A METHOD FOR THE 3D MODELLING OF HISTORIC MONUMENTS: THE CASE OF A GOTHIC ABBEY

C. Chevrier [a, *], Y. Maillard [a] and J.P. Perrin [a]

[a] UMR MAP CRAI, school of architecture of Nancy, 2 rue Bastien Lepage, 54000 Nancy, France, - (chevrier, perrin)@crai.archi.fr

Commission V, WG V/4

ABSTRACT:

The modelling of historic monuments is a tedious task whatever the method employed. The complexity is of two kinds. The **first** comes from the architectural elements themselves (many types with varying shapes throughout the ages and according to the architectural styles). The **second** complexity is due to the number of architectural elements required to create a given monument. We have conceived and developed a parametric shape generator tool for virtual 3D reconstruction of cultural heritage monuments. Our method allows rapid modelling and accurate adjustments to the measured data. We also present the example of the vault study. The results obtained with the 3D model of Saint-Sauveur abbey in Figeac (France) are promising. The modelling time is greatly reduced in comparison with CAD, photogrammetry or laser scanning tools.

1. INTRODUCTION

The modelling in three dimensions of historic monuments is a tedious task. The complexity is of two types. The **first** complexity comes from the architectural elements themselves. Many types of element exist: not only walls, openings and roofs but also balconies, cornices, pediments, columns, vaults, cupolas, sculptured elements, and so on. It is enough to observe some classical or gothic façades to have an idea of the numbers of different elements. Each architectural element can be, by itself, a complex object. It can be a compound of elements. Variations throughout the ages and according to the architectural styles are often considerable. A ancient window, a new age one, a gothic one and a modern one can have in appearance only the hole in the wall in common. The **second** complexity is due to the number of architectural elements required to create a given monument. Comprehension of the building scheme (from plans, pictures and point clouds) is important to place each piece of the puzzle correctly and relatively to its neighbours.

Modelling a historic monument in three dimensions takes a long time whatever the method employed. Using 2D plans with a CAD tool is very tedious. Photogrammetry methods allow rebuilding the global shape of the building, but not its details in a simple and rapid way (flutes of a column, volutes, vaults...). Laser scanning techniques produce point clouds with high precision. However, only simple geometrical shapes are automatically adjusted to cloud points. Furthermore, with the two last methods, only visible parts of the objects can be rebuilt. There are always some parts of elements that cannot be captured by the tool (camera or laser). However, as far as architectural elements are concerned, these invisible parts are often predictable: the hidden or damaged parts of a Corinthian capital can be created as we are aware of its composition. Finally all these techniques require architectural and geometrical knowledge to create architectural elements that respect architectural and geometrical rules. Only architects specialised in old styles have that knowledge. As an example, arches in vaults or cupolas follow criteria that depend on the building period.

All these remarks, the lack of a suitable tool for quick but accurate modelling of architectural scenes and our experience in the laboratory in the 3D modelling of historical monuments has led us to conceive and develop a tool that produces accurate, consistent and reusable models. The main specificities of this tool are:
- The generation of parametric architectural elements that can be adjusted to practical cases. Architectural knowledge is included making the use of a specialist in architecture and history unnecessary. It takes just one click to create a Gothic groin vault with all its details (transverse arches, ribs, profiles, keystone).
- Data enabling the adjustment of architectural object parameters to the user's needs. All the data we used can be inserted in the 3D scene, and allow the dimensioning and the positioning of the element in the scene: 2D plans, photographs and laser point clouds.

Section 2 presents a selection of related works. Section 3 presents the specificities of the Gothic style and of the Figeac abbey. In section 4, we explain the process to study an architectural element with the example of the vault. Section 5 is related to the creation of the Saint-Sauveur Gothic abbey. Finally, section 6 concludes and presents future work.

