Structural Simulations and Conservation Analysis -Historic Building Information Model (HBIM)

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ABSTRACT:

In this paper the current findings to date of the Historic Building Information Model (HBIM) of the Four Courts in Dublin are presented. The Historic Building Information Model (HBIM) forms the basis for both structural and conservation analysis to measure the impact of war damage which still impacts on the building. The laser scan survey was carried out in the summer of 2014 of the internal and external structure. After registration and processing of the laser scan survey, the HBIM was created of the damaged section of the building and is presented as two separate workflows in this paper. The first is the model created from historic data, the second a procedural and segmented model developed from laser scan survey of the war damaged drum and dome. From both models structural damage and decay simulations will be developed for documentation and conservation analysis.

1. INTRODUCTION

1.1 Overview

The specific aim of this paper is to present the research outputs to date of a Historic Building Information Modelling (HBIM) of the Four Courts, a historic classical building in Dublin City. This case study forms part of an overall project to develop a prototype system for national monuments in Ireland for the conservation, maintenance and management of historic properties, based on HBIM.

1.2 Definition

As a multi-disciplinary and evolving system, Historic Building Information Modelling (HBIM) has been developed in the Dublin Institute of Technology. The HBIM process (Murphy, M. et al, 2013) consists of the survey of existing structures using remote sensing followed by the mapping of parametric and information rich objects onto a geometric framework based on the remote survey data. The parametric objects which represent the architectural elements are built using a geometric descriptive language and are based on historic architectural documents (architectural rules and shape grammars). In addition these rules and grammars are exploited to procedurally model parts of the structures to speed up and automate parts of the process (Dore, C. and Murphy, M. 2014).The resultant HBIM can then be used for automatically producing conservation documentation and analysis of historic structures in addition to visualisation.

1.3 Complementary Research

Within the field of Virtual Cultural Heritage, Historic BIM was preceded by researchers (Chevrier, et al 2010; De Luca, L. 2012) developing parametric CAD objects which are then mapped onto laser scan or photogrammetric surveys. The parametric primitives or objects can be modified to fit the range of geometry and texture requirements for virtual representation of historic structures. Parametric modelling was then improved by introducing the benefits of using Building Information Modelling (BIM) for cultural heritage preservation. 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. Two problems existed for researchers in generating HBIM, the first is the absence of complex historic architectural elements in BIM libraries and secondly a system for mapping the objects onto remotely sensed survey data.

While these problems are been improved upon by the developments of HBIM carried out in the DIT (1), research in HBIM is becoming fairly widespread. This includes for example the work in Carleton University (Fai, S. et al, 2011; 2013; 2014), Polytechnic of Milan (Oreni, D. et al, 2014), KU Leuven (Boeykens, S., 2011; Boeykens, S. et al 2013) and others (Baik, A. et al 2014; Wu, T. C. et al 2013). The later research initiatives are case study based (modelling of historic structures) using various remote sensing hardware and software systems and BIM software platforms. In addition, in the later research the problem of building parametric architectural libraries is mainly overcome graphically as opposed to coding the parametric objects. In contrast, HBIM developed in the DIT; the library objects are built using Geometric Descriptive Language (GDL). Generative Modelling Language (GML) in addition to the existing Geometric Descriptive Language (GDL) is now being examined to allow for the libraries to be used as stand-alone or cross-platform. The systems used for mapping the objects onto point clouds or mesh models are based on manually aligning the objects onto orthographic projects from the point cloud or mesh model. More recent work concentrates on automation for improving the current slow process of converting unstructured point clouds into structured semantic BIM components; this includes DIT research (Dore, C. and

Murphy, M. 2014) and the University of Bologna (Garagnani, S., 2013). The principal results from this research, which converts laser scan or photogrammetric survey data to HBIM is the creation of intelligent computer models which are used for conservation analysis and solutions for historic structures and their environments.

1.4 Case Study – Four Courts

The Four Courts is a late 18th century classical building in Ireland; the building was partially destroyed in 1922 during the civil war in Ireland which occurred during the early establishment of the Republic (see Figure 1). The effects of the civil war damage to the building are once again a threat to the structural stability of parts of the building. The intention is to use the HBIM to illustrate virtually the current extent of the damage/decay and as a basis for the proposed conservation interventions.

