Metadata of the chapter that will be visualized online

Chapter Title	Virtual Historic Centers: Digital Representation of Archaeological Heritage	
Copyright Year	2022	
Copyright Holder	Springer Nature Switzerland AG	
Corresponding Author	Family Name	**Murphy**
	Particle	
	Given Name	**Maurice**
	Suffix	
	Organization	Virtual Building Lab
	Address	Dublin, Ireland
	Email	morris.murphy@TUDublin.ie
Author	Family Name	**Fai**
	Particle	
	Given Name	**Stephen**
	Suffix	
	Organization	Carleton University
	Address	Ottawa, Canada
	Email	sfai@cims.carleton.ca
Author	Family Name	**Chow**
	Particle	
	Given Name	**Lara**
	Suffix	
	Organization	Carleton University
	Address	Ottawa, Canada
	Email	lchow@cims.carleton.ca
Author	Family Name	**Meegan**
	Particle	
	Given Name	**Eimear**
	Suffix	
	Organization	Virtual Building Lab
	Address	Dublin, Ireland
Author	Family Name	**Scandurra**
	Particle	
	Given Name	**Simona**
	Suffix	
	Organization	Polytechnic of Milan
	Address	Milan, Italy

	Email	simona.scandurra@unina.it
Author	Family Name	**Pavia**
	Particle	
	Given Name	**Sara**
	Suffix	
	Organization	Trinity College Dublin
	Address	Dublin, Ireland
	Email	PAVIAS@tcd.ie
Author	Family Name	**Corns**
	Particle	
	Given Name	**Anthony**
	Suffix	
	Organization	Discovery Programme
	Address	Dublin, Ireland
	Email	anthony@discoveryprogramme.ie
Author	Family Name	**Cahil**
	Particle	
	Given Name	**John**
	Suffix	
	Organization	Office of Public Works
	Address	Dublin, Ireland
	Email	john.cahill@opw.ie

Abstract

Digitization and virtual representation of archaeology and architectural heritage potentially connects tangible and intangible cultural assets allowing for recording, conserving, and documenting cultural heritage. Process workflow, case study, and design framework are presented for virtual historic centers intended for archiving, storage, and dissemination of heritage knowledge and information. The process commences with remote sensing and data capturing technologies such as terrestrial and aerial laser scanning, Global Positioning System (GPS), and digital photogrammetry. The resultant survey data is enriched with new methods for 3D modelling of historic environments based on heritage geographic information systems (HGIS) and historic building information modelling (HBIM). The enhancement of 3D data with semantic attributes as intelligent virtual representation of historic environments allows multiple user scenarios ranging from engineering conservation to education and knowledge extraction in addition to object visualization. Open access computing systems for large data management and dissemination are now being considered; these are based on game engine platforms and Oracle and PostgreSQL spatial databases, which are used for managing large datasets.

Keywords (separated by '-')

Historic building information modelling - HBIM - Digital surveying - Historic structures - Building conservation - Architectural conservation - Laser scanning - SFM - Photogrammetry - Virtual cultural heritage

Virtual Historic Centers: Digital Representation of Archaeological Heritage

51

AU1

Maurice Murphy, Stephen Fai, Lara Chow, Eimear Meegan,
Simona Scandurra, Sara Pavia, Anthony Corns, and John Cahil

Contents

M. Murphy (✉) · E. Meegan
Virtual Building Lab, Dublin, Ireland
e-mail: morris.murphy@TUDublin.ie

S. Fai · L. Chow
Carleton University, Ottawa, Canada
e-mail: sfai@cims.carleton.ca; lchow@cims.carleton.ca

S. Scandurra
Polytechnic of Milan, Milan, Italy
e-mail: simona.scandurra@unina.it

S. Pavia
Trinity College Dublin, Dublin, Ireland
e-mail: PAVIAS@tcd.ie

A. Corns
Discovery Programme, Dublin, Ireland
e-mail: anthony@discoveryprogramme.ie

J. Cahil
Office of Public Works, Dublin, Ireland
e-mail: john.cahill@opw.ie

S. D’Amico, V. Venuti (eds.), *Handbook of Cultural Heritage Analysis*,
https://doi.org/10.1007/978-3-030-60016-7_51

Abstract

Digitization and virtual representation of archaeology and architectural heritage potentially connects tangible and intangible cultural assets allowing for recording, conserving, and documenting cultural heritage. Process workflow, case study, and design framework are presented for virtual historic centers intended for archiving, storage, and dissemination of heritage knowledge and information. The process commences with remote sensing and data capturing technologies such as terrestrial and aerial laser scanning, Global Positioning System (GPS), and digital photogrammetry. The resultant survey data is enriched with new methods for 3D modelling of historic environments based on heritage geographic information systems (HGIS) and historic building information modelling (HBIM). The enhancement of 3D data with semantic attributes as intelligent virtual representation of historic environments allows multiple user scenarios ranging from engineering conservation to education and knowledge extraction in addition to object visualization. Open access computing systems for large data management and dissemination are now being considered; these are based on game engine platforms and Oracle and PostgreSQL spatial databases, which are used for managing large datasets.

Keywords

Historic building information modelling · HBIM · Digital surveying · Historic structures · Building conservation · Architectural conservation · Laser scanning · SFM · Photogrammetry · Virtual cultural heritage

51.1 Introduction

Virtual historic centers are proposed as dynamic repositories and portals to digitally represent and assemble connected tangible and intangible cultural assets for both historic urban and rural centers. The intelligent digital representation of architectural heritage, archaeology, and objects allows for multiple user scenarios ranging from conservation to education and knowledge extraction in addition to object visualization. The combination of digital recording, modelling, and data management systems enables the interaction with complex, interlinked three-dimensional structures containing rich and diverse underlying data. End users can encompass architectural and engineering conservation, education, and research in addition to public engagement and cultural tourism. It is essential to incorporate within design frameworks international principles concerning authenticity, integrity, and philosophical approaches such as those promoted in ICOMOS Charters [1] (Fig. 51.1). AU2

Initially in this chapter, a state of the art for digital data capture and modelling for virtual representation for archaeology and architectural heritage is presented. One case study is then presented: The Virtual Historic Parliament and Precinct District in Ottawa. The case study presents an ongoing design framework based on data collection and modelling of historic sites and structures using historic BIM. In conclusion, a design framework is presented for systems architecture and workflows for digital representation of virtual historic centers in archaeology and architectural heritage for archiving and storage and dissemination based on game engine platforms.

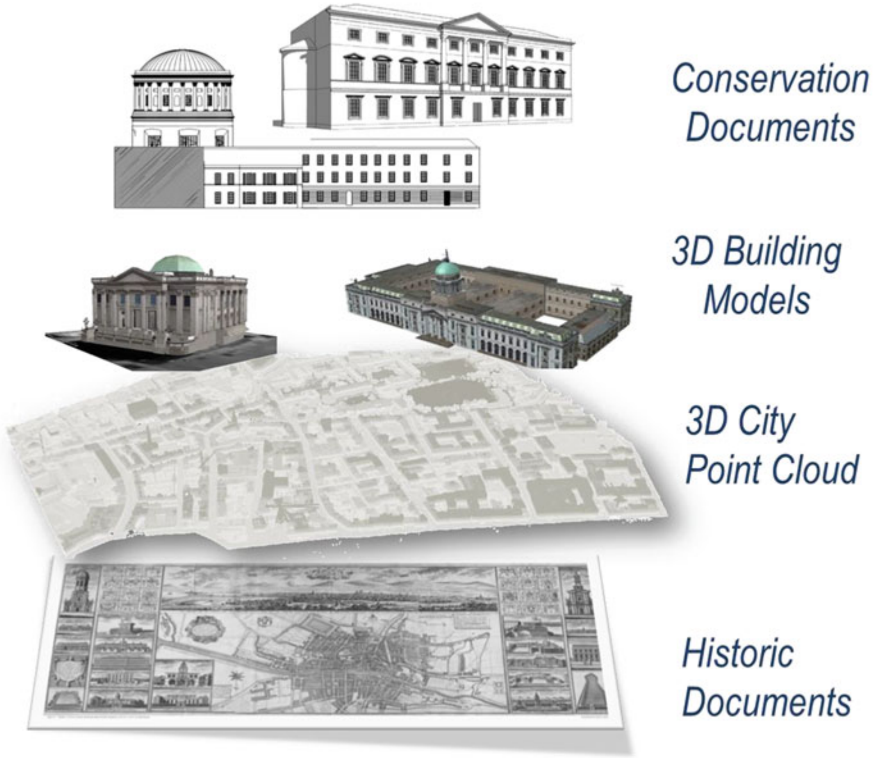


Fig. 51.1 Virtual historic Dublin – digital representation of architectural heritage and archaeology [2]

51.2 Data Collection and Preprocessing

The use of terrestrial laser scanning (TLS), photogrammetry, and traditional surveying techniques in addition to processing the captured data is outlined in this section. At this point, 20 years of research and development have been carried out by scientists and engineers for the application of laser scanning and photogrammetry for digitally recording architectural heritage and archaeology. To understand the current approaches for recording historic assets, it is necessary to comprehend its evolution.

51.2.1 Terrestrial Laser Scanning (TLS)

Terrestrial laser scanning (TLS) captures multiple points using a laser to measure distances and angles from the scanner sensor to an object that is being scanned with millimeter to centimeter accuracies being possible (see Fig. 51.2). TLS operates on AU3 three different principles: time of flight, triangulation, and structured light. All three types of laser scanners produce a 3D point cloud of the object. A time-of-flight scanner uses a laser light probe to detect the surface of an object and determines the distance between the object surface and the scanner through measuring the time from omitting the signal and receiving it when it returns. Angular measurements are recorded on the vertical and horizontal axes for each signal, and the xyz coordinates AU4 are calculated as a single point and collected a point cloud for the scanned object. Triangulation scanners calculate 3D coordinate measurements by triangulation of the spot or stripe of a laser beam on an object's surface that is recorded by one or more

Fig. 51.2 Data capture, terrestrial laser scanner is a device that automatically measures the three-dimensional coordinates of a given region of an object's surface [2]

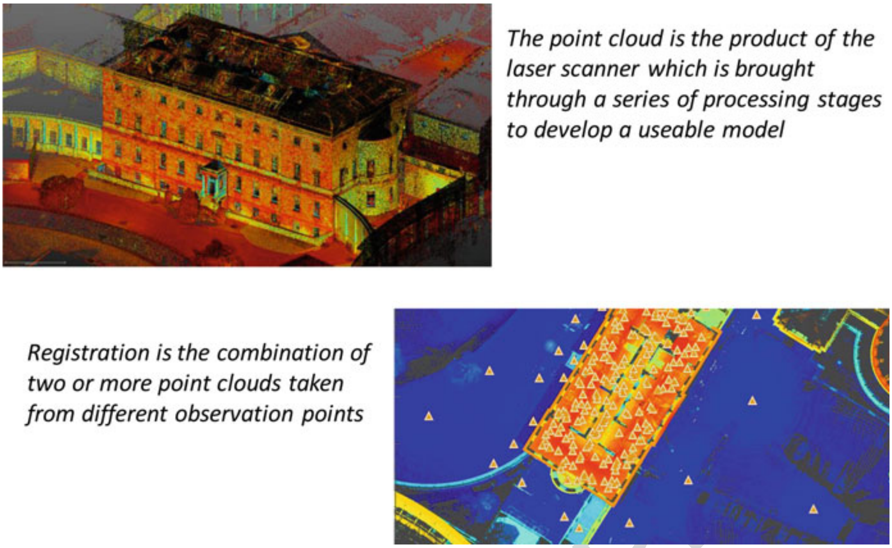
CCD (charge-coupled device) cameras and the sensor. The process of structured light scanning involves projecting a known light pattern onto the subject. The light patterns will deform in relation to the surface of the object. These deformations in light will then be picked up by two cameras placed each side of the light projector. Most modern scanning systems are fitted with a CCD (charge-coupled device) digital camera, and the image data that is captured can be used to color the product of the laser scan survey data (the point cloud). The prime factor in selecting a scanning method is the required accuracy and the distance and size of the object. While time-of-flight method is accurate, it suits measurement and recording of larger objects and environments over large distances. Triangulation and structured light scanners are much more accurate, achieving sub-millimeter accuracies. For smaller and more detailed scans, structured light or triangulation is used. Structured light scanning is fast and very accurate, but this method requires a dark environment to produce the best results (see Fig. 51.3) [3].

Early works include Allen et al. [4], which includes the scanning of Beauvais Cathedral and dealt with issues of point cloud registration. Registration is the combination of two or more point clouds taken from different observation points or the referencing of the scanned object in a global or project coordinate system. This is achieved using tie and control points that are either features of the object (e.g., corners) or special targets (spheres, flat targets with high reflectivity), which are identifiable in the point cloud at the processing stage.

AU5

Software for registering point clouds (see Fig. 51.4) usually facilitates registration by special targets or by overlapping point clouds or a combination of both [3]. In the case of large structures where the placing of targets is not always possible, known features on the object are used to fully transform and align the scans [3]. GPS can determine the coordinates of the laser scanner position allowing for the scans from

Fig. 51.3 For higher accuracy, the process of structured light scanning involves projecting a known light pattern onto the subject, Corinthian Capital Survey, Four Courts Dublin [2]



The point cloud is the product of the laser scanner which is brought through a series of processing stages to develop a useable model

Registration is the combination of two or more point clouds taken from different observation points

Fig. 51.4 Registration – the combination of two or more point clouds [2]

each position to be brought into a common frame of reference in a global or project coordinate systems. Alternatively, registration by cloud matching is carried out by selecting a pair of partially overlapping scans and transforming one scan into alignment with the other using appropriate algorithms [4]. Early work [5] developed protocols for cleaning and removing erroneous data or artifacts such as reflections of the scan through objects before point clouds are registered. Once identified, reflections from objects in the background and in the space between the scanner and object, e.g., trees and other objects in the foreground, moving persons, or traffic and atmospheric effects such as dust, can be dealt with.

Early research also resolved issues of accuracy of laser scanning concentrating on smaller cultural objects, which require very high scan resolution. This is best illustrated by Stanford University and the University of Washington [6] in the digitizing of the sculpting of the Renaissance artist Michelangelo. The triangulation scanner at a resolution of 1/4 mm captured detail of the geometry of the artist's chisel marks. The problems of random errors and object occlusion in the laser scan survey can be greatly reduced by integrating other survey data. In addition, the level of detail can be enhanced for smaller features by introducing independent data collection based on digital photo modelling. Ground truth using other precise surveying instruments (e.g., total station) should be established and collected during the survey process to evaluate the accuracy of the laser and image survey data [3, 6–9].

The product of terrestrial laser scanning (TLS) is point clouds and in some cases registered images, and these require processing steps in order to generate products that can be used to create 3D CAD models. Data processing stages include segmenting point clouds and filtering out unwanted data. Automatic triangulation of 3D points can also be carried out to create a mesh surface model from the 3D point

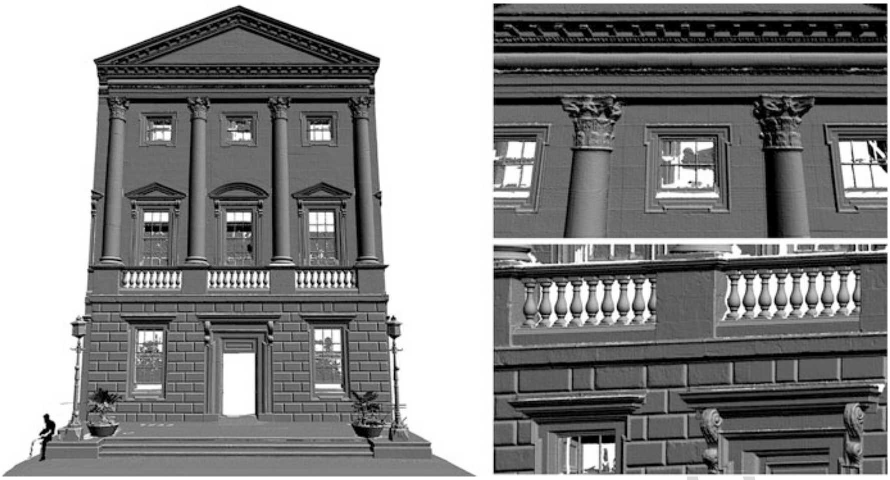


Fig. 51.5 Mesh surface model from 3D point cloud – Leinster House Dublin [2]

cloud. This 3D mesh surface model (see Fig. 51.5) can then be used to generate orthographic images by combining the 3D surface model with 2D images. 3D mesh models can also be textured using referenced image data. 2D cut sections and 3D vectors can also be generated from the 3D point cloud or 3D surface model. Research over the last 20 years includes validation and identification of the most efficient and accurate processing pipeline and established good practice for determining accuracy and registration of scans and the potential for documentation of cultural heritage objects [10–15].

51.2.2 Photogrammetry

Photogrammetric techniques use images taken at different viewpoints to record the 3D geometry of a building or object. Low-cost digital cameras, powerful computer processing, and the greater availability of commercial and open source photogrammetric software have changed the availability and use for photogrammetry. Digital photogrammetry can provide a point cloud, 3D solid model, and texturing based on high-quality imagery and color information. Modelling of large areas, buildings, and small objects can be produced by either aerial or close range (ground-based) photogrammetry. The main principles of digital photogrammetry are based on triangulation where lines of sight (rays) from two different camera locations are located on a common point on the object. The intersection of these rays determines the three-dimensional location of the point. Using this technique with two images is known as stereophotogrammetry, and where multiple images and camera positions are utilized, this is described as structure from motion. The term bundle adjustment is used to concurrently compute all the unknown parameters. The outputs from photogrammetric surveys are identical to products obtained from laser scanning and

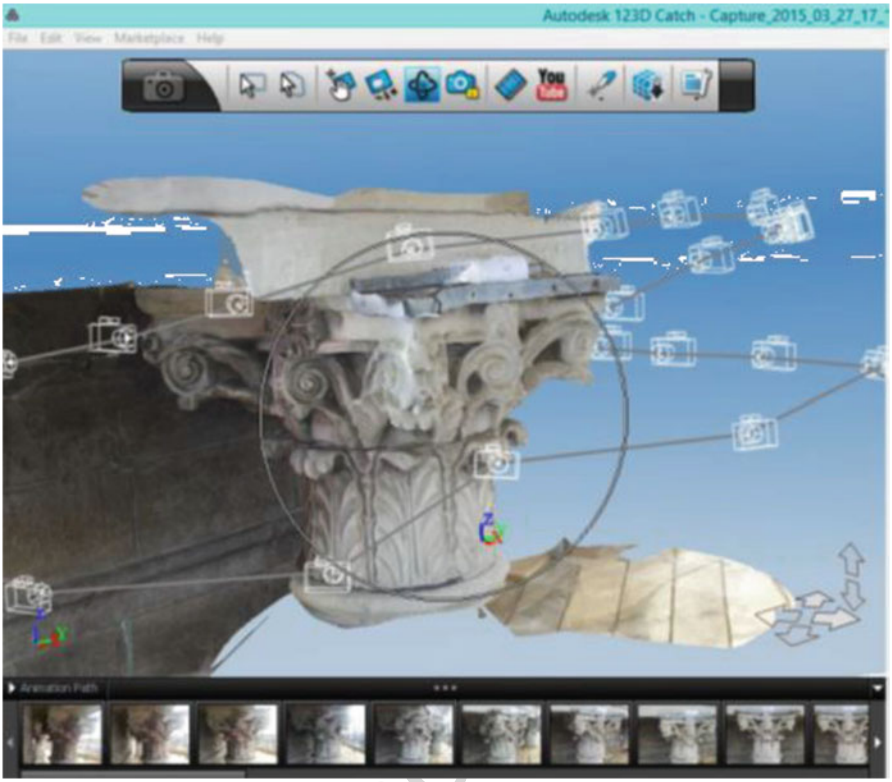


Fig. 51.6 Digital data capture using photogrammetry structure from motion [2]

include orthographic images, point clouds, triangulated surface models, and also textured surface models [16].

Low-cost digital photogrammetry is based on hardware for data capture such as SLR digital cameras or in some cases off-the-shelf cameras. The acquired data is then processed, fused, and integrated using state-of-the-art photogrammetric and computer vision algorithms, which are readily available with software platforms Autodesk ReCap, Agisoft PhotoScan, Microsoft Photosynth, Micmac, Pix4D, etc. Geo-referencing image-based approaches are gaining momentum because they are much more cost-effective than laser-based or structured light scanning methods. No expensive equipment is required, but off-the-shelf digital cameras or even mobile phones and tablets can be appropriate to obtain 3D models from photo sequences. Single objects or small monuments can be acquired with a handheld camera [10] (Fig. 51.6).

Postprocessing for close range digital photogrammetry includes stereo processing and multi-convergent processing (bundle adjustment). Common processing stages include selecting common feature points between images, calculating camera positions, orientations, distortions, and reconstructing 3D information by intersecting feature point locations [12, 13]. Improving accuracy requires human interaction in the preprocessing of image data, for example, the introduction of object measurement coordinates and scaling for real-world metrics.

51.2.3 Other Survey Techniques

Traditional survey equipment such as total stations and GPS/GNSS equipment can provide very accurate measurements. These tools are much slower for data capture as each individual point is manually recorded. For large cultural heritage projects, millions of points are often required to accurately record a complex building or structure. Total station and GPS/GNSS methods can be employed to record accurate control points needed for registration of point clouds or ground truth data for confirming accuracy.

51.3 Historic Building Information Modelling and GIS (HBIM and HGIS)

Building information modelling (BIM) was developed for the design, build, and future management of new buildings and facilities. In BIM, the production of virtual models can automatically generate not only standard drawings and schedules but also provides for structural, economic, energy, and project management analytical data. BIM can automatically create cut-sections, elevations, details, and schedules in addition to orthographic projections and 3D models (wireframe or textured and animated). All these views are linked to the 3D model and automatically update in real time, so if a change is made in one view, all other views are also updated. This enables fast generation of detailed documentation required in the architecture engineering and construction industries [12–15].

Applying BIM for historic structures involves initially data capture of the geometry and texture for the structure using laser scanning or digital photogrammetry and converting the digital survey data to solid building information models (BIM). Two problems exist for researchers in generating historic BIM; the first is the absence of complex historic architectural elements in existing BIM libraries, and the second is a system for mapping the objects onto remotely sensed survey data. While these problems were initiated by the developments of historic BIM (HBIM) carried out in Carleton University and the Technological University of Dublin, research in HBIM is now extensive across the heritage research sector [17–23]. More recent work concentrates on automation in detecting objects and features in point clouds for improving the current slow process of converting unstructured point clouds into structured semantic BIM components [24–28] (Fig. 51.7).

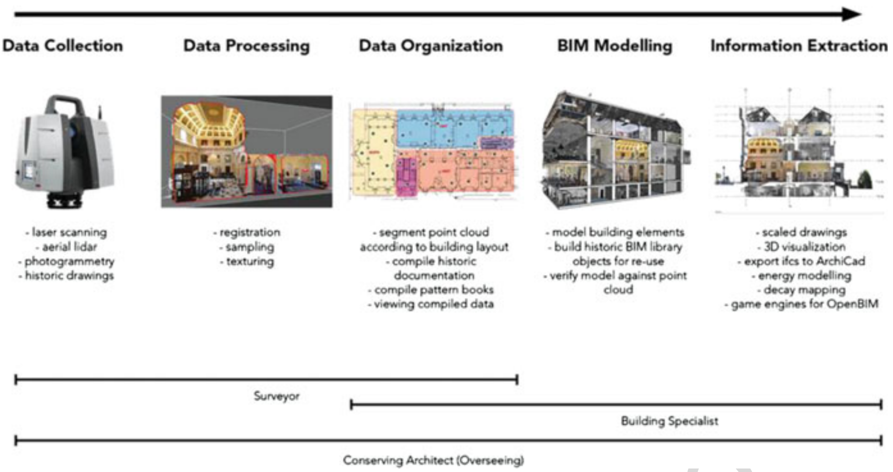


Fig. 51.7 The scan to historic building information modelling stages [2]

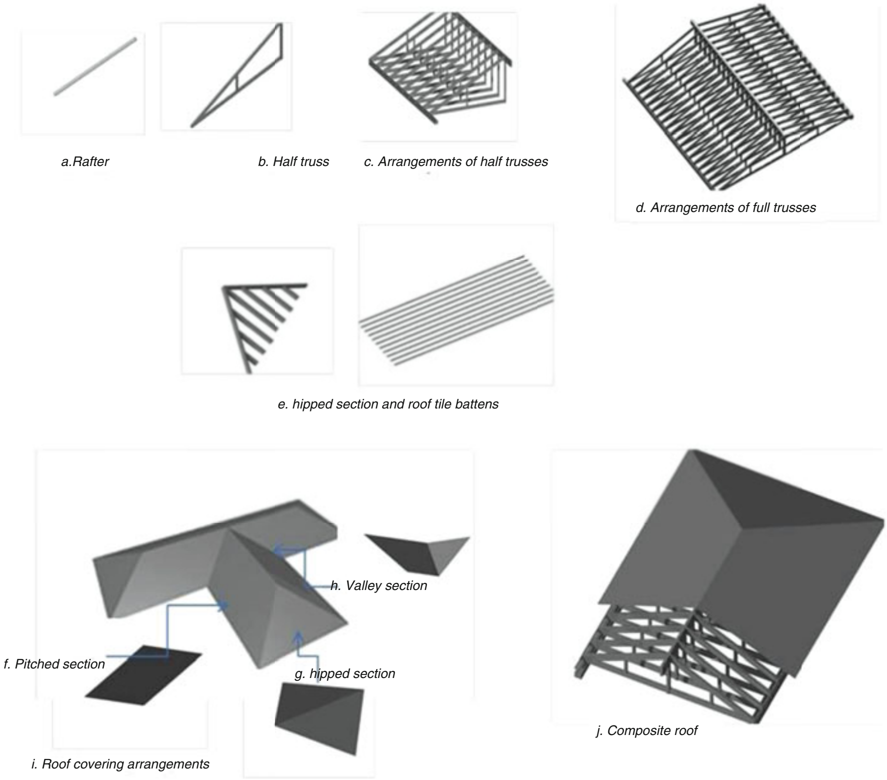
51.3.1 Parametric Modelling

While BIM evolves from 3D CAD principles, its novelty is built on both feature-based modelling and parametric modelling. Feature based is an object-oriented approach where in addition to geometry, objects are intelligent and exist in a database or library with semantic attributes, i.e., a door objects or window objects, etc. In addition, the objects are coded to interact spatially; for example, if an object is revised in plan, it will also change to the new value in 3D and in other orthographic iterations. Objects also interact with each other; for example, a door or window placed in a wall will cut an opening in the wall.

Parametric-based design is based on variable values such as dimensions, angular, AU6 and location, which can be revised for mapping and fitting within the point cloud or image survey. An object is created in relation to other objects in its class; for example, if the length or angular value for an element is revised, the other dependent elements will change to accommodate this. The rules that control the parameters can also assign operations to objects such as scale, extrude, revolve, and hide. These AU7 rules can be added, modified, or removed as and defined. Parametric library objects (such as doors or windows) allow objects to be reused multiple times in a model or in many different models with varying parameters. This approach is very efficient for modelling elements that are repeated but may contain geometric variation between different instances [12–15, 17, 20] (Fig. 51.8).

51.3.2 Automatic HBIM Generation from Point Clouds

Object recognition and feature extraction from an unstructured point cloud are being developed by researchers as an automatic process for the automatic generation of



AU18 **Fig. 51.8** Parametric roof model; the figure above illustrates the initial extruded rafter, which is combined with other elements to build the hipped roof; each element can be changed in shape position to create different iterations for many types of roofs [2]

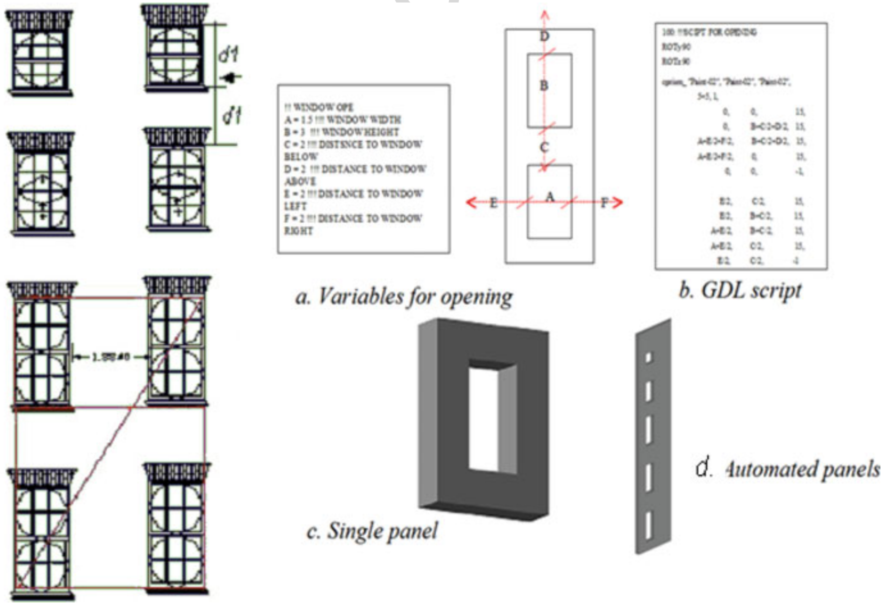
structured BIM models from the point cloud data, [27–31]. By identifying automatically distinguished elements such as planes, surface models, openings, and 3D vectors from point cloud survey data, these objects are used as basis to plot the HBIM. The extracted objects are attached with semantic attributes and can also be converted into parametric building components, but this process requires human interaction. Historical architecture and archaeology contain complex shape, and geometry and decay require human intervention, which cannot be replicated by a machine [24].

51.3.3 Procedural Modelling

Perhaps more promising for historic architecture and archaeology are the approaches of procedural modelling where generation of 3D objects and 2D shapes is based on computer algorithms and rules introduced by the user to generate automatically buildings and spaces from a grammar and vocabulary of shapes. Procedural modelling was originally developed for film and gaming industries and later adapted in GIS as CityEngine platform applied procedural modelling techniques for existing buildings [25, 32–35]. While the automatic generation of building is generated by rules that are initially defined by the user, unfortunately, the application of procedural modelling for converting laser scan surveys to historic BIM has limitations. Converting laser scan surveys to BIM requires human interaction to distinguish the variances and complexity of historic architecture and archaeology which the machine cannot identify without human supervision.

51.3.4 Semiautomatic Procedural Modelling

In the work of Dore et al. [27], procedural modelling rules are developed in HBIM environments to accelerate the mapping process of parametric objects onto point clouds. *Geometric and feature information is detected in point clouds and used as input for developing parameters for the intelligent library objects, which represent the architectural elements of buildings*. In the case of historic structures, when decorative features are striped from buildings, the facades and roof structures are made up of much simpler geometric shapes. For example, a facade to a building consists of the wall structure with openings that are cut into the wall, and the openings contain doors or windows. In Fig. 51.9, a typical classical building facade



```
!! WINDOW OPE
A = 1.5 !!! WINDOW WIDTH
B = 3  !!! WINDOWHEIGHT
C = 2 !!! DISTSNCE TO WINDOW
BELOW
D = 2 !!! DISTANCE TO WINDOW
ABOVE
E = 2 !!! DISTANCE TO WINDOW
LEFT
F = 2 !!! DISTANCE TO WINDOW
RIGHT
```

a. Variables for opening

b. GDL script

c. Single panel

d. Automated panels

Fig. 51.9 Procedural modelling for a typical classical building facade [2]

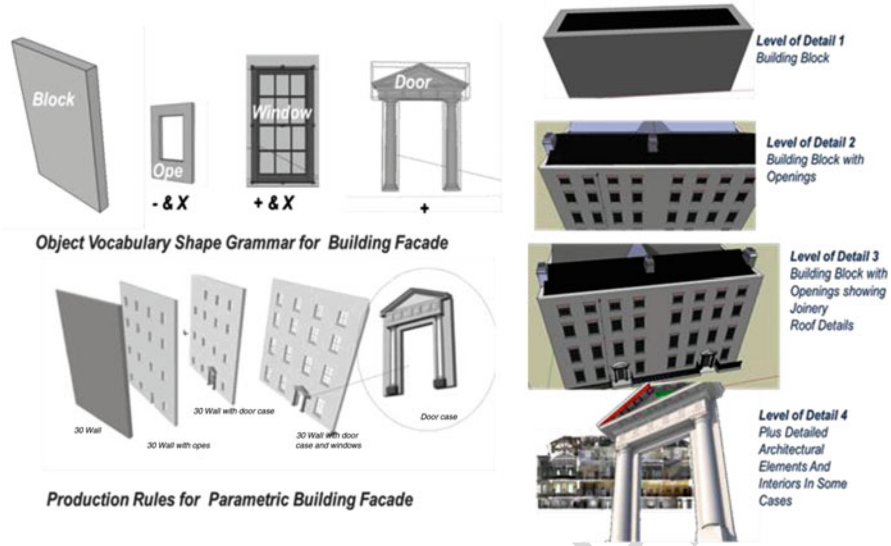


Fig. 51.10 Shape arrangement for facade generation based on procedural rules [2]

stripped of ornament is illustrated; this consists of a panel with two large windows, one medium and one small.

In Fig. 51.9, detail a illustrates the variables to establish geometric parameters, and detail b shows a partial GDL script for implementation for the variable geometry to build a wall panel. A single panel is constructed in Fig. 51.9c and finally a series of sub-routines, which brings the opening panels together to automate the panel with a set of openings, and these are brought together to form the panel facade. Further detail can facilitate the single panels to be adjusted for any opening size or distance between openings.

In Fig. 51.10, the final shape vocabulary and arrangements for forming a historic structure are illustrated on the left side of the figure. The basic elements that make up the vocabulary of shapes include blocks forming walls, window openings, and window and door joinery as infill tiles; a panel containing a door opening. Additional AU8 library objects relating to a door and door case such as columns and pediments are AU9 linked with this shape their respective shapes. The block forms the walls of the structure, openings are cut and multiplied, and windows and doorcases are added to openings. On the right side of Fig. 51.10, the levels of detail are based on initially the block representing the walls followed by LOD 2 where openings are cut; building elements in LOD 3 are then added, for example, joinery, roof, classical details, etc. Shape elements to create detail for ashlar stone, moldings, and another wall geometry are added in LOD 4. A more detailed classical shape grammar and vocabulary is detailed in Fig. 51.11.

The shape grammars can be applied to form numerous facade arrangements with variable values controlling dimensions and object position in 3D space [25].

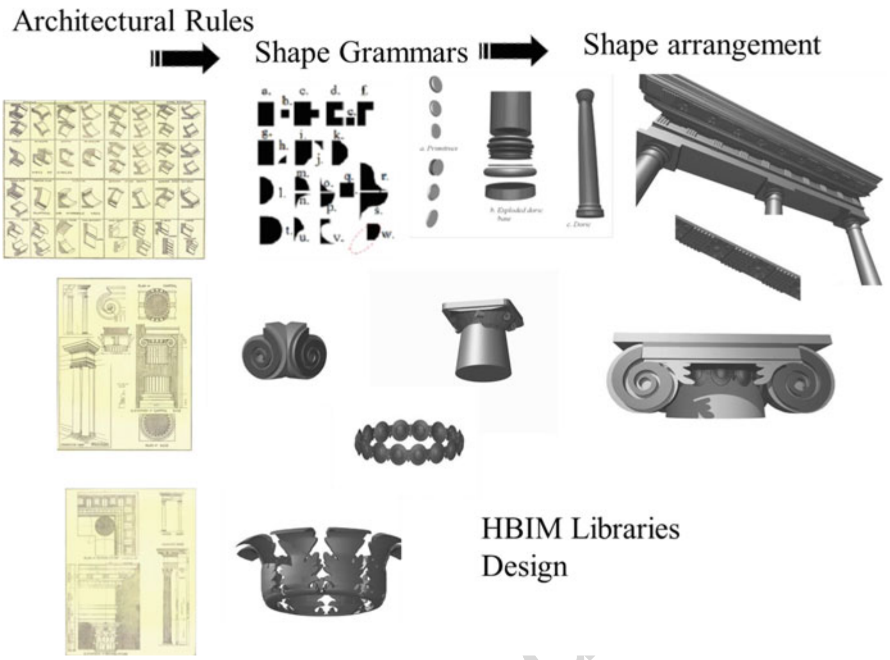


Fig. 51.11 Shape rules, grammars, and arrangement [2]

Classical orders formulated the rules which govern the distribution and combination of parts and resulted in what is described as a grammar of ornament and composition. The elements (moldings, profiles, symbols, etc.) make up the architectural vocabulary. The rules of classical architecture can be described as a grammar. Shape grammars introduced the concept that buildings are based on different architectural styles and can be divided and represented by sets of basic shapes, which are a limited arrangement of shapes in three-dimensional Euclidean space. These shapes are governed by replacement rules whereby a shape can be changed or replaced by transformations and deformations. The shape commands combined with a library of primitives allow for all configurations of the classical orders in relation to uniform geometry. Nonuniform and organic shapes are developed through a series of procedures using deformation and Boolean operations while attempting to maximize parametric content of the objects. These shapes are stored as individual parametric objects or combined to make larger objects in a library. When the parametric objects are used in the historic BIM platform, they can be transformed and deformed to match real-world requirements. In Fig. 51.11, the architectural rules are represented by architectural manuscripts on the left in the figure. In the center of the figure, shape grammars consist of vocabularies of primitive shapes that are combined using operations such as extrude, combine, replace, and deform to create library objects. The library objects are mapped onto the survey data according to the conditions for final shape arrangement [25].

51.3.5 Historic BIM Documentation

Laser scanning and photogrammetry surveying systems for cultural heritage objects emphasize the collection and processing of data. As a result, the output is the accurate 3D model mainly suitable for visualization of a historic structure or artifact. On the other hand, BIM software platforms can automatically create cut sections, details, and schedules in addition to orthographic projections and 3D models (wire frame or textured and animated). The documentation for conservation of objects is achieved through producing 2D and 3D features, plans, sections, elevations, and 3D views. Conservation documentation can be automatically generated from completed HBIM models. Where conservation or restoration work is to be carried out on an object or structure, conventional orthographic or 3D survey engineering drawings are required (Figs. 51.12, 51.13, and 51.14).

51.3.6 LOD AND LOA Specifications for HBIM

Existing standards for new buildings have not addressed the challenges for BIM in the context of architectural conservation or rehabilitation. Literature reviews concerning HBIM have recognized the limited application of BIM for existing buildings. Since then, the application of and literature on BIM for historical buildings has been increasing rapidly. However, one of the fundamental problems, as outlined by several reviews, is the lack of agreed-upon HBIM standards and

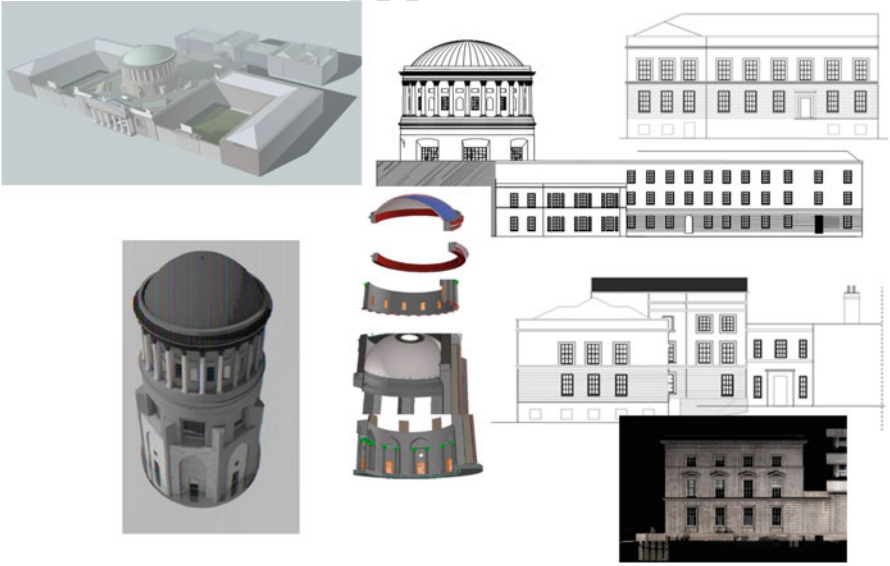


Fig. 51.12 HBIM documentation, ortho projects, and 3D details [2]

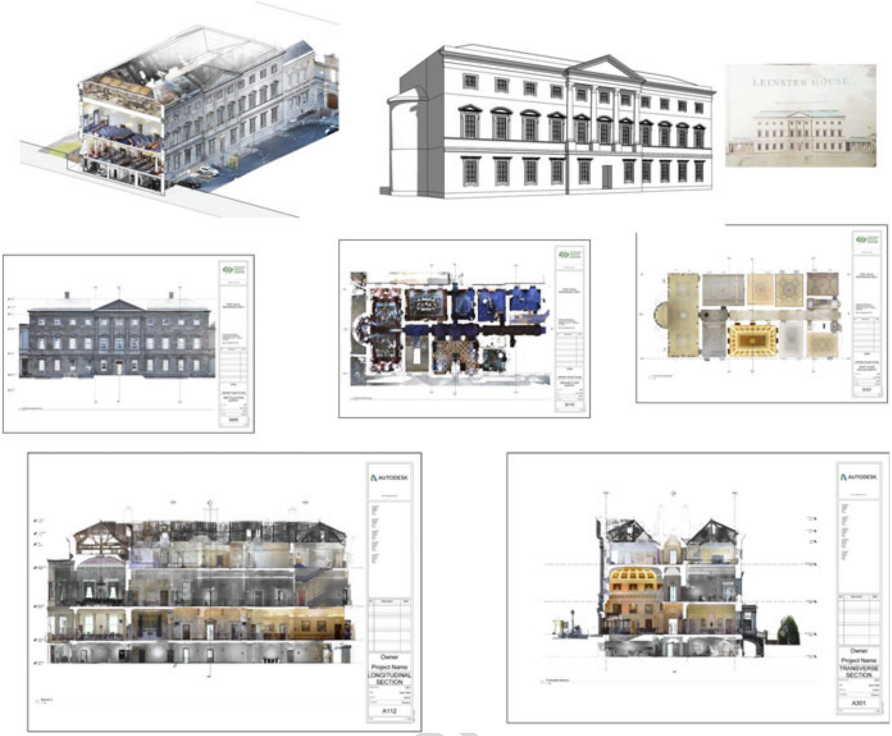
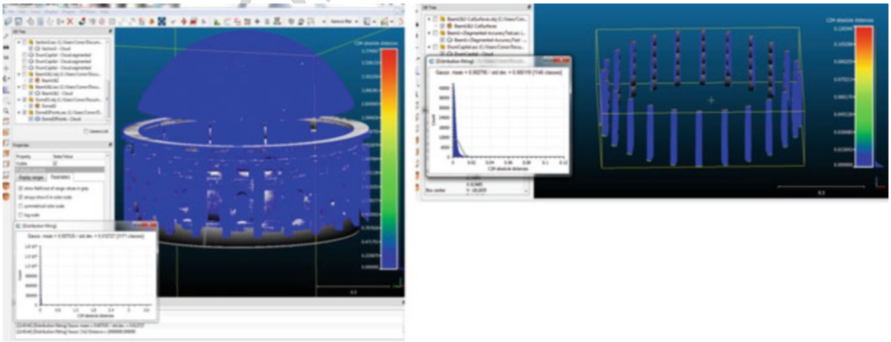


Fig. 51.13 HBIM documentation combining scan and HBIM [2]



AU19 **Fig. 51.14** Accuracy measurement documentation – comparing HBIM and point cloud [27]

classifications. Further detail concerning level of detail is discussed and illustrated in the following case study: the HBIM of Ottawa Parliament Precinct [23].

51.4 Case Study: Virtual Historic Parliament and Precinct District in Ottawa

In 2012, Public Services and Procurement Canada (PSPC) and Carleton Immersive Media Studio (CIMS) began a research partnership to explore the application of digital technologies for architectural rehabilitation and heritage conservation. Our research has focused on the Parliament Buildings National Historic Site of Canada and has explored: methodologies for digitization (integrating photogrammetry and terrestrial laser scanning), building information modelling of historic structures (HBIM), digitally assisted fabrication (robotic milling and 3D printing), and digitally assisted storytelling (web, mobile, and virtual and augmented reality).

In this section, the focus is placed on the evolution of our BIM practices on Parliament Hill stemming from the research initiative with PSPC, and more specifically the challenges in selecting the appropriate level of detail (LOD) and level of accuracy (LOA)/model tolerance are addressed. Establishing an appropriate LOD and LOA is a crucial decision in defining the scope of a BIM project as it has a significant impact on model use, efficiency, and management. However, the complex geometry and deformations often found in existing and historical buildings make it difficult to adopt existing BIM standards that have been developed for new construction. Our study will revolve around three of the four heritage buildings situated on the Hill – West Block, Centre Block, and the Library of Parliament. A detailed analysis of the scope of the project, data management practices, and modelling methodology will demonstrate an evolution of modelling practices and workflows leading to best practices and lessons learned.

51.4.1 Canada’s Parliament Hill National Historic Site

The Parliament Hill National Historic Site of Canada is comprised of the Centre Block, East Block, West Block, and the Library of Parliament and is Canada’s most recognized national monument. As both the political and symbolic locus of Canada’s parliamentary democracy, the site is in every sense a stage where Canada’s nationhood is played out for national and international audiences. Construction of the Parliament Buildings began in 1859, and in 1866, they were officially opened to the public. In 1916, tragedy struck when the original Centre Block building was destroyed by fire. Reconstruction of Centre Block began immediately with the new design developed by architects John A. Pearson and Jean-Omer Marchand. The first sitting of Parliament in the new building occurred 4 years later, but it was not until 1927 that the 98-meter (320-foot) Peace Tower was completed. Today, the Parliament Hill National Historic Site is admired for its exemplary Gothic Revival style. Both the grounds and buildings are recognized for their heritage significance and have been designated as Federal Heritage Buildings (FBHRO).

A comprehensive rehabilitation program for Parliament Hill commenced in 2002 – beginning with the Library of Parliament – with the intention of repairing the historic fabric, modernizing services, and addressing changes in the functional program. Following the library, the rehabilitation of West Block began in 2011 and was completed in late 2018. The Centre Block program of work is now underway. The East Block will see two phases of rehabilitation – the first beginning in 2017 and the second phase will be started soon.

51.4.2 Level of Detail (LOD), Level of Information (LOI), and Level of Accuracy (LOA) – LODIA

During the development of the West Block BIM (2013) and the initial stages of the Centre Block BIM (2015), LOD and LOA standards or guidelines for modelling heritage buildings did not exist. In order to establish consistency in our own work, CIMS began the development of internal guidelines in 2015. The three-tier, five-category level of development system borrows from the architecture, engineering, construction, and operations (AECO) industry standards and guidelines and indexes level of detail (LOD), level of information (LOI), and level of accuracy (LOA) – LODIA – for each element type. CIMS LOD describes graphical and geometric representation in a scale from simple placeholder to detailed model and is based on existing standards for new buildings (Fig. 51.15). The selection of a specific level of detail is determined by available sensor data and reference material and anticipated HBIM uses. The LOD breakdown is as follows:

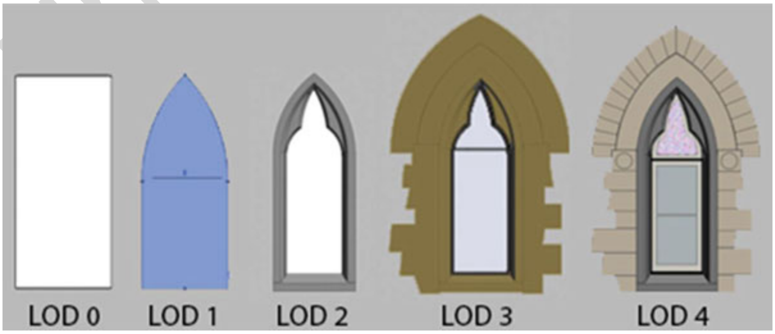


Fig. 51.15 CIMS level of detail 0 to 4 of a window, CIMS LOA classification system – level of detail (LOD), level of information (LOI), and level of accuracy (LOA) – LODIA [23]

LOD 0 – the element may not be modelled and may be represented by a placeholder (e.g., point cloud, historical drawing). If modelled, the element is a generic form with nonspecific dimensions and geometry.
LOD 1 – the model element shows the generic size and shape graphically but does not contain additional information such as material and detailing. For example, a window is represented as an outline only. It contains proper dimensions but does not show details.
LOD 2 – the model element is represented graphically with primary materials shown. Connections and secondary materials are minimally represented.
LOD 3 – the model element is accurately represented graphically. The material palette is shown, and connections are modelled – but fasteners are not.
LOD 4 – the model element represents ALL graphical and geometric information, including fasteners and the size of individual members. This LOD is reserved for areas where comprehensive detail is required.

In the context of the CIMS LODIA protocol, LOA reflects the level to which the deflection and deviation of the building element are modelled in the BIM. LOA is characterized as:

LOA 0 – no deflection/deviation is modelled. An average dimension is used for position and material thickness.
LOA 1 – element deflection/deviation is modelled at corners and changes of materials. Deflection/deviation shown is in positioning and not in material thickness.
LOA 2 – element deflection/deviation is modelled at a predetermined grid spacing (typically between 1000 mm and 3000 mm) and at corners or changes of material. Deflection/deviation is shown in positioning, not in material thickness.
LOA 3 – element deflection/deviation is modelled at a predetermined grid spacing (typically between 300 mm and 1000 mm) and at corners or changes of material. Large deflections/deviations (typically 50 mm to 1000 mm) between grid spacing are added. Deflection/deviation is shown in positioning and in material thickness if the thickness shows a deflection/deviation greater than 25 mm.
LOA 4 – the highest level of accuracy is accomplished through the creation of a mesh generated from point cloud data and contains all deflection and deformation.

51.4.3 West Block BIM (2013)

In July 2013, an HBIM of the West Block building using geo-referenced point cloud data was started. At the time, the development of BIM for historical buildings of that scale was a novel idea – the potential uses, challenges, and best practices were unknown. Therefore, the intention was to investigate the potential value of digitization and HBIM technology for the documentation, rehabilitation, and long-term management of the Parliament Hill site and beyond.

The primary data used to develop the West Block BIM was from geo-referenced point cloud data, augmented with a diverse set of secondary data including photographs, historical drawings, 2D CAD plans, 2D CAD elevations based on orthographic photographs, and total station surveys. The interior survey was completed using the Faro Focus 3D. The exterior was surveyed using the Leica C10, with supplementary data from the Faro. The point cloud data was supported by an extensive photographic record, field notes, and hand measures taken during site inspections.

In instances where scanning was not possible, the BIM followed secondary sources such as the CAD files prepared by PSPC. To amplify the complexity of the project, the building was an active construction site, requiring several scanning campaigns to capture the building through the construction phases to completion. Due to construction, some areas were not accessible to scan – such as the stairwells, portions of the interior, and the North Facade – until after the construction was complete. In total, 1.5 terabytes of geo-referenced point cloud data were captured.

To enhance workstation performance and decrease model file size, the model was also divided into several component models that, when linked together, created a federated model. The component models included roof, shell, interiors, slabs, and historic structure (Fig. 51.16).

The first step in developing the West Block BIM was to integrate the geo-referenced point cloud data into AutoDesk Revit 2014 by linking the individual .pts. files. The point cloud data was then viewed in a series of 2D section, elevation, and plan views to trace the profiles of the building element geometry to the assigned LOD and LOA. Next, using Revit's modelling tools, a solid 3D model element was created.

For LOD 1, elements were modelled as a simple placeholder with a minimal level of detail. Secondary sources were relied on heavily, as most areas specified at LOD 1 were not captured in the initial set of point cloud data. For LOD 2, building element types were developed from point cloud data in Revit – such as a window – and used to produce a library of parametric families. These building elements were then parametrically adjusted to accommodate their location in the model. At LOD 3, building elements were meshed from sensor data to generate model-in-place elements that afforded very specific and accurate models of unique geometric characteristics.

Regarding LOD and efficiency, modelling to the highest LOD capturing most deformations required using model in-place components such as meshes or segmented point clouds. Producing solid HBIM elements was a time-consuming process but increased the functionality of the model. Modelling at a lower LOD produced a model with a lower LOA but improved model functionality. Another important observation regarding LOD and LOA is the quality of the survey data. During the modelling of West Block, the resolution of the point cloud data was not high enough to model at a high LOD without relying on secondary sources. Based on our experience, it is imperative that a detailed documentation strategy is undertaken prior to developing a BIM for heritage documentation, conservation, and management in order to determine and reconcile the LOD of both the survey and the model.

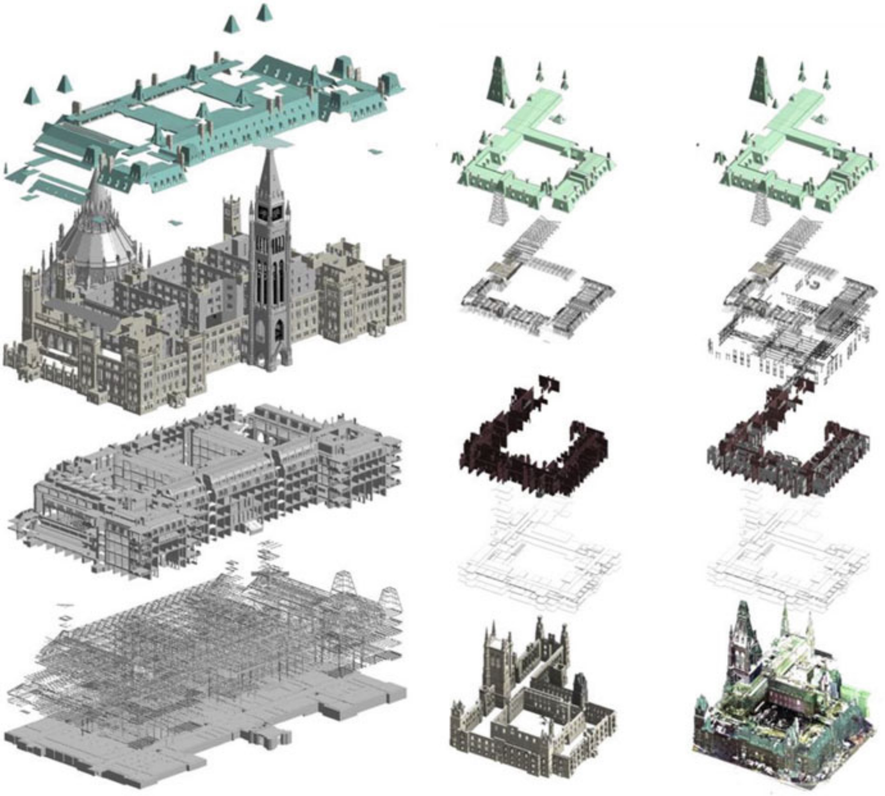


Fig. 51.16 Component models for West Block BIM as modelling progressed and exploded axonometric of the Centre Block BIM showing the linked models [23]

Following the initial phase of modelling (2013–2015), the second phase of modelling began in the summer of 2015.

51.4.4 Centre Block (2015)

The intention of creating an HBIM of the Centre Block was to facilitate aspects of an integrated project delivery (IPD) method for the Centre Block Program of Work. CIMS would develop the BIM and hand the model over to the AEC consultant team responsible for the rehabilitation work. In addition to capturing the existing conditions of the building, the model was developed in anticipation of specific model uses including, but not limited to, the generation of drawings, site analysis, design coordination, and design authoring.

In order to meet these objectives, the appropriate LOD for each building element category required specification. Our initial proposal was to utilize a commonly accepted BIM specification classification system – the level of development specification developed in the United States by BIMFORUM. The system combined level of detail with level of information classifications into level of development. A simplified level of development system was established between PSPC and CIMS for the initial scope, assigning LOD to specific building element categories:

LOD 300: exterior walls, roofs, foundations, structural elements (verified to point cloud).
LOD 200: interior walls, stairways, slabs, structural elements (not verified to point cloud).
LOD 300 was also assigned to spaces of significant heritage value such as the Senate Chamber, House of Commons chambers, Senate and House of Commons foyers, Rotunda, and Hall of Honour.

The model tolerance for the Centre Block BIM was determined by comparing the deflection and deviation of the building element to point cloud data. It was determined that a tolerance of less than 25 mm of modelled elements to point cloud data was acceptable. Any deviations greater than 25 mm would be captured within the geometric representation of the building element. Additionally, when the deflection or deformation was determined to be worth noting – based off the defined LOA – it was recorded in a customized properties panel. Three categories were defined: lateral deviation, vertical deviation, and irregularity of geometry. Lateral and vertical deviation referred to changes in the profile, whereas irregularity of geometry referred to deviations such as missing or broken elements.

The Centre Block BIM required the synthesis of large, diverse data sets. The primary data source was geo-referenced point cloud data from terrestrial laser scanning and photogrammetry. The data was captured by CIMS using a Leica C10 and P40 (exterior and large interior spaces) and a Faro Focus (small to mid-sized interior spaces). Significant heritage interiors including the Senate, Senate Foyer, House of Commons, House of Commons Foyer, Rotunda, Hall of Honour, and the exterior of the Peace Tower were also captured by HCS using photogrammetry. Over 2000 individual scan stations were required to capture the interior and exterior of Centre Block – resulting in over four terabytes of point cloud data.

Secondary sources such as archival drawings, photographs, historical steel catalogues, and technical reports were referenced in cases where point cloud data was not available. For example, the structural steel that is normally hidden from view and cannot be captured by laser scanning or photogrammetry. To increase workstation performance while modelling, the .pts. files were imported into Autodesk ReCap and divided into .rcp files by areas per floor, for instance, third floor south-west, third floor south-east, third floor East Office Block, etc. This way, model users could turn on/off specific areas of point cloud through the Revit Visibility and View settings for a small, localized area instead of loading in a large data set. Due to the size of the physical building, to minimize model file size, multiple component models when linked together created a federated model. The component models included roof, shell, interiors, circulation and slabs, and structure (Fig. 51.16). AU10

Similar in methodology to the West Block BIM, the first step in modelling Centre Block was integrating the geo-referenced point cloud data into Revit by linking the individual .rcp files. The point cloud data was then viewed in a series of 2D section, elevation, and plan views to trace the profiles of the building element geometry to the assigned LOD and LOA. Next, using Revit's modelling tools, a solid 3D model element was developed into parametric families.

As modelling progressed, we realized that BIMFORUM specification was insufficient for developing BIMs of historical buildings such as Centre Block. The availability of information for in situ building elements varied significantly, creating the need to identify levels of geometric detail, non-graphical information, and accuracy. In an effort to clarify the terms of reference, CIMS proposed the use of the CIMS LODIA – resulting in a more nuanced system of classification.

The LODIA of each component was based on an understanding of the available data from the source material, as well as the anticipated use for that data. For example, the structural steel beams within the floor slabs could be identified as LOD 2, LOI 2, and LOA 0. The LOD and LOI were high because of the available archival drawings and historical catalogues. However, since there was no point cloud data available – most of the steel was behind masonry walls and not visible to remote sensors – the LOA was 0.

In comparison, the Senate Chamber exhibited a different LODIA. While all specialty rooms in the Centre Block BIM were initially targeted to be modelled at a LOD 3, the Senate Chamber increased in graphical detail to a LOD 4 and LOA 4, while LOI was reduced to 2. This was because the model geometry of the Senate Chamber was leveraged for a virtual reality project related to the rehabilitation and required a high LOD for visualization purposes. High-resolution laser scanning and photogrammetry were used to record the space. However, very little verified information about wall assembly or materiality was available.

A low LOD was required for conceptual/schematic planning, making the existing model too detailed, while a high LOD was required for visualizations and heritage asset management. One approach that we explored was developing model elements to three LODs. Using the Revit coarse, medium, fine detail settings, users were able to view all three LOD within one model depending on required information or use (Fig. 51.19). As the second phase of modelling progressed, the LOD and scope transformed prompting another division of the models due to increased file size. Model elements were divided into additional linking files including basement, heritage, courtyards, interiors (floors 1–3), and interiors (floors 4–6) (Fig. 51.17).

The interdisciplinary research taking place between members of industry and academia has proven to be tremendously beneficial for both groups. The exchange of innovative workflows from research and standard practices from industry has pushed the application of digital tools for heritage conservation. The initiative is also supporting the development of highly qualified personnel (HQP) preparing researchers for both the intellectual and technical demands of a leadership role in defining the role of digital tools for heritage conservation in Canada and beyond.

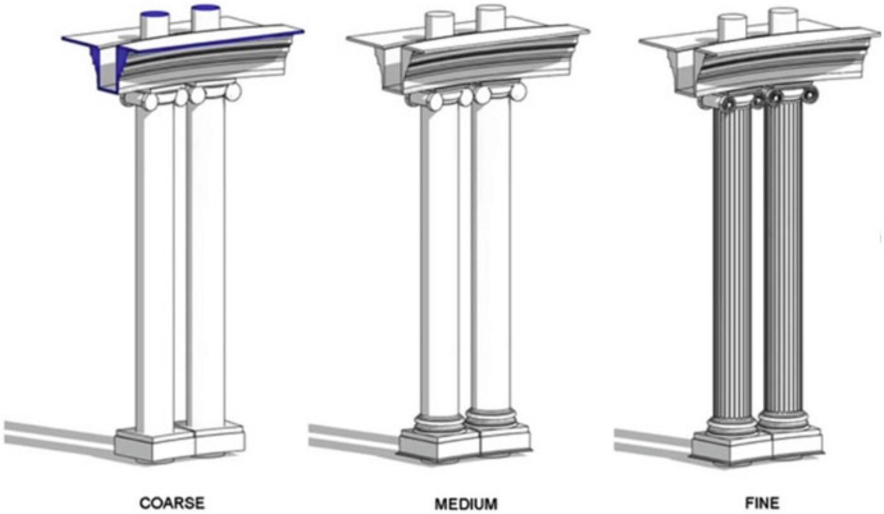


Fig. 51.17 Column developed at three LOD for the coarse, medium, and fine Revit detail levels [23]

51.4.5 Library of Parliament BIM (2017)

Our work on Parliament Hill culminated in the fall of 2017, with the digitization and modelling of one of Canada's most significant heritage assets – the Library of Parliament consisted in developing a BIM of the library in anticipation of the following BIM uses: visualization for communication, scheduling/phase planning, site utilization planning, digital and digitally assisted fabrication, heritage asset management, field management, and record model. As a tool for heritage asset management and visualization purposes, the model required the highest level of detail and accuracy. Following research from the Centre Block BIM, it was determined that a tolerance of less than 25 mm of modelled elements to point cloud data was suitable for the Library BIM. In a similar methodology, any deviations greater than 25 mm would be captured within the geometric representation of the building element, and any deviations worth noting would be documented within the properties of an individual model element.

The digitization program for the library was limited in scope. Only the main reading room, stairwells, attic, a few typical offices, and exterior were surveyed to produce geo-referenced point cloud data. We also requested highly detailed meshes of individual heritage assets in the main reading room – such as the hand-carved wood rosettes and the statue of Queen Victoria – from photogrammetry since they would be required for the planned visualization applications. The data was captured using a Leica P40 (main reading room) and a Faro Focus (typical offices, staircases, and attic). One of the challenges in digitizing the main reading room was minimizing occlusions due to the room's complex multilevel, circular geometry. The survey of the main reading room required 97 high-resolution scans in order to meet the required LOD and LOA for the BIM – taking approximately 5 days to complete. The exterior of the library was captured by HCS using UAV photogrammetry. We also relied on scan data from the Centre Block digitization campaign since the library data was geo-referenced to the same survey network as Centre Block. 2D CAD record drawings from the recent rehabilitation project (2007–2011) were referenced in cases where point cloud data was not available. However, we found significant discrepancies in instances where both point cloud data and record drawings existed.

To increase workstation performance while modelling, the .pts. files were imported into Autodesk ReCap and divided into .rcp files by areas per floor. An exception to this was the main reading room where the 97 .rcs files were imported into Revit as individual scan station locations. The geometry of the room and file size of each scan made it difficult to group the scans into an effective and manageable .rcp file. From our previous research, we were confident that through proper Revit work-set management, we could contain the whole Library of Parliament building at a high LOD within a single Revit file. This eliminated the inefficiency of switching between models in order to adjust model elements – especially at the join conditions where linked files are connected.

Similar in methodology to both the Centre Block and West Block BIM, the first step in modelling Centre Block was integrating the geo-referenced point cloud data into Revit by linking the individual .rcp and .rcs files. The point cloud data was then viewed in a series of 2D section, elevation, and plan views to trace the profiles of the geometry of the building elements to the appropriate LOD and LOA. Next, using Revit's modelling tools, solid 3D model elements were developed into parametric families. Despite our experience in modelling complex existing conditions, the geometry and detail of the library – including curved windows, elaborate fixtures, and flying buttresses – proved to be an extraordinary challenge. Modelling double curved geometry, intricate details, and surface deformations to a high level of detail from point cloud data required a return to exploring the possibilities of model-in-place families in special situations. For example, the geometry of the domed ceiling of the main reading room was extremely irregular. Our workflow involved producing a conceptual mass family generated directly from point cloud, then applying a generic model ceiling family, and deleting the conceptual mass.

Our earlier research on Parliament Hill allowed us to evaluate the trade-offs between LOD and BIM performance, communicate data sources effectively, and use our existing protocols for modelling workflows outlining step-by-step instructions for modelling building elements from point cloud data. However, the increased complexity of the building required the augmentation of our existing protocols and development of novel ones to capture the LOD and LOA required for the specific BIM uses. This resulted in the Library of Parliament Model being our most complex BIM project to date.

51.4.6 Conclusion: HBIM Quality Assurance

The process for verifying a model created from point cloud data involved creating multiple sectional views along elements in Revit and measuring the deviations that appeared to be the greatest between the point cloud and the model element. This method was time-consuming – notably for large BIM projects – and it limited the verification of the model to specific section locations.

In the summer of 2018, a plug-in for Revit – 3D Analysis – was developed at CIMS (in association with the Photogrammetry and Geometrics Group, INSA). The plug-in is a first step toward an automated visualization of the deviations between Revit wall elements and adjacent point cloud data in a 3D view. After minimal computation time, points are colorized according to the computed deviations, and a 3D color map is displayed. To help the user analyze the deviations, a window containing information about the repartition of deviations is also displayed. The plug-in is proving more efficient in relation to the previous LOA verification processes. Moreover, deviations are represented in a 3D view making the identification of potential modelling errors and deviations more visible.

Although we have achieved some success in automating the point cloud to BIM process, it must be acknowledged that the manual process used for the development of the Parliament Hill BIM has resulted in highly detailed and accurate models. Further, not all information for modelling a historic building is born digital. By synthesizing sensor data with secondary sources such as historical drawings, we have been able to generate a comprehensive representation of the fabric of the building. For example, the structural steel in Centre Block that is hidden from view within walls and floor slabs is now visible in the model and can be understood contextually. These secondary sources – integrated into the properties of the model elements for all three models – also offer the beginning of a rich database of non-geometrical cultural information related to the construction of the building (e.g., steel catalogues).

As we develop LODIA workflows that produce more efficient and geometrically rich models, we continue to augment existing and create new protocols. The implementation of these protocols in the lab ensures consistency across all modelled elements in terms of modelling methodology. The ongoing work on LODIA is not intended as an attempt to develop an industry standard but rather as a forum for discourse and consensus building with our partners in a rapidly evolving field of research. Our intention in this chapter is to demonstrate to our public and private partners and to academic colleagues the value added for all parties in applied, collaborative research (Fig. 51.18).

51.5 Conclusion: A Design Framework for Digital Representation of Virtual Historic Centers

In conclusion, a design framework is presented for systems architecture and workflows for digital representation of virtual historic centers in archaeology and architectural heritage for archiving and storage and dissemination based on game

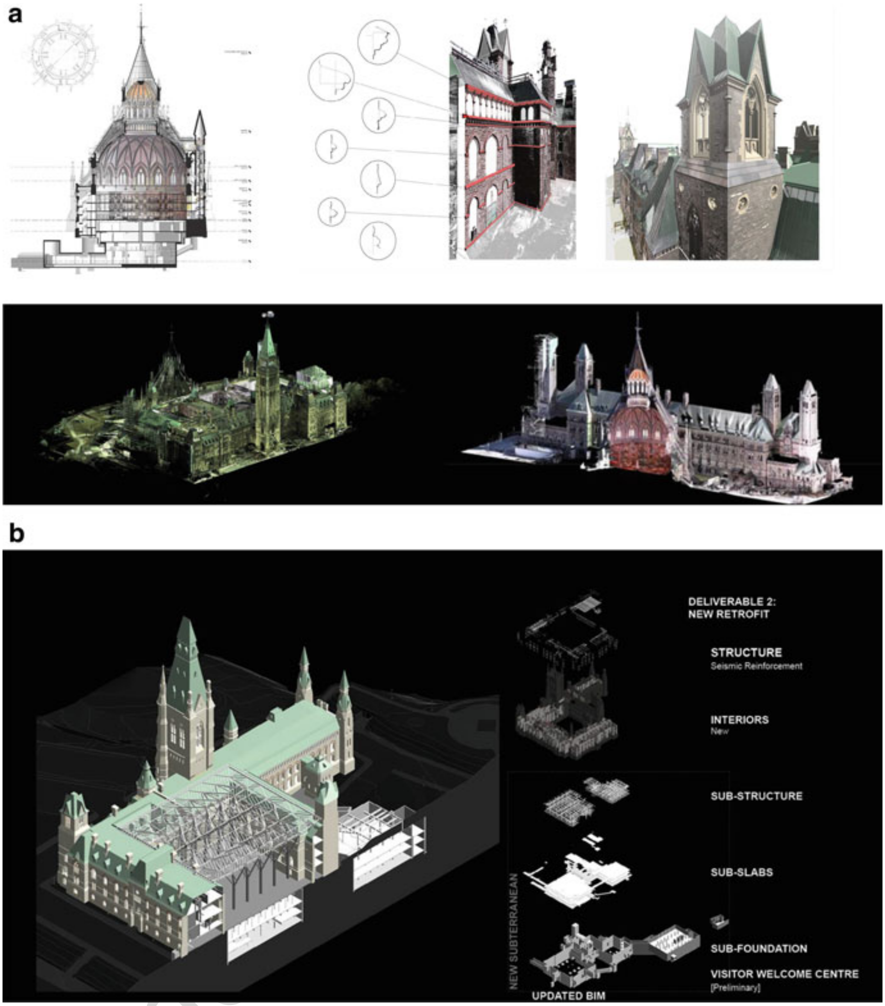


Fig. 51.18 (**a** and **b**) Historic BIM Parliament Precinct – graphic overview of scan and HBIM models [23]

engine platforms. Game engine platforms allow a low-cost method of making intelligent models and linked data more easily accessible to users. It is the nature of interactive video game applications to be intuitive to the user quickly upon assuming controls. A packaged "game file" is designed to execute in a standalone fashion, requiring no additional proprietary software installed on the end-user's computer system. Current mainstream industry packages include Unity3D and Unreal Engine, which allow for highly developed workflows and community support, but recent game engine software like Autodesk's Stingray package holds promise for greater interoperability with BIM.

With regard to educational applications, game engines can give public access to information that is usually restricted to specialists. The nature of video game engines is scalable and multiplatform and can potentially be viewed on a variety of systems with different performance capabilities, from tablets to sophisticated virtual reality workstations. A packaged "game file" is designed to execute in a standalone fashion, AU11 requiring no additional proprietary software installed on the end user's computer system. In addition, augmented reality (AR) and immersive experiences using wearable technology enhance the VR experience whether for entertainment or education. The virtual worlds are constructed in 3D graphic modelling platforms before they are exported into game engine platforms and only contain geometry and texture and are therefore limited to applications for visualization. The enhancement of the 3D visualization model for immersive experience with user interaction is generated within the game engine platform. This enables end users to interact with the virtual building and to access the rich data related to the model without needing to install specialist BIM software. Shape, geometry, and geo-location can be linked to enriched data in the model and are held externally. User queries can be linked to the locations of elements in the building, to shapes (such as design features), and to the semantics of the information and will be facilitated by data flow between the game engine, 3D HBIM component server, and data stores. The delivery options for the Virtual Historic City range from WEB-based and VR immersion to augmented reality [36] (Fig. 51.19).

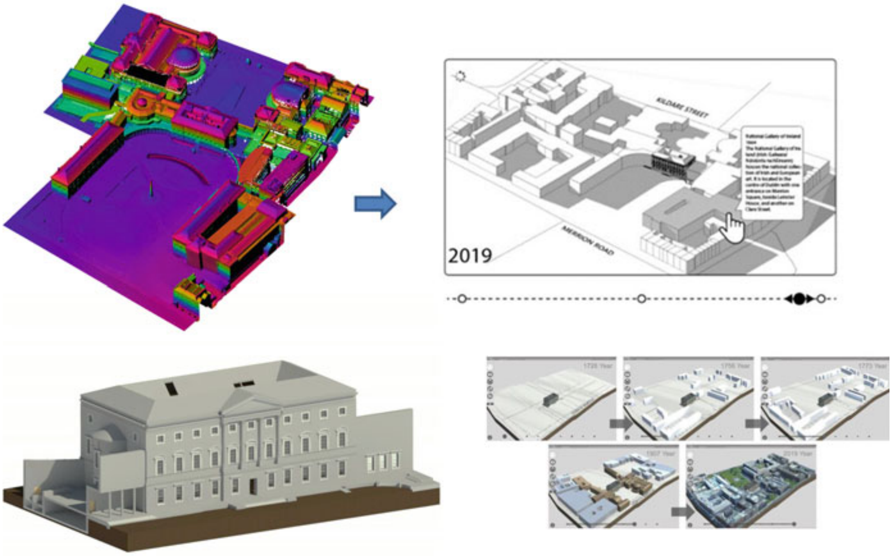


Fig. 51.19 Irish Parliament – Leinster House, aerial scan and HBIM model imported into Unity Game Engine Platform showing morphology of the parliament and ancillary buildings [2]

51.5.1 Systems Architecture

A design system safeguards lasting value and lessens the risk of digital obsolescence. Open repositories ensure that curated data not only survives but is shared with wider communities for their use and enhancement avoiding duplication of effort. System design starts with the capture of data followed by its classification and organization. The organized data is then enriched with semantic attributes from other sources and stored within a database or repository allowing access for various end user scenarios. The entire workflow is continuously updated and improved through a continuing conceptualization, planning, and evaluation process and managed to ensure quality and survival of data.

The initial design framework for virtual historic centers is presented in Fig. 23. AU12 Stage 1 illustrates the input data ranging from historic to laser scan and other survey AU13 data. This data is then processed and enriched with knowledge and information attributes (stage 2) but also can be used in raw state. There are a series of database servers; the first is the historic components as 3D HBIM, which maintains the libraries of intelligent objects that represent the elements of a building structure. BIM authoring platforms are mostly tailored for modern architecture, and their libraries of parametric architectural elements/objects are limited to basic components. To overcome this problem, a new design model is applied using architectural rules and shape grammars to code primitive and complex historic architectural objects. The architectural objects are mapped onto a geometric framework made up of point cloud, image data, and historic digital surveys. A server is dedicated to game engine assets, and the system can also be linked into external data bases.

The model at stage 3 holds AEC information and is then enhanced with geo-location, except for the 3D HBIM components server (detail 2); this can be AU14 considered a standard process pipeline. While BIM platforms have the potential to AU15 create a virtual and intelligent representation of a building, its full exploitation and use are restricted to a narrow set of expert users with access to costly hardware, software, and skills. In the final stage, the semantically enriched model is transferred into a WEB-based game engine platform. This not only enables interaction with the virtual building but also allows users to access and query related information rich data contained in the model and externally. The user access and queries are linked to the geo-location of elements of the building and to geometry shape and attributed semantics facilitated by data flow between the game engine asset server (detail 4) and the 3D HBIM component server (detail 2) (Fig. 51.20).

Acknowledgments The authors wish to thank the Parliamentary Precinct Branch, Public Services and Procurement Canada, for their ongoing support of our research. They acknowledge Heritage Conservation Services, Real Property Branch, and Public Services and Procurement Canada for their technical support. This project was funded in part by the Social Sciences and Humanities Research Council (SSHRC) of Canada through the New Paradigm New Tools for Heritage Conservation in Canada internship program [37].

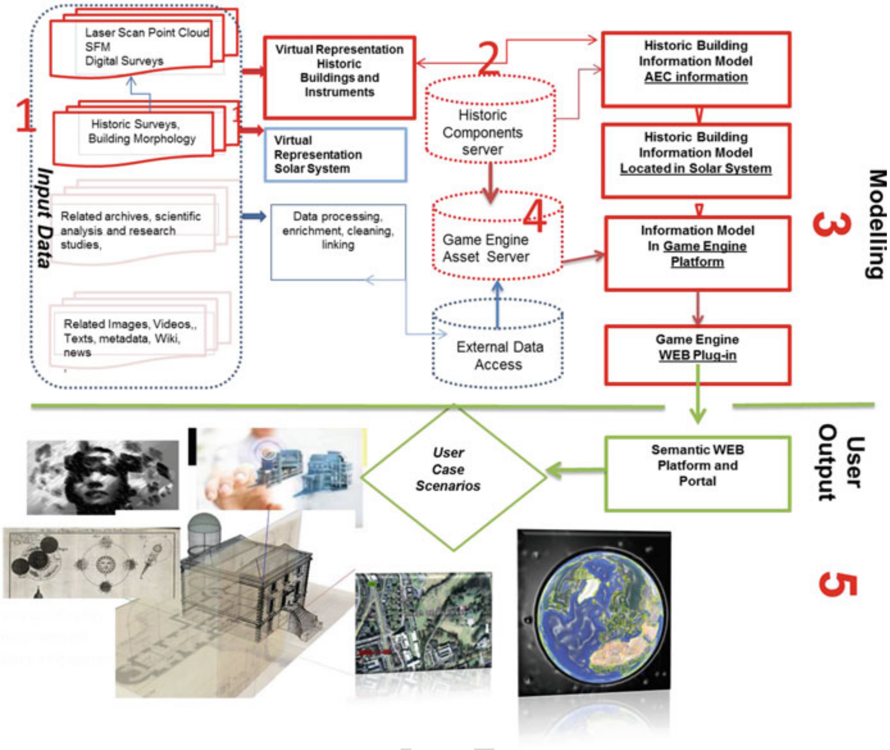


Fig. 51.20 Systems architecture for virtual historic centers

References

1. Charters Adopted By the General Assembly of ICOMOS., https://www.icomos.org/en/charters-and-other-doctrinal-texts. Accessed 8 May 2019
2. Figures developed from authors project archive material, Discovery Programme. www.discoveryprogramme.ie
3. Murphy M, Corns A, Cahill J, Eliashvili K, Chenau A, Pybus C, Shaw R, Devlin G, Deevy A, Truong-Hong L (2017) Developing historic building formation modelling guidelines and procedures for architectural heritage in Ireland. Int Arch Photogramm Remote Sens Spat Inf Sci ISPRS Arch 42:539–546
4. Allen PK, Troccoli A, Smith B, Murray S, Stamos I, Leordeanu M (2003) New methods for digital modeling of historic sites. IEEE Comput Graph Appl 23(6):32–41
5. Boehler W, Heinz G Documentation, surveying, photogrammetry. In: XVII CIPA symposium, Olinda, Brazil, 3rd–6th October 1999
6. Levoy M, Pulli K, Curless B, Rusinkiewicz S, Koller D, Pereira L, Ginzton M, Anderson S, Davis J, Ginsberg G, Shade J, Fulk D (2000) The Digital Michelangelo project: 3D scanning of large statues. Siggraph. In: Proceedings of the 27th annual conference on computer graphics. ACM Press/Addison-Wesley, New Orleans
7. Bernardini F, Rushmeier H (2002) The 3D model acquisition pipeline. Comput Graphics Forum 21(2):149–172

8. Beraldin JA (2004) Integration of laser scanning and close-range photogrammetry – last decade and beyond. In: XXth International Society for Photogrammetry and Remote Sensing (ISPRS) Congress Istanbul, Turkey, July 12–23, pp 972–983
9. Barber D, Mills J (2007) 3D laser scanning for heritage: advice and guidance to users on laser scanning in archaeology and architecture. English Heritage
10. El-Hakim S, Beraldin J-A, Remondino F, Picard M, Cournoyer L, Baltsavias M (2008) Using terrestrial laser scanning and digital images for 3D modeling of the Erechtheion, Acropolis of Athens. In: Proceedings of the Digital Media and its Applications in Cultural Heritage (DMACH 2008). 3–6 November 2008. NRC 50721
11. Grussenmeyer P, Hanke K (2010) Cultural heritage applications. In: Maas GVaH-G (ed) Airborne and terrestrial laser scanning. Wittles Publishing, pp 271–272 AU16
12. Dore C (2017) Procedural historic building information modelling (HBIM) for recording and documenting European classical architecture. Doctoral thesis, Dublin Institute of Technology. https://arrow.dit.ie/builtdoc/17/
13. Dore C, Murphy M (2017) Current state of the art historic building information modelling. Int Arch Photogramm Remote Sens Spat Inf Sci 42:185–192
14. Murphy M (2012) Historic building information modelling (HBIM) [For recording and documenting classical architecture in Dublin 1700 to 1830]. Doctoral thesis, Civil, Structural & Envi. Engineering, Trinity College Dublin. https://www.researchgate.net/publication/265396963_Historic_Building_Information_Modelling_HBIM_For_Recording_and_Documenting_Classical_Architecture_in_Dublin_1700_to_1830_PhD_thesis
15. Murphy M, McGovern E, Pavia S (2013) Historic building information modelling – adding intelligence to laser and image based surveys of European classical architecture. ISPRS J Photogramm Remote Sens 76:89–102
16. Remondino F, Del Pizzo S, Kersten T, Troisi S (2012) Low-cost and open-source solutions for automated image orientation – a critical overview. In: Proc. EuroMed 2012 conference, LNCS, vol 7616, pp 40–54
17. De Luca L (2012) Methods, formalisms and tools for the semantic-based surveying and representation of architectural heritage. Appl Geomat (1866–9298). https://doi.org/10.1007/s12518-011-0076-7 AU17
18. Baik A, Alitany A, Boehm J, Robson S (2014) Jeddah historical building information modelling JHBIM – object library. ISPRS Ann Photogramm Remote Sens Spatial Inf Sci II-5:41–47. https://doi.org/10.5194/isprsannals-II-5-41-2014
19. Boeykens S (2011, July 6–8) Using 3D design software, BIM and game engines for architectural historical reconstruction. Paper presented at the CAAD Futures 2011, Liège, Belgium
20. Chevrier C, Charbonneau N, Grussenmeyer P, Perrin J-P (2010) Parametric documenting of built heritage: 3D virtual reconstruction of architectural details. Int J Archit Comput 08(02): 131–145
21. Fai S, Rafeiro J (2014) Establishing an appropriate level of detail (LoD) for a building information model (BIM) – West Block, Parliament Hill, Ottawa, Canada. ISPRS Ann Photogramm Remote Sens Spatial Inf Sci II-5:123–130. https://doi.org/10.5194/isprsannals-II-5-123
22. Fai S, Sydor M (2013, Oct 28 2013–Nov 1 2013) Building Information Modelling and the documentation of architectural heritage: between the 'typical' and the 'specific'. Paper presented at the Digital Heritage International Congress (DigitalHeritage), 2013
23. Chow L, Graham K, Grunt T, Gallant M, Rafeiro J, Fai S (2019) The evolution of modelling practices on Canada's Parliament Hill: an analysis of three significant heritage building information models (HBIM). Int Arch Photogramm Remote Sens Spat Inf Sci XLII-2 (W11):419–426
24. Garagnani S (2013) Building Information Modeling and real world knowledge: a methodological approach to accurate semantic documentation for the built environment. Paper presented at the Digital Heritage International Congress (DigitalHeritage), 2013
25. Hichri N, Stefani C, Veron P, Hamon G, De Luca L (2014) Review of the "as-built" BIM approaches. Journal of Applied Geomatics. Springer Berlin/Heidelberg

26. Oreni D, Brumana R, Della Torre S, Banfi F, Barazzetti L, Previtali M (2014) Survey turned into HBIM: the restoration and the work involved concerning the Basilica di Collemaggio after the earthquake (L'Aquila). ISPRS Ann Photogramm Remote Sens Spatial Inf Sci II-5:267
27. Dore C, Murphy M Semi-automatic generation of as-built BIM façade geometry from laser and image data. ITcon 19:20–46. http://www.itcon.org/2014/2
28. Jung J, Hong S, Jeong S, Kim S, Cho H, Hong S, Heo J (2014) Productive modeling for development of as-built BIM of existing indoor structures. Autom Constr 42:68–77
29. Volk R, Stengel J, Schultmann F (2014) Building information modeling (BIM) for existing buildings – literature review and future needs. Autom Constr 38:109–127
30. Xiong X, Adan A, Akinci B, Huber D (2013) Automatic creation of semantically rich 3D building models from laser scanner data. Autom Constr 31:325–337
31. Zhang R, Zakhor A (2014) Automatic identification of window regions on indoor point clouds using LiDAR and cameras. Paper presented to Applications of Computer Vision (WACV), 2014 IEEE Winter Conference on, 24–26 March 2014
32. Hohmann B, Krispel U, Havemann S, Fellner D (2009) CityFit – high-quality urban reconstructions by fitting shape grammars to images and derived textured point clouds. Paper presented to 3DARCH 2009 – 3D Virtual Reconstruction and Visualization of Complex Architectures, Trento, Italy, 25–28 February 2009
33. Muller P, Wonka P, Haegler S, Ulmer A, Gool LV (2006) Procedural modeling of buildings. ACM Trans Graph 25:614–623
34. Parish YIH, Müller P (2001) Procedural modeling of cities. Paper presented to 28th annual conference on computer graphics and interactive techniques, New York, 2001
35. Thaller W, Krispel U, Havemann S, Redi I, Redi A, Fellner DW 2011) Developing parametric building models – the gandis use case. Paper presented to 4th international workshop 3D-ARCH 2011, "3D Virtual Reconstruction and Visualisation of Complex Architectures", Trento, Italy, 2–4 March
36. Edwards G, Li H, Wang B (2015) BIM based collaborative and interactive design process using computer game engine for general end-users. Vis Eng 3(1):4
37. https://cims.carleton.ca/#/home

Author Queries

Chapter No.: 51 478580_1_En

Query Refs.	Details Required	Author's response
AU1	Please be aware that your name and affiliation and if applicable those of you co-author(s) will be published as presented in this proof. If you want to make any changes, please correct the details now. Note that corrections after publication will no longer be possible. If no changes are required, please respond with "Ok".	
AU2	Please check if inserted citations for Figs. 51.1, 51.6–51.8, 51.12–51.14, 51.17–51.20 are okay.	
AU3	Please check if edit made to the sentence “TLS operates on three different principles” retains the intended meaning.	
AU4	Please check the latter part of the sentence “and the xyz coordinates . . . for the scanned object” for clarity.	
AU5	Please check if edit made to the sentence “This is achieved using . . . cloud at the processing stage” retains the intended meaning.	
AU6	Please check the phrase “such as dimensions, angular, and location” for completeness in the sentence “Parametric-based design is based on variable values such as dimensions, angular, and location, which can be revised for mapping and fitting within the point cloud or image survey”	
AU7	Please check the sentence “These rules can be added, modified, or removed as and defined” for clarity.	
AU8	Please check the sentence “a panel containing a door opening” for completeness.	

AU9	Please consider rephrasing the sentence “Additional library objects relating to a door and door case such as columns and pediments are linked with this shape their respective shapes” for clarity.	
AU10	Please check the sentence “For example, the structural steel that is normally hidden from view and cannot be captured by laser scanning or photogrammetry for completeness.	
AU11	The sentence “A packaged “game file” is designed to execute in a standalone fashion, requiring no additional proprietary software installed on the end user’s computer system” appeared twice in text. Please check if the second occurrence should be deleted.	
AU12	Please provide appropriate figure citation instead of Fig. 23.	
AU13	Please check if edit made to the sentence “Stage 1 illustrates the input data ranging from historic to laser scan and other survey data” retains the intended meaning.	
AU14	Please check if edit made to the sentence “this can be considered a standard process pipeline” retains the intended meaning.	
AU15	Please check if edit made to the sentence “While BIM platforms … software, and skills” retains the intended meaning.	
AU16	Please check the editor name in Ref. [11] if correct.	
AU17	References [17] and [21] were identical and Reference [21] has been deleted. The subsequent references have been renumbered. Please check and confirm if appropriate.	

AU18	Text within the figure is too small and the image is blurred for Figs. 51.8, 51.9 & 51.11, please provide better quality figure.	
AU19	Text within the figure is too small for Figs. 51.14, 51.15, 51.18 & 51.19, please provide better quality figure.	

Note:
If you are using material from other works please make sure that you have obtained the necessary permission from the copyright holders and that references to the original publications are included.