2. RELATED WORKS

Various ways exist to model architectural buildings in 3D: using 2D architectural plans with a CAD tool is the most time-consuming method. Photogrametry techniques (photomodeler, Debevec et al. 1996; El Hakim et al. 2002) allow the building of the main parts of a building rapidly. For detailed and complex

---

* Corresponding author

objects (volutes, vaults) a great number of pictures and/or corresponding points are required, increasing the modelling time. Mueller et al (2007) have conceived a method for a quick reconstruction of façades from upright pictures. Horizontal and vertical straight lines are computed for the creation of simple shape (box) elements. The user enters the depth position of the elements. However, their method is suitable for simple modern façades of buildings, but is not adaptable to complex architectural façades that are ancient or classical.

Laser scanning techniques (Trimble, Remondino, 2003) produce point clouds with very high precision. However, the modelling task is tedious and only geometrically simple objects can be automatically created (spheres, cubes, plans, cylinders). Boulassal et al. (2007) retrieve lines of façades in laser point clouds and can, therefore, dimension the openings and the walls. However, their tests were made on relatively simple façades (not classical façades with columns, pediments, balconies and so on).

Modelling with images or point clouds allows building the visible captured parts of the objects. There will always be invisible parts in complex shapes. Furthermore, if we have to model the inside and the outside parts of a building, it is quite difficult to match data because of the low amounts of redundant data.

Finally parametric objects are now available in libraries for specific fields (steel structures, the boiler making industry, mechanics…) but no architectural libraries exist. Modelling from architectural rules (old treaties for ancient and classic style) (DeLuca 2007, Fuchs 2006) appears to be a promising field of research. However, only moulding objects are considered. No libraries of parametric architectural components exist.

As far as Gothic styles are concerned, some work exists. Chassagnoux et al. (1998) developed a tool to automatically create a gothic vault from its 2D representation in order to study its movement in time. Not all particularities can be created because 2D plans do not contain all characteristics. Havemann *et al* (2004) and Charbonneau *et al.* (2006) studied Gothic rose windows in order to generate parametric models. Havemann (GML 2008) conceived a low level interpretive language called Generative Modelling Language for the description of procedural shapes. GML can be used by developers to create domain-specific modelling tools. "The goal of the GML architecture is to facilitate the composition of high level tools for 3D modelling". The authors show examples of architectural objects, car components, furniture, but no library of architectural parametric elements. No software has been developed to handle this library and to adjust elements to measured data.

Contrary to point cloud and photogrammetry techniques that build 3D elementary shapes from the data and assemble them to create more complex shapes, we take the problem from the other side: our tool creates parametric 3D models of architectural elements. The adaptation of the shapes to measured data (pictures, 2D plans or point clouds) is processed by the adjustment of parameters.

3. SPECIFICITIES OF THE GOTHIC STYLE AND OF THE FIGEAC ABBEY CHURCH

3.1 Specificities of the Gothic style

The Gothic style can be classified into four types corresponding to its historical evolution: proto-Gothic, classic Gothic, radiant (rayonnant) Gothic and flamboyant Gothic. Each of these styles have stylistic specificities according to its geographical distribution: France, England, Germany, Italy or Spain. Whatever the style, its building is based on architectural rules and layout of elements having themselves their own dimensioning rules (Figure 1). Few documents describe these canons of the Gothic architecture. The main reason was the rarity and the preciosity of the paper at that period. The communication of knowledge was essentially oral. A second reason is due to the fact that layouts were directly drawn on the ground or on the material itself (Figure 2). Building knowledge and rules can be considered as schemes used as models for effective implementation.
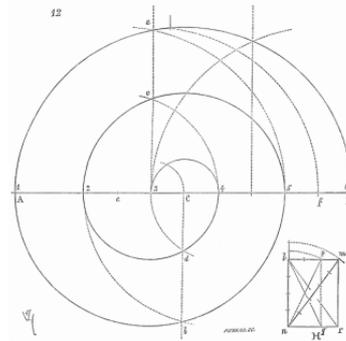

Figure 1: Scheme of dimensional rules between the various arches according to Villard de Honnecourt.

Figure 2: Layouts directly drawn on the ground itself.

The "carnet" (notebook) of Villard de Honnecourt (Honnecourt, 2008) is commonly admitted as a reference text for building art in the Middle Ages. It was written around 1230 and only sixty pages remain from one hundred. More recently in the 19th century, Viollet-le-Duc published his "French Architecture Argumentative Dictionary, from 11th to 16th century" (Viollet-le-Duc, 1967). He studied precisely Gothic styles from a theoretical point of view. Viollet-le-Duc and all the later writings have contributed to demonstrate the wealth and the variety of the Gothic style.

Our study of Gothic architecture focused firstly on the gothic vault. All the vault types (derived from previous Romanesque styles) can be classified depending on their plans, as well as their ridge and web geometrical and structural constitution:

pointed barrel, groin vault, rib vault... The choice of a set of geometric parameters can then be used to entirely build a specific vault by instantiating its architectural elements (boss, ridge, web...) and applying to them the geometric rules of that particular vault type.

3.2 Specificities of the Saint-Sauveur abbey church

The Saint-Sauveur abbey in Figeac (Figure 3) was built from the end of the XIth century to the end of the XIIIth century in the classic Gothic style. In 1572, the Protestants ruled the town and started on demolishing the church. The choir, part of the transept and some vaults of the nave have collapsed. The church was partially rebuilt in the XVIIth century. In 1840, it was considered as an historical monument. It was restored but the lantern of the cross between the transept and the nave collapsed on the nave and transept vaults in 1917. This eventful story left some marks that make the specificities of the abbey's architecture.

The bays have big variations because of the demolishing and rebuilding of large sections of walling (bell church, porch, cloister). Another peculiarity is visible in the vaults of the nave: the architects simplified the geometry of the transverse arches and of the diagonal ribs. The bottom parts of the arches and ribs are original but the upper parts are the simplified rebuilt parts (Figure 4, red circle). Finally, the main specificity is the difference between the two elevations of the nave: one side (filled in red in Figure 5) is composed of three parts (aisles, triforium and high windows) and the other side (filled in blue in Figure 5) has only two parts (aisles and very high windows) because it was not rebuilt as originally created. Beyond these architectural aspects, these differences allowed us to test the efficiency of our tool applied to Gothic architecture.
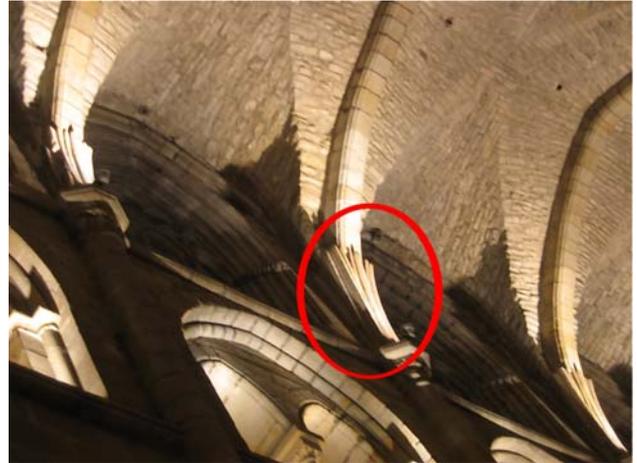

Figure 4: Inside view of the abbey church: transverse arches and diagonal ribs were simplified when rebuilt. The bottom parts are original (red circle).
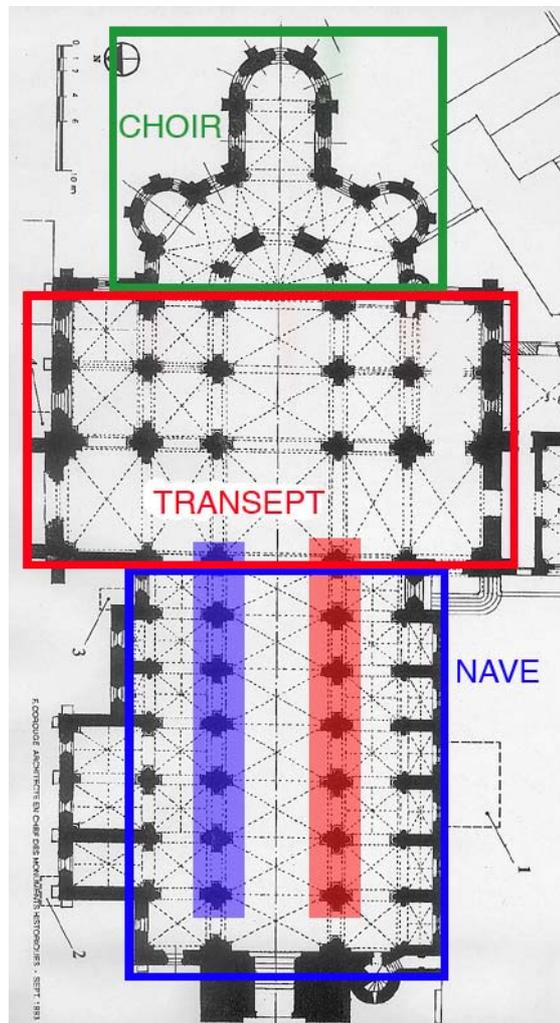

Figure 5: 2D Plan of the abbey church.

Figure 3: Outside view of the abbey church.

4. GEOMETRICAL STUDY OF THE VAULTS

The study of each architectural element allows us to define the dimensions and the various shapes according to the period and the space. This step is important because good parameters and building methods depend on it. It must cover at best all the

existing cases and allow us to keep only the minimal number of parameters enabling the object modelling.

The rib vault is one of the main elements that symbolized Gothic architecture. But there are many kinds of vaults, almost as many as there are churches. These differences were justified by the needs of the designers of these structures to assess their religious powers through an architecture more and more monumental and complex. They wanted also to express a strong religious art that encouraged the builders to be more and more innovative and creative.

A vault is an architectural term for an arched form used to provide a space with a ceiling or roof. The parts of a vault exert a thrust that requires a resistance. When the vault is built above ground, various replacements are employed to supply the needed resistance (thicker walls in barrel vaults, flying buttresses). The simplest kind of vault is the barrel vault (Romanesque) which is generally semicircular in shape. Then appeared the groin and rib vaults with all their variations.

The elements that compose a vault are (Figure 6):

- Main elements: diagonal ribs (A), wall arches (B), transverse arches (C) and filling surfaces.
- Secondary elements: lierne ribs (D), tiercerons (E), secondary ribs (F), main key vault (G), secondary keys (H).
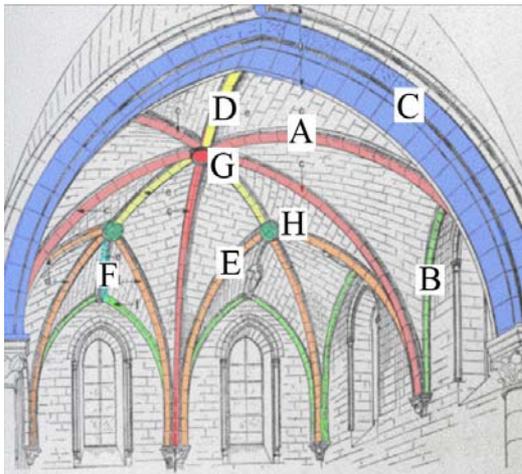

Figure 6: Elements that compose a vault.

Arches used in the vaults can be of various kinds. Villard de Honnecourt (Figure 1) identified the arches used in the Gothic styles and described them by indicating the centre of each arch (Figure 7). Once the dimension of the arch base is set, the user chooses the position of the centre (type of arch), and one can build in 3D the arches (transverse, wall and diagonal arches).
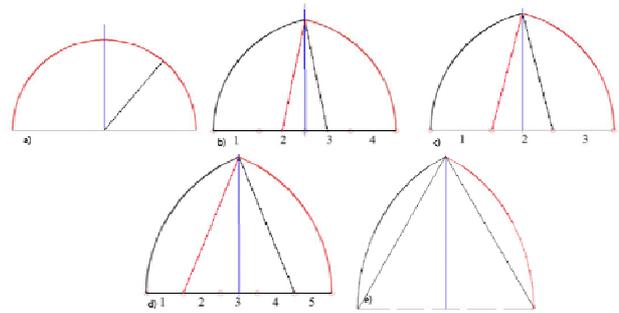

Figure 7: Various arch types; a) circular arch: the centre is on the axis. b) Two quarters and a half arch: the centre of the arches is at 5/8 of the arch basis. c) Three point arch: centre at 2/3. d) Five point arch: centre at 4/5. e) Arches created with an equilateral triangle.

We classified the vault according to its geometrical shape and summarized the results in a topological graph (Figure 17). Multiple nerve rib vaults are widely used and many examples constitute unique cases. We studied various cases but all of them have not been implemented yet. For instance, the main parameters for a quadrilateral vault are:

- Height, width and depth. For some kinds of vaults, parameters can be deduced from the others. Nevertheless the user is given the possibility to modify these values in order to adjust the theory to practical cases.
- Number and dimensions of wall arches, number and dimensions of transverse arches (red in Figure 8). If one of these two numbers is null, a barrel vault is modelled.
- Kinds of wall and transverse arches (Figure 7).
- Offset between wall and transverse arches (green in Figure 8),
- Presence or not of profiles along the various arches (wall, transverse) and ribs (diagonal, lierne, tierceron and other secondary ribs). Ribs can have a simple profile or have a complex shape (Figure 9) and can support various ornaments.
- Shape of the various profiles (blue in Figure 8).
- Presence or not of a key vault and shape (yellow cross in Figure 8). Keys are also various, complex and often composed of sculptured elements.
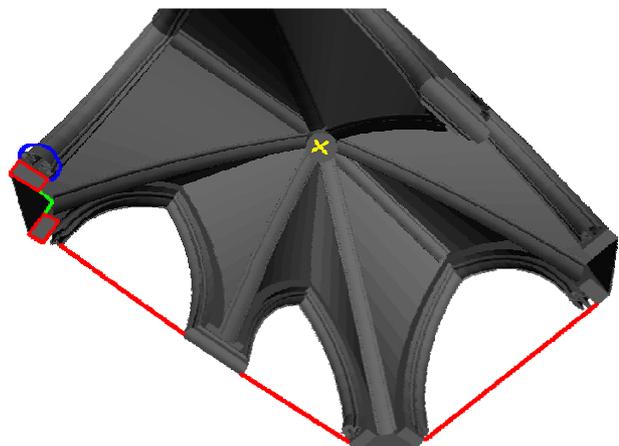- Deformation parameters to create trapezoidal vaults.

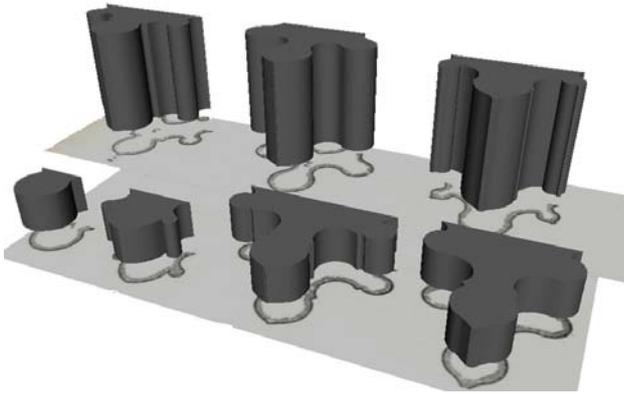Figure 8: 3D parametric model of a sexpartite vault.

Figure 9: Examples of profiles used for the ribs. We use moulding profiles to describe these shapes and create these ribs.

5. CREATING THE MODEL OF THE CHURCH

The modelling project of the Saint-Sauveur abbey was the first of this magnitude we had to carry out and with this complexity in the number of elements and in the geometry of certain architectural elements. We possessed laser point clouds of some elements (some vaults and sculptures), pictures, 2D plans and architects' sketches (details and picked-up dimensions of the moulding of pillars, scheme of ribs and their profiles that leave from the pillars…). 2D plans with measurements were used to dimension the main objects. Pictures and sketches have been used to parameter details.

5.1 Accuracy of the model, level of detail

The accuracy required for the model will be different according to the use that will be made of that model. For a game where real time is required, the elements will be generated in a simple shape. It is not necessary to add nerves to the ribs, complex sculptures and other small surfaces. Texturing will increase the visual result. On the other hand, for scientific or architectural studies, some details can be essential and thus be modelled. Our tool allows modelling according to the user's needs. An architectural element can be detailed or, on the other hand, can be simplified. The user determines the elements that are present and how they are represented. Of course, we have not yet implemented all architectural objects, and we never will. For example, we have not yet studied Gothic windows and all vault types are far from being implemented. We develop new components as needs require.

The project of the Saint-Sauveur abbey was to simulate an illumination project. We looked at the 3D model in its entirety. Some details have been illuminated to create a particular ambiance. We did not insert sculptures in the scene parametric description and did not model other small details because they would have considerably increased the volume of the data bases and the computation times for an insignificant visual result.

5.2 Modelling the Gothic church

The 3D model of the abbey requires more than 200 parametric objects (no duplications taken into account), for the interior and exterior parts. The object parameters have been adjusted from 2D plans, pictures and laser point clouds. The modelling task was structured in several parts (nave, transept, choir). Each part

has been split into floors. To proceed to the modelling, we have begun with parts that seemed to have symmetries. Then we have enlarged them, step by step, till we arrived at the external walls and the roofs.

Pillars of the nave have been created from moulding surfaces (Figure 10). More details on mouldings can be found in (chevrier 2008a).
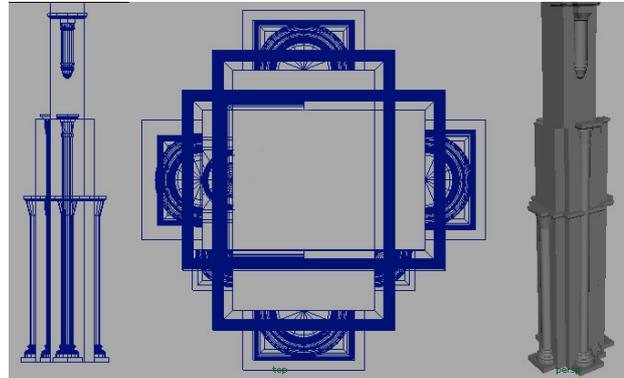

Figure 10: side, top and perspective view of a pillar.

The various bays of the nave do not have the same width: 206, 226, 240, 246, 240, 260, 228 cm. Therefore, we could not simply use duplication parameters; for each bay, we had to use other parametric objects with various values.

The most difficult part was the choir because of circular and deformed objects (walls and vaults) and because of the difficulty to lay out the non-linear objects relatively to each other. The main vault of the choir is a non-regular circular vault: the angle of each part of the vault is not the same, a parameter defines the angle value for each part. The length of each branch (Figure 11, value L) can also be specified if branches have various lengths. In order to create the deformed vaults of the deambulatory (vaults around the main circular vault of the choir), we have extended the parametric circular vault: secondary vaults are automatically added if a secondary vault is specified. Each part of the main vault generates a secondary deformed vault (deformation parameters are automatically computed) moved forward from a parametric given value (D on Figure 11) horizontally and vertically (Figure 12).

The choir is also composed of circular walls (containing openings). For such cases, we have deformation parameters to create a rounded object from a linear object. A part of wall becomes curved, leaving the sides as they were originally or making them perpendicular to the curve.
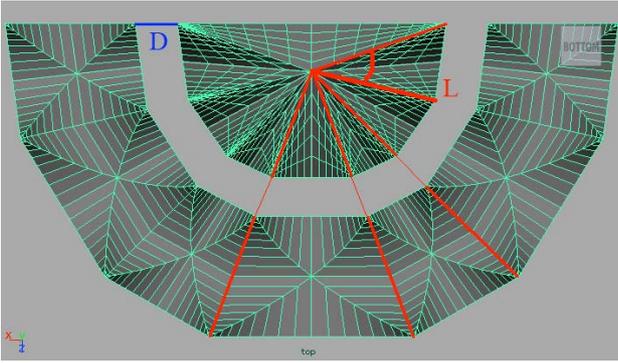
Figure 11: Top view of the vault set of the choir; Secondary vaults are deformed according to the main vault.
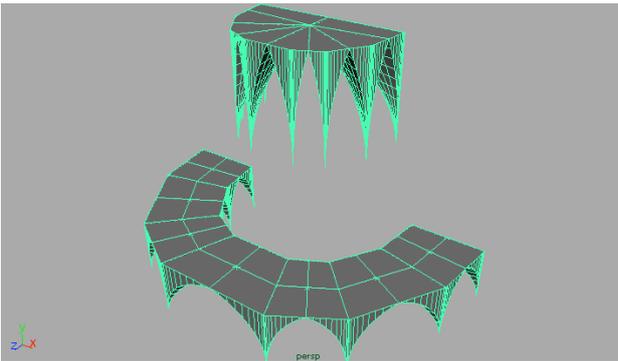

Figure 12: Perspective view of the vault set of the choir

5.3 Using bounding boxes

In order to adjust parameters to the existing data (2D plans, pictures and laser point clouds) we have used bounding boxes. For the adjustment using only pictures and point clouds, see (chevrier, 2008b) for other details. When using bounding boxes, we proceed as follows: the user creates a box B (our plug-in with a MyBox object). Then he positions, dimensions and deforms the box B to adapt the shape to his needs, with the help of 2D imported plans for example (Figure 14). Once this is done, the user can choose any of our parametric objects in the library to be created inside the box B. The object is dimensioned, positioned and deformed according to the box B. If necessary, the user can still adjust dimensioning, positioning and deforming parameters. He can also set the other parameters (type of arches, roundness of the various arches, presence or not of sub-elements like ribs, keys with their own parameters).

When using laser data, selected points in the cloud allow us to build a bounding box that will be used for the creation of a parametric object. Two points must be at least selected, and no more than eight. If there is a lack of points in the cloud, the user can create a new point and position it in the scene. When creating the box, the user specifies whether he is creating a parallelepipedic box or a deformed box.

In the case of a parallelepipedic box, according to the number of selected points, the bounding box is created differently:
- Two points with three different coordinates: a box is created parallel to the X, Y and Z axis of the scene. The position and the three dimensions of the box are indicated with the points.
- Three or four points: indicate also one or two directions for the orientation of the box, which remains parallelepipedic with right angles. If there are

several solutions, the user can choose between several proposals and adjust the box before creating the object.

In the second case, the deformed box is created as follows:
- Two points: the box cannot be a deformed box; some information is lacking.
- More than two points: according to the number of points, a box is created with the selected points as vertices. The lacking summits are added to complete the box. As previously, if there are several solutions, the user can choose between several proposals and adjust the box before creating the object.

Figure 13 shows the result of a rib vault created on a laser point cloud and Figure 14 shows the creation of a MyBox to position and dimension an object.
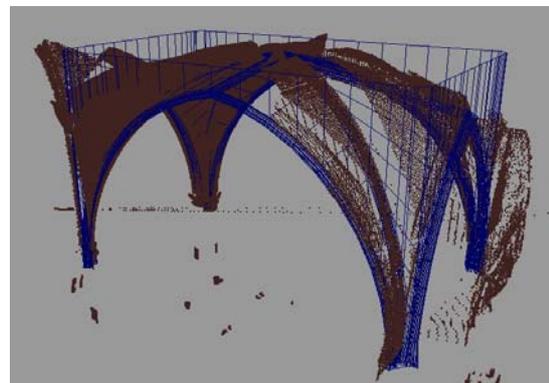

Figure 13: The position and the X, Y, Z dimensions of the 3D model of the vault is automatically adapted to the point cloud bounding box.
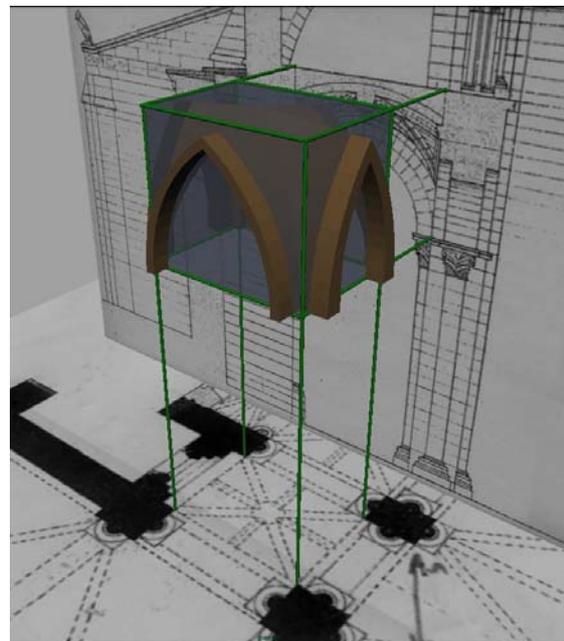

Figure 14: Using 2D plans and bounding boxes to dimension and position architectural parametric elements

5.4 Results

The whole 3D model was created with our parametric elements. The model was then textured and illuminated. Figure 18 shows various views of the 3D model. Figure 15 and Figure 16 show inside and outside views of the church.

Figure 15: 3D model of the Saint-Sauveur abbey, interior view.

Figure 16: Exterior view of the Saint-Sauveur abbey.

6. CONCLUSION AND FUTURE WORK

In this paper we have presented the method we have conceived and developed for the 3D virtual reconstruction of cultural heritage monuments. We took the example of a Gothic abbey. This project allowed us, on one hand, to prove the usefulness of parametric objects in such cases, and, on the other hand, to test our tool on an existing monument. The results are satisfactory and encouraging. In the future, we plan to study and develop other architectural elements to complete our library. We also plan to combine our tool with photogrammetry and point cloud techniques to improve the adjustment stage.

References:

Boulaassal H, Landes T and Grussenmeyer P, 2008: Automatic extraction of planar clusters and their contours on building façades recorded by terrestrial laser scanner. VSMM 2008 - Conference on Virtual Systems and MultiMedia Dedicated to Digital Heritage. Limassol Cyprus - October 20th - 25th.

Charbonneau, N., Boulerice, D., Booth, D. W. (2006). Understanding Gothic Rose Windows with Computer-Aided Technologies. *Proceedings of the 24th eCAADe Conference*, Bourdakis, V., Charitos, D., éditeurs, p.770-777.

Chassagnoux, A. and Guena, F. and Maille, M. and Untersteller LP.:1998, Modelisation and calculation of gothic or ogive vaults, First european congress on restoration of gothic cathedrals, Europa Congress Hall, VITORIA - GASTEIZ.

Chevrier, C. and Perrin, J.P., 2008a. Interactive parametric modelling: POG a tool for the cultural heritage monument 3D reconstruction. CAADRIA conference, Chiang Mai, Thailand, April 9-12 2008, pp.487-493.

Chevrier, C. and Perrin, J.P., 2008b. Laser range data, photographs and architectural components. ISPRS conference, Beijing, pp. July 3-11, p 1113-1118.

Debevec, P. and Taylor, C. and Malik J.: 1996, Modeling and Rendering Architecture from Photographs : A hybrid geometry and image based approach, Proceedings of SIGGRAPH, pp. 11-20.

De Luca, L. and Véron, P. and Florenzano, M. 2007, A generic formalism for the semantic modeling and representation of architectural elements, The Visual Computer, Volume 23, number 3, pp. 181-205.

El-Hakim, S. and Beraldin, J.A.: 2002, Detailed 3D reconstruction of Monuments using Mutiple Techniques, Proceedings of the internaltional workