édifices non conventionnels, pour lesquels les bibliothèques de constituants n'existent pas. Cette méthode permet par contre la mise en place de bibliothèques d'objets spécifiques pouvant être réutilisées dans le cas de modélisations d'édifice datant de la même époque.

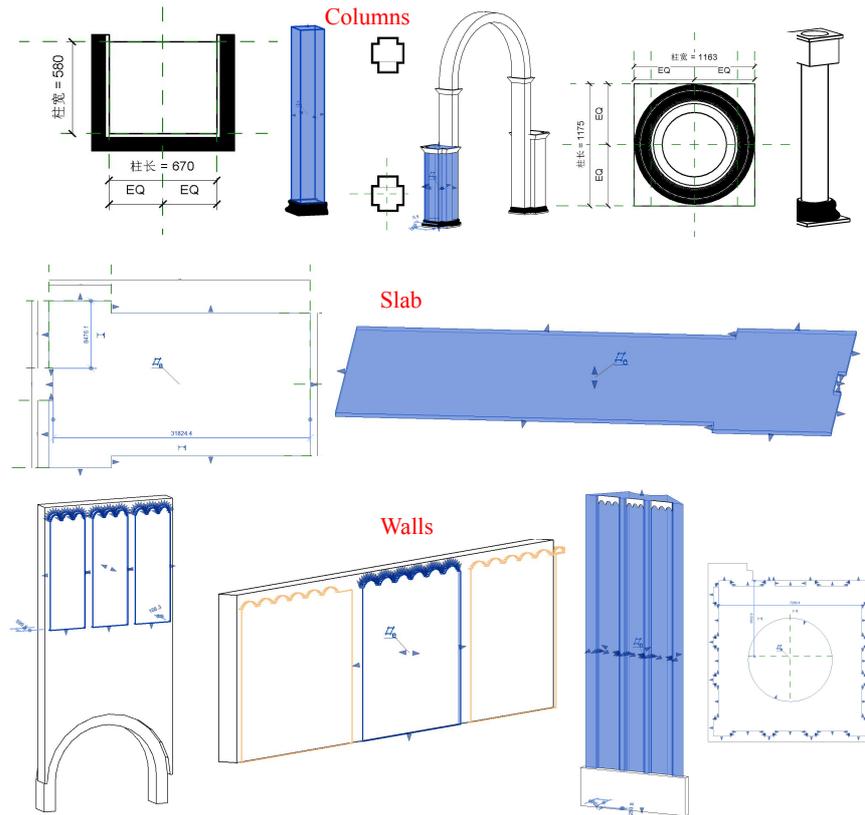


Figure 5. Les primitives paramétriques créées en tant que "*Familles*" Revit de L'Abbaye de Niedermunster

Dans le cas de l'Abbaye de Niedermunster, les parties extérieures ont été modélisées en priorité. Comme une partie du massif occidental est encore accessible sur le site, les murs d'enceinte ont pu être reconstruits avec des détails assez fins. Il n'était pas envisagé de reconstruire l'édifice pierre à pierre, mais plutôt d'en créer un modèle 3D complet pour pouvoir en étudier la volumétrie globale. Ainsi, les "*Familles*" Revit sont constitués d'éléments structurants complets comme des murs avec des décors, des ouvertures, des arcs, des colonnes, etc. Les objets étant guidés par des paramètres, les dimensions les plus probables se basant sur les relevés des restes ont pu être affectées aux différents constituants, ce qui permet finalement d'en obtenir une volumétrie correspondants aux hypothèses émises par l'archéologue en charge du site. La structuration initiale des objets avait été réalisée sous *Sketchup* en utilisant une structure de calques et de composants et sous-composants. Cette structuration a pu être partiellement reprise sous *Revit* tout en restructurant l'édifice en grands ensembles constructifs (Figure 5).