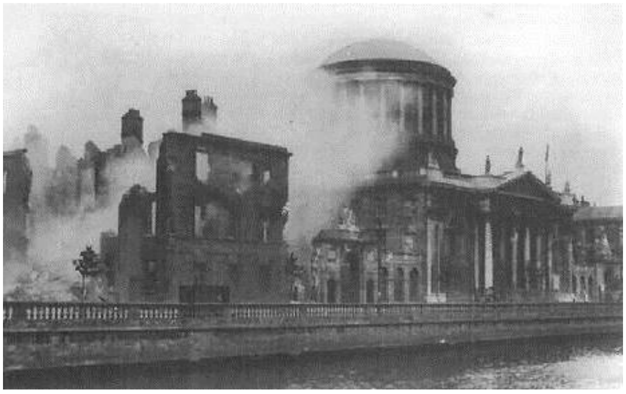

Figure 1: War Damage to the Four Courts

1.5 Summary of Methodologies Used

Two data sets are available for creating the HBIM, the first is the archive of historic surveys carried out since the 1780s through to recent years. The second data set is a recent laser scan survey. The laser scan survey was carried out in the summer of 2014 of the internal and external structure using a Leica HDS C10. For this reason the HBIM work programme is divided into two workflows, the first based on the historic data and the second on the laser scan survey (see Figure 2).

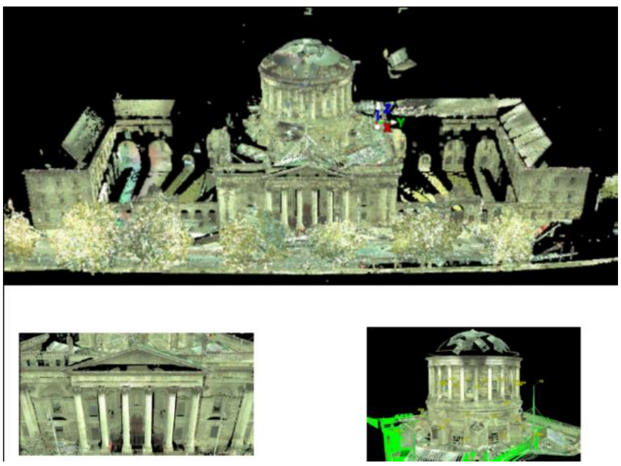

Figure 2: Laser Scan Survey

The historic documents (drawings, documents and iconographic sources of the specific building) are interpreted and identified from an art and architecture historical perspective to accompany the computing research methods. In addition to this, information concerning historic European construction techniques and architectural details can be found in architectural manuscripts, which have evolved from Vitruvius (70 – 35 BC) to the 17th and 18th century architectural pattern books. These architectural pattern books are employed to supplement specific architectural records for creating library objects.

The second model is created as a procedural and segmented model from the laser scan of part of the war damaged drum and dome. Using concepts from procedural modelling, a new set of rules and algorithms have been developed to automatically combine parametric library objects and generate Historic Building Information Models (HBIMs) from survey data. The procedural HBIM workflow is shown in Figure 3. First a laser scan or photogrammetric survey is carried out to acquire data to generate a HBIM. In the second stage survey data is processed to produce segmented point clouds and cut-sections which are imported into BIM software. Next procedural rules are applied to survey data to automatically generate the required BIM geometry. The generated geometry can then be refined by adjusting parameters to accurately match the geometry to specific survey data. Once a HBIM has been generated and precisely mapped to survey data, documentation can be automatically generated from the model. This includes plans, elevation drawings, sections and 3D perspectives. Further analysis can also be carried for structural and conservation analysis of historic buildings.

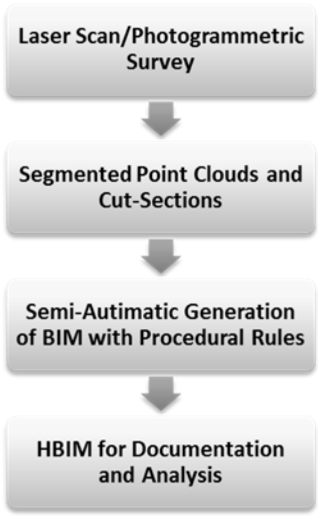

Figure 3: Procedural Workflow

2. WORKFLOW 1 - HISTORIC RECONSTRUCTION

2.1 HBIM

The series of routines for building the first model is based on historic data entirely and no input is introduced from the laser scan survey and is illustrated in the Figure 4 below. Given that the Four Courts is one of the Dublin city's most important historic buildings a large collection of drawings and surveys from a period over 220 years are still available within the state archive. These documents have been scanned and scaled for re-mapping in HBIM. The historic documents are reviewed from an art and architectural history perspective to accompany the computing methodological approaches in order to identify correct uses and interpretation of historic sources.

In Figure 4, (Detail 1) a sample of the historic drawings is shown, the columns, wall and beams are placed on a scaled plan and the section detail which contains imperial measurements allows for vertical positions as shown in detail 2. Other sets of data are used to position the wall (Detail 3), beams and dome (Detail 4). Mouldings and details such as dental block are added (see Detail 5), windows and accompanied openings are inserted, as illustrated in Details 7, 8 and 9. The internal dome is added (see Detail 10) and the supporting buttresses are added as shown in Detail 11.

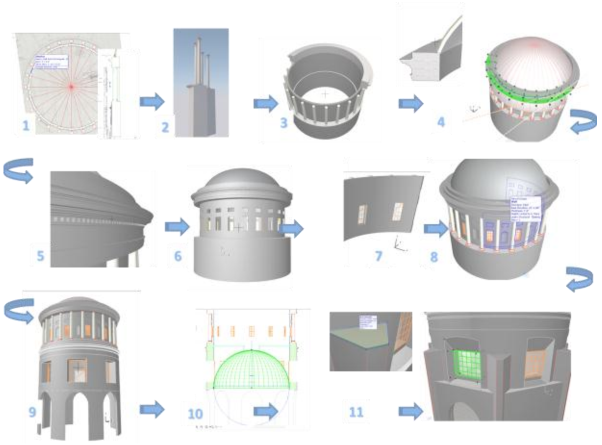

Figure 4: Details 1 to 11 - Historic Model

2.2 Building Morphology

The model illustrated in the figure 4 above, indicates a number of relevant physical characteristics concerning the damaged section of the building. These are the original historic construction techniques used in the 18th century and the interventions to repair to the building after war damage in the 1920s. In summary, almost all of the Corinthian columns surrounding the dome had been shattered. The inner walls of granite appear to have remained intact. The Corinthian columns, which had originally been carved on all sides were removed and rotated so that the damaged sides face inwards. Two of the columns which had been destroyed were replaced with replicas cast in artificial stone. An internal system of steel framing was employed to brace the external walls and reinforced concrete floors replaced the original floors. The dome was replaced using reinforced concrete, which was a very progressive solution for the time, as a thin skin of ferro-concrete was used. This consists of a very slender, complex curved leaves of reinforced concrete used for shell roof construction.

2.3 Creating the Library of Architectural Elements

In the case of this building, an understanding of classical architecture within its correct time-frame is essential. This is required to identify significant rules, which can be applied to developing the library of objects used to plot the model. The historic surveys and drawings (see Figure 5) usually show the spatial positions of architectural elements but do not contain the construction detail, the architectural rules and shape grammars for composing these elements. This information can be found in various historic architectural texts. Therefore a substantial portion of the investigation for creating accurate parametric objects relates to locating and understanding these texts within the correct historic and geographic framework.

Figure 5: 18th Century Section of Four Courts (Architect Gandon)

2.4 Historic Framework for Classical Architecture

The first recorded treatise concerning classical architectural rules was “De Architectura” by the Roman scholar Vitruvius. Later, during the classical revival of the Italian Renaissance the following three tractates on architectural theory are of key importance: “De re Aedificatoria” (1443-1452) by Leon Battista Alberti, “Regole Generali D'Architettura” (1537) by Sebastiano Serlio and “Regola Delli Cinque Ordini D’Architettura” (1562) by Giacomo Barozzi da Vignola. Vitruvius’s influence stretched across Europe with the treatises of Claude Perrault who published the only French translation of ‘De Architectura’ in 1673 and hereby contributed to revive the feeling for the rules and principles in architecture. In 18th century Britain, Andrea Palladio’s work “Quattro Libri dell'Architettura” (1570) influenced the production of crucial architectural treatises. ‘The Rules for Drawing the Several Parts of Architecture’ (1732) by James Gibbs can be considered as a precursor for the production of practical pattern books (see Figure 6 below) throughout the 17th and 18th centuries in Britain (with an extension in 19th century Irish architecture) .

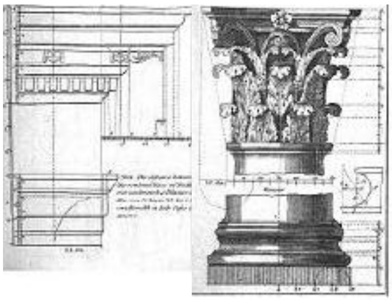

Figure 6: Pattern Book Detail – Corinthian Capital

The interpretation and understanding of architectural rules can be more easily adapted from these architectural pattern books, which can fill the hiatuses in historic archival documents. The coding or graphic system for developing the libraries follows on from this, below is an example of sash window library parts developed from these rules and pattern book sources (Murphy, M., 2012).

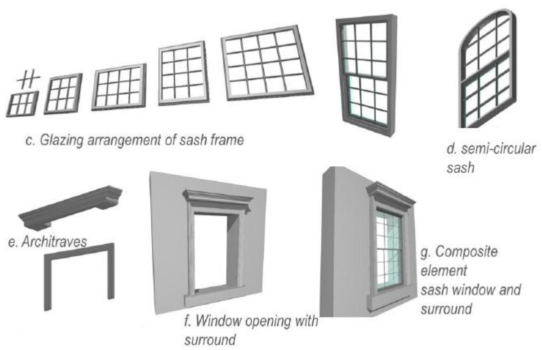

Figure 7: Library Objects

3. WORKFLOW 2 – PROCEEDURAL RECONSTRUCTION

3.1 Procedural Rules for HBIM

Procedural rules have been developed for modelling building façades and complete external building geometry. A prototype plug-in has been developed with these rules for the ArchiCAD BIM software. This prototype plug-in allows for semi-automatic generation of existing buildings from survey data. The design and implementation of the procedural HBIM rules are described in this section.

3.1.1 Design and Conceptual Framework

The design and conceptual framework for the HBIM procedural rules are based on concepts from shape grammars. A shape grammar is a production system used in procedural modelling to automatically generate two or three dimensional geometries from a basic vocabulary of shapes and a set of production or shape rules. A HBIM library of parametric architectural elements (Murphy etal, 2013) are used as a shape vocabulary on which the rules and algorithms are applied.

Architectural rules and proportions are also used to assist the reconstruction process. Architectural rules and proportions outlined in pattern books relating to classical buildings are used to provide an initial estimate for the position and size of building elements on a generated building. This greatly reduces the amount of further editing required when modelling classical buildings from survey data.

3.2 New Procedural Rule for Modelling Deformed Drum Walls

This new procedural rule is designed for accurate and efficient modelling of curved walls that contain deformation such as the walls supporting a dome and drum of the Four Courts. As a result of deformation the walls which support the dome may not be perfectly vertical and may contain different levels of deviation at different heights and locations. A design for accurately modelling this type of irregular wall has been developed using multiple cut sections from a point cloud (see Figure 8). Horizontal cut sections through a circular wall at different heights will show areas where the wall is bulging or warping. Creating a surface from cut sections through the wall at different heights allows the variances of the surface to be accurately represented. This new procedural rule allows users to select a group of horizontal cut sections which are then used to automatically generate the irregular wall surface (Figure 9). The non-vertical wall is created by generating a surface between each horizontal cut section. This rule results in automatically generated geometry for a drum wall which represents the true condition of the wall with deformation based on scan data. The design and implementation of this rule is described more in in this section.

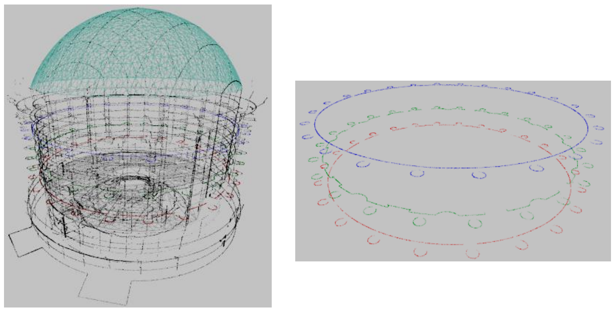

Figure 8: Segmented point cloud and horizontal cut sections imported into BIM software

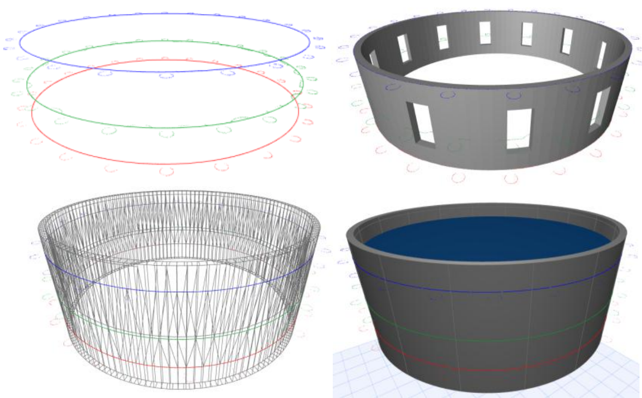

Figure 9: Irregular non-vertical walls containing deformation automatically generated from cut-sections. A split rule is used to automatically add window openings.

3.2.1 Conceptual Design for New Procedural Rule

The input for this rule is a set of horizontal cut sections which are created from the point cloud. For this rule the cut sections need to be represented as closed polygons made up of arcs or lines. Each cut section also must have an associated height parameter for that section. The conceptual design for this rule involves a user selecting any number of cut sections from the point cloud and applying the rule which automatically generates the irregular wall surface.

The main challenge in implementing this rule is in determining how points in one cut section correspond and relate to points in the next cut section above and below it. As all cut sections will vary there are no common points between each section. To overcome this problem a common framework is set up to identify relating points between each section (Figure 10). An algorithm is used to calculate coordinates at the intersection of this regular framework and each cut section. The wall surface is then created by connecting these relating points between each section.

3.2.2 Implementation of New Procedural Rule

This new rule has also been implemented as part of the prototype plug-in to the ArchiCAD BIM software. The C++ programming language is first used with the software API to retrieve data relating to the group of cut sections selected by a user. This data is then passed on to a GDL script where the main code for this rule is implemented. An algorithm is used to calculate the corresponding points between cut-sections (Figure 10). The 3D "RULED" function in GDL is then used to create the new surface which connects the cut sections based on corresponding points. Offsets for the inner wall surface are then calculated based on a user parameter for the wall thickness.

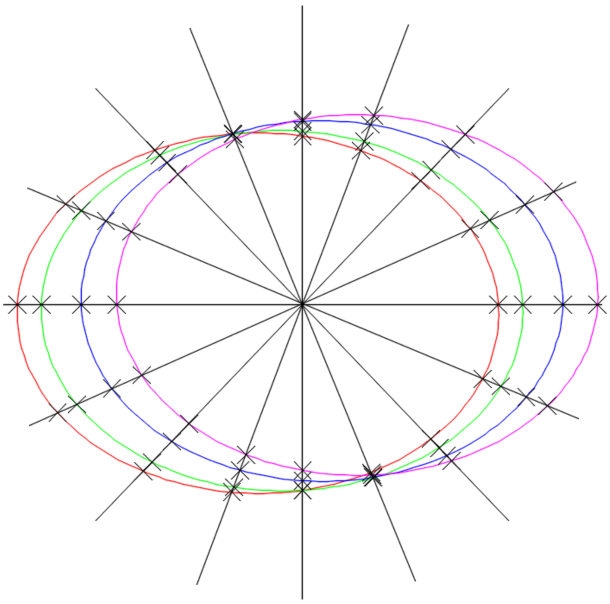

Figure 10. Framework (black lines) for identifying corresponding points between horizontal cut sections (coloured)

Once the walls have been automatically generated with this new procedural rule then other rules can also be applied such as the split rule described in the previous section. This split rule will automatically divide the drum wall into any number of equal tiles with openings (Figure 11). The positions and size of window openings can then be graphically refined to precisely fit the survey data. An additional rule is also used to create a mesh surface for the roof of the dome from a sample of points from the scan data (Figure 11). Continued work will involve developing additional procedural rules for automatically arranging columns and mouldings to complete the HBIM for this section of the Four Courts building.

Existing tools within the ArchiCAD BIM software are very limited for modelling non-vertical circular walls which contain deformation. This new rule allows for more accurate and efficient generation of HBIMs from survey data which can facilitate structural and conservation analysis of existing buildings.

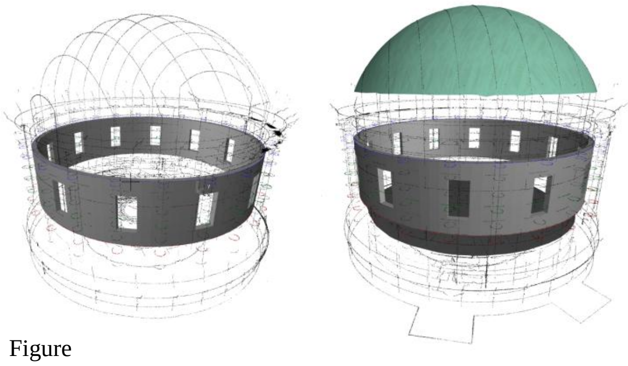

Figure
11. Wall containing deformation automatically generated from cut sections. Additional mesh surfaces used to represent dome roof and floor surfaces (right).

4. NEXT PHASE OF WORK

4.1 Sub-Phases

The project is multidisciplinary; the initial phase for developing the Historic Building Information Model involved surveyors and architectural historians. The next phase encompasses using the model to automate documentation to identify and propose solutions for decay, damage and structural integrity, which will involve material scientists and engineers.

4.1.1 Building Decay and Damage Mapping

Three approaches are recommended: initially, manually mapping of decay onto 2D scaled orthographic projections of the model in plan, elevation and section. The second is an attempt to locate the decay and damage onto the 3D geometry using total station or other instruments, which will locate 3D coordinate positions. Finally the use of digital photogrammetry is proposed, to build the elements where the scan data is not sufficiently dense or cannot access. Below is an example of a digital photogrammetric reconstruction of part of the scroll from the Corinthian capital which broke away from the capital of the column.

Figure 12: Corinthian capital – Photogrammetric Model

4.1.2 Structural Analysis

Open BIM is a model-based design approach based on the Industrial Foundation Class or IFC model exchange format. Using standard international formats such as the Industry Foundation Class (IFC) it is also possible to export HBIM data for further analysis in other software. This has been shown by Oreni et al. (2014) where the interoperability of HBIM was tested with other software such as Rhino for performing geometric analysis and simulations and Midas for finite element analysis. An example of structural behaviour is illustrated in the Figure below, a Section through dome and drum walls automatically created from survey data with procedural rules (workflow 2) shows true condition of wall which outlines deformation, which may be due to the traditional materials used or movement. A warping of the drum wall is clearly evident from this section.

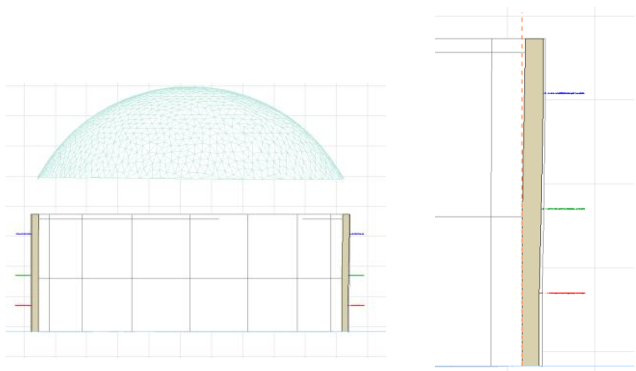

Figure 13. Section through dome and drum walls automatically created from survey data with procedural rules. Section shows true condition of wall which contains deformation.

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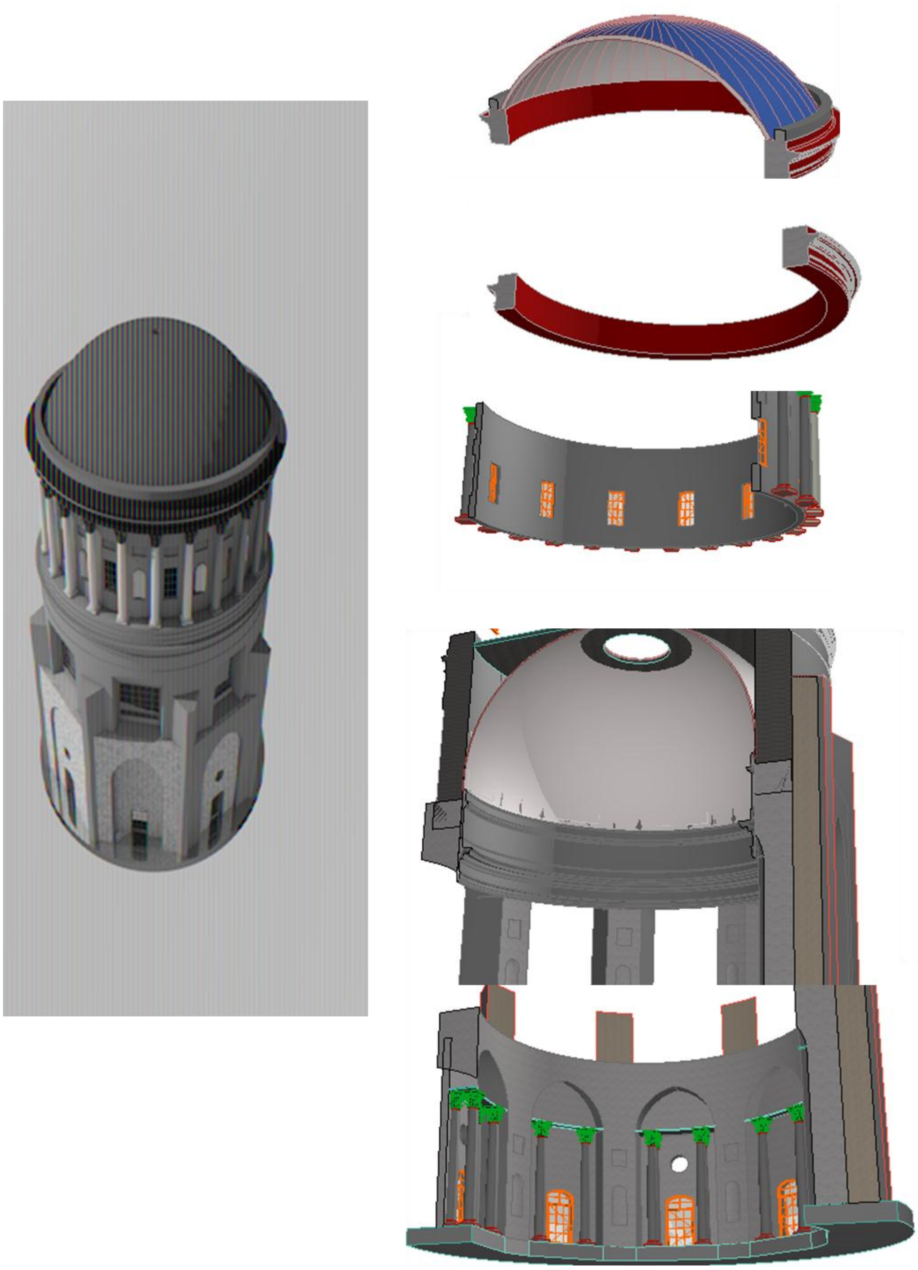
APPENDIX



HBIM model of dome and drum