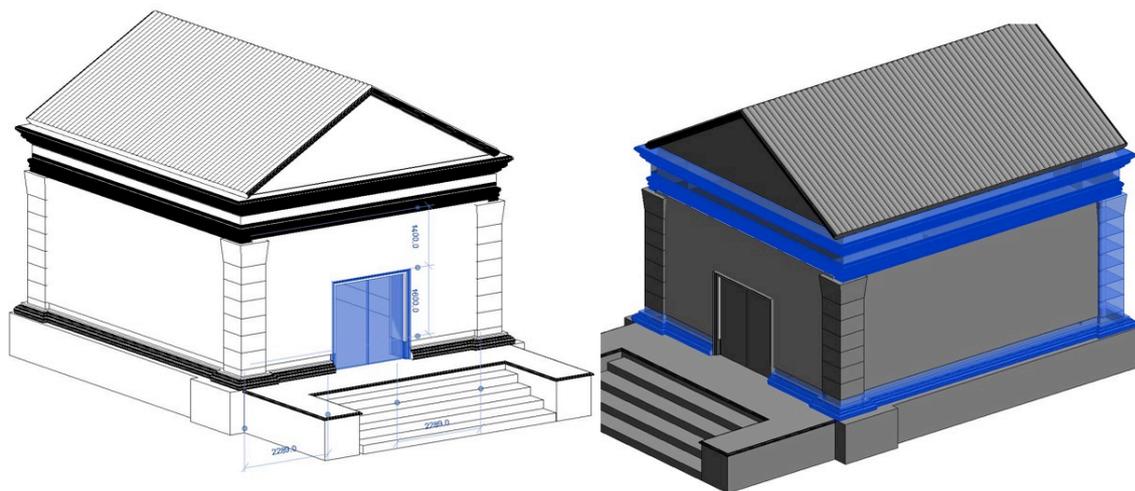


Figure 6. Modèles 3D obtenus à partir de modélisations paramétriques reposant sur des structures ruinées (“Petit Château du Meisenbach”).

Le modèle final obtenu (Figure 6) permet une inspection, une cotation, un dimensionnement voire un redimensionnement des différents constituants.

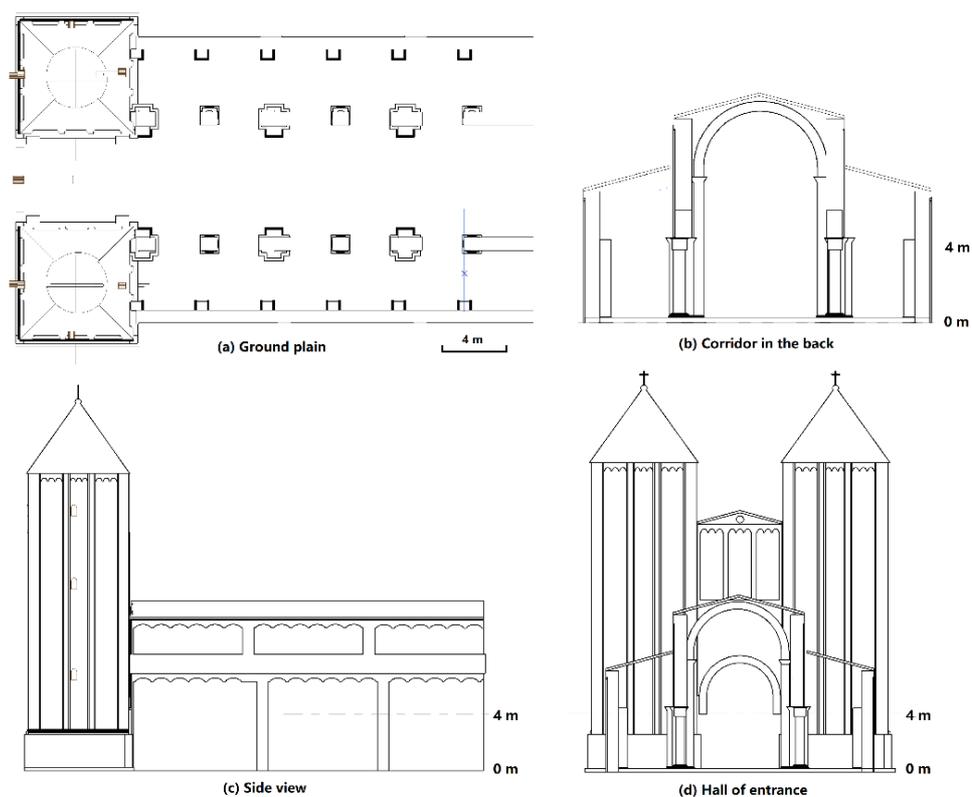


Figure 7. l'Abbaye de Niedermunster en vue 2D

Les éléments constructifs structurants de l'Abbaye de Niedermunster ont été modélisés sous *Sketchup* (avec une structuration en composants et sous-composants) ce qui permet d'en extraire des visualisations, coupes et d'analyser la constitution générale (Figure 7). La Figure 8 montre certaines parties constitutives individualisées sous forme de "Familles". La relation entre les entités et des propriétés (par l'intermédiaire d'une interface) permet d'associer des attributs descriptifs pour caractériser les différents constituants.

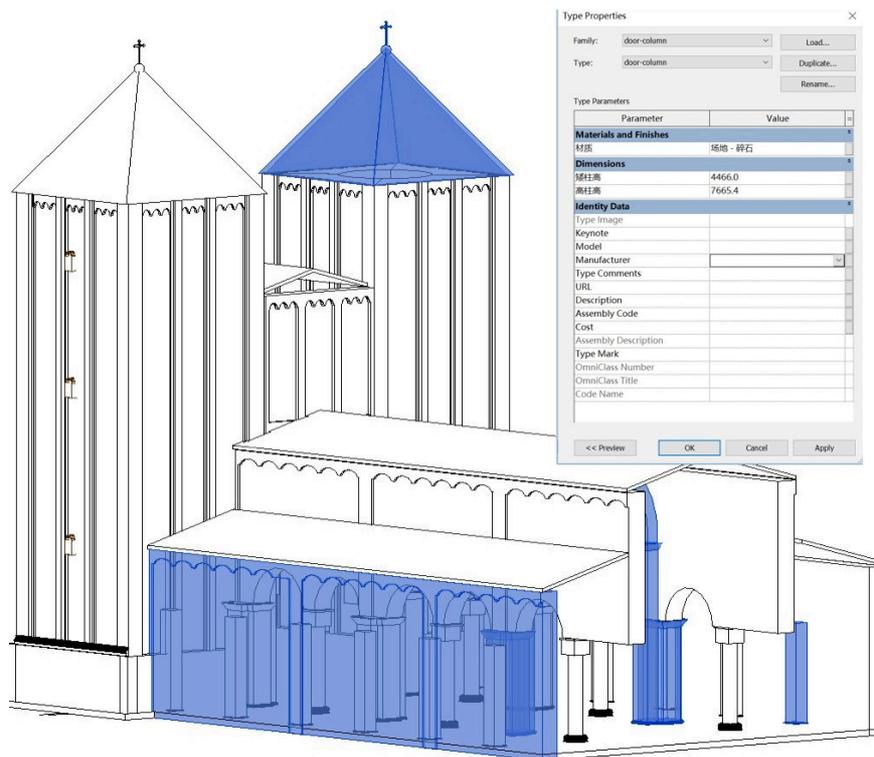


Figure 8. Visualisation 3D du modèle paramétrique HBIM final de l'Abbaye de Niedermunster et ses propriétés éditables

HBIM-TQC à partir de maillage surfacique :

Un nouveau processus maillage-vers-HBIM (*mesh-to-HBIM*) à partir d'un maillage surfacique a été développé pour réduire l'implication humaine dans la reconstruction du HBIM-TQC et comparé au *scan-to-HBIM* (nuage-vers-HBIM), modélisation manuelle traditionnelle basée sur le nuage de points (Figure 10). Deux modèles de HBIM ont été obtenus respectivement à partir du nuage de points – processus *scan-to-BIM* (Figure 11) -, de la géométrie maillée - processus *mesh-to-BIM* (Figure 12)-. Dans le cas du processus *scan-to-BIM*, les éléments paramétriques (colonnes, toits, dalles et murs) sont créés manuellement dans la plateforme *Revit* à partir du nuage de points (Figure 13). Dans le cas du processus *mesh-to-BIM*, les primitives volumiques segmentées sont créées de manière

semi-automatique dans l'environnement de modélisation *Rhino 3D* (Figure 14) à partir de du maillage surfacique et transformées en éléments *Revit* via *Dynamo* (Figure 15). Les modèles HBIM finaux sont générés manuellement à partir d'éléments paramétriques et de primitives solides par programmation *Dynamo*. La modélisation semi-automatique du processus *mesh-to-HBIM* a réduit le nombre d'opérations manuelles. Le modèle HBIM composé des éléments solides est généré de manière semi-automatisée par l'intermédiaire d'un schéma *Dynamo*. Les éléments segmentés peuvent être stockés et gérés dans l'environnement BIM avec des informations d'attributs et des relations associant les éléments entre eux.

Le modèle BIM obtenu ne possède cependant pas de paramètres géométriques, car la génération automatique de "*Familles*" *Revit* à partir du maillage géométrique renvoie des éléments de type solides non modifiables.

Les processus généraux de *scan-to-BIM* et de *mesh-to-BIM* développés sont présentés dans la figure 9.

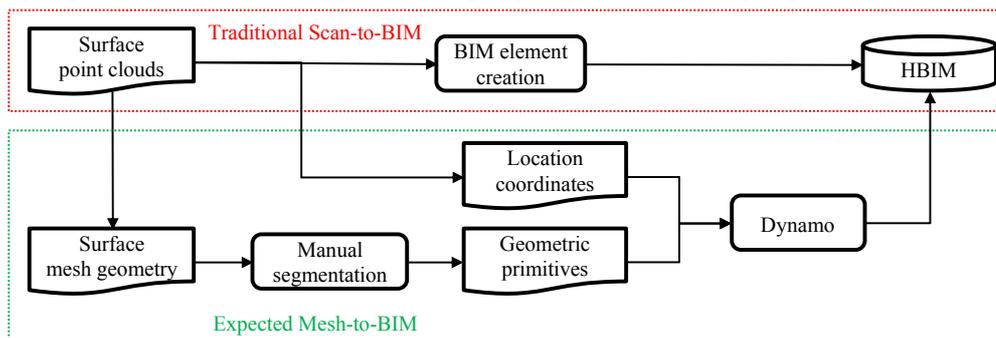


Figure 9 : Processus général du scan-to-BIM et mesh-to-BIM

Les phases principales de ces processus ont été mises en application sur l'exemple de la modélisation de l'église Saint-Pierre le Jeune. À partir d'une acquisition photogrammétrique par drone, complétée par scanner-laser terrestre 3D, un premier modèle sous forme de nuage de points a été généré. Selon le processus *scan-to-BIM*, une modélisation manuelle est effectuée en redessinant les différents composants tout en s'appuyant sur le nuage de points (Figure 11).



Figure 10. Façade principale de l'Église St-Pierre-le-Jeune, Strasbourg - Nuage de points intégré dans *Revit*, (au milieu) et acquis par scanner-laser terrestre 3D et imagerie drone - Maillage (à droite) réalisé dans l'environnement *Rhino3D*.

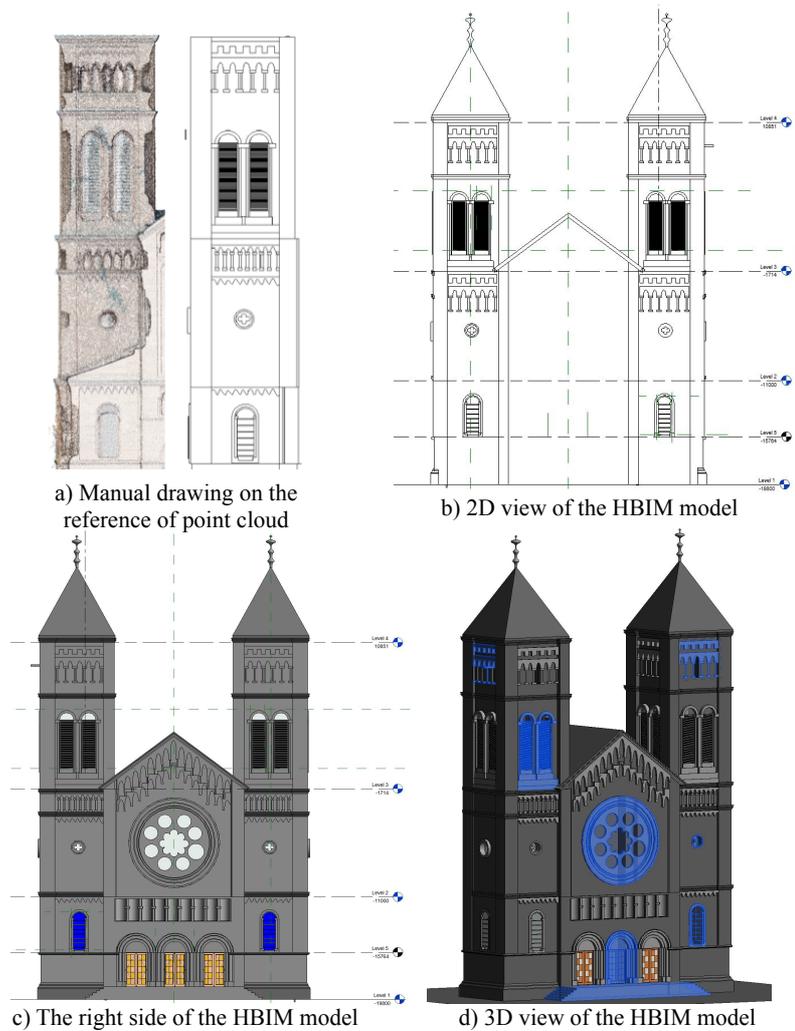


Figure 11. Dessin manuel 3D dans *Revit* à partir d'un nuage de points de référence et modèle HBIM final construit selon le processus *scan-to-HBIM*

Résumé des travaux en français

Ce maillage peut ensuite être transformé en modèle surfacique sous la forme d'un maillage triangulaire. Ce dernier est réalisé sur la plateforme *Rhino3D*. La mise en place de scripts *Dynamo* permet ensuite de segmenter le maillage en composants de même nature et ainsi de structurer le modèle en composants et sous-composants (élémentaires) (Figure 12).

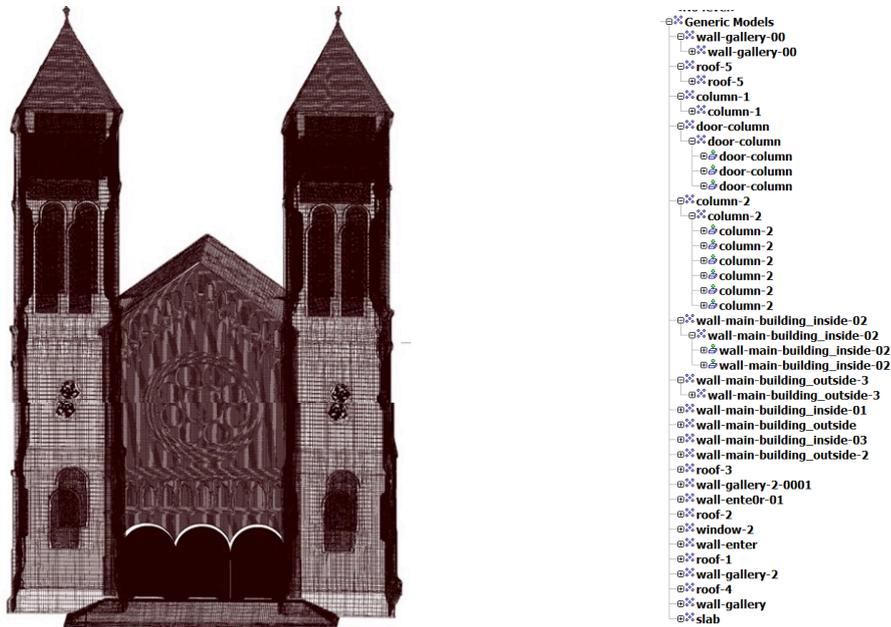


Figure 12. Structuration du modèle HBIM obtenu à partir d'une géométrie maillée traitée par une décomposition en composants élémentaires sous *Dynamo*.

Ces mêmes composants sont à la base de la création de primitives paramétriques sous forme de "*Familles*" *Revit* dont le degré de détails peut être augmenté en fonction des besoins. On retrouvera dans la figure 13 quelques primitives traitées dans ce cas d'étude.

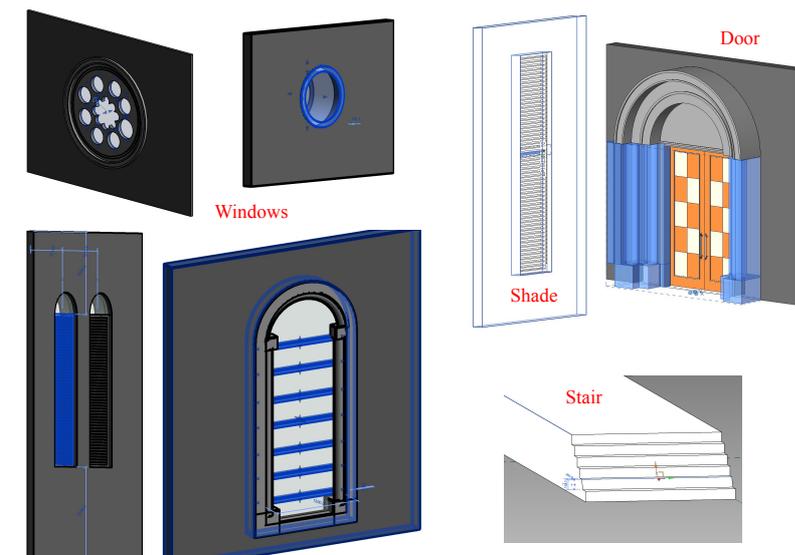


Figure 13. Les primitives paramétriques créées en tant que "*Familles*" *Revit*

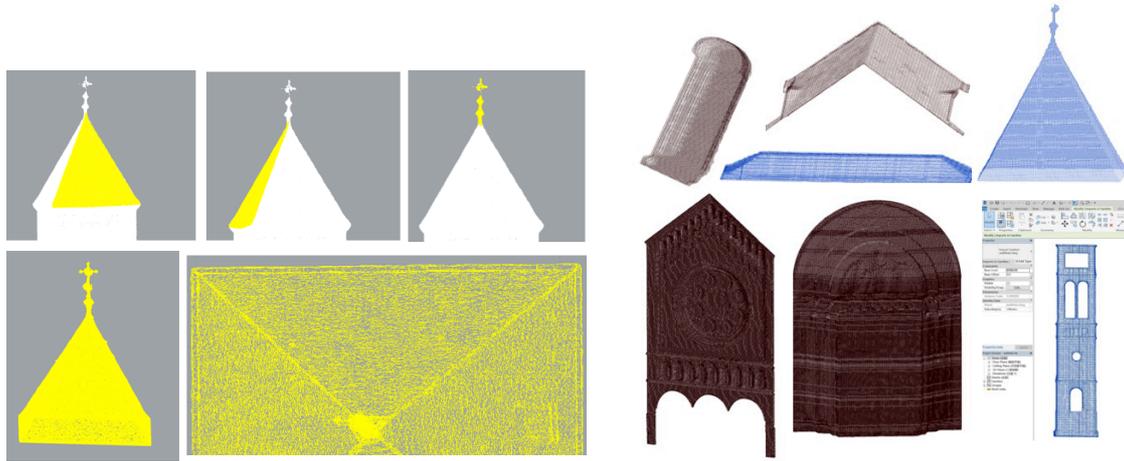


Figure 14. Processus de segmentation supervisée en parties individuelles (à gauche) -
Maillage fermé de composants individualisés (à droite)

Ce processus permet la transformation de maillages en objets. Les différentes parties reconnues en tant que composants individuels peuvent être associées en composants complexes auxquels peuvent être associés des attributs descriptifs complémentaires. Ces géométries complexes provenant de maillages ne peuvent néanmoins pas être transformées en géométries paramétriques car elles reposent déjà sur des géométries fixes.

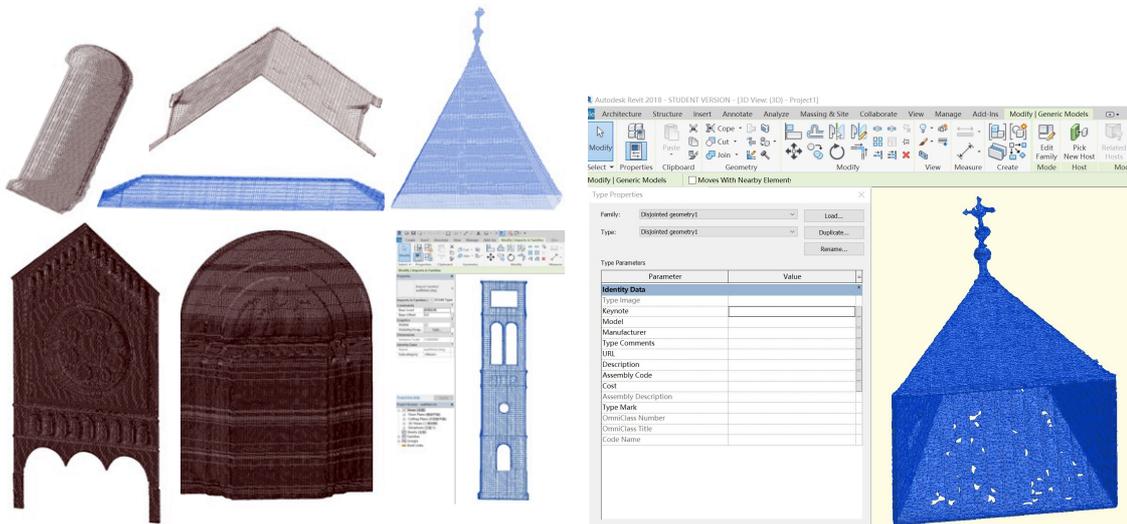


Figure 15. Famille figée de Revit à partir d'une géométrie volumique fermée produite sous
Rhino 3D

4. Conclusion

La modélisation HBIM traditionnelle est conduite de manière totalement manuelle et reste de ce fait très chronophage. Ainsi, nous nous sommes efforcés de réduire l'implication humaine du long processus de dessin manuel dans la modélisation HBIM conventionnelle. Le développement d'API *Revit* et l'utilisation du langage visuel *Dynamo* sont intégrés dans le processus de modélisation HBIM.

La thèse présente des méthodes de constructions HBIM à partir de la documentation historique, de nuages de points (acquis par scanner-laser 3D), de maillage de surface et de géométrie solide. Dans le projet HBIM, la modélisation consiste en la création de "*Familles*" *Revit* paramétriques intégrés dans un processus de reconstruction de bâtiment semi-automatisée.

Deux types de modèles HBIM de différents formats de "*Familles*" *Revit* sont créés: (i) HBIM paramétrique avec des classes "*Familles*" paramétriques créées manuellement, et (ii) HBIM sémantique avec des "*Familles*" *Revit* non modifiables mais directement transformées à partir de géométries maillées ou solides.

Les besoins des utilisateurs permettront ainsi de choisir l'une ou l'autre méthode. Si l'utilisateur préfère la géométrie paramétrique, un dessin manuel de "*Familles*" *Revit* est nécessaire. D'autre part, si l'utilisateur préfère la géométrie de maillage d'origine, le processus *mesh-to-HBIM* permettra d'optimiser les traitements en termes de temps, mais sans pour autant obtenir des géométries paramétriques éditables.

Le processus de transformation de géométries vers des structures BIM a donc pu être développé sous la forme de deux variantes privilégiant respectivement la flexibilité et le réemploi mais nécessitant une modélisation fine sur des bases manuelles, d'une part, ou privilégiant le traitement de masse (nuage de points), plus rapide, tout en fournissant des modèles TQC, dont la géométrie n'est pas éditable, d'autre part.

TRAVAUX PUBLIES LORS DE LA THESE

Chapitre dans ouvrage collectif :

Yang, X., Koehl, M., Grussenmeyer, P., Automating Parametric Modelling From Reality Based Data by Revit API Development. *Book Chapter “Latest Developments in Reality-Based 3D Surveying and Modelling”*, 307–325, 2017. doi:10.3390/books978-3-03842-685-1/15

Actes de colloque avec comité de lecture :

Yang, X., Koehl, M., Grussenmeyer, P., Mesh-to-BIM: from segmented mesh elements to BIM model with limited parameters, *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2, 1213-1218, 2018. doi: [10.5194/isprs-archives-XLII-2-1213-2018](https://doi.org/10.5194/isprs-archives-XLII-2-1213-2018)

Yang, X., Koehl, M., Grussenmeyer, P., Parametric Modelling of As-built Beam Framed Structure in BIM Environment. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W3, 651-657, 2017. doi: [10.5194/isprs-archives-XLII-2-W3-651-2017](https://doi.org/10.5194/isprs-archives-XLII-2-W3-651-2017)

Yang, X., Koehl, M., Grussenmeyer, P., & Macher, H., Complementarity of Historic Building Information Modelling and Geographic Information Systems. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI/B5, 437-443, 2016. doi: [10.5194/isprsarchives-XLI-B5-437-2016](https://doi.org/10.5194/isprsarchives-XLI-B5-437-2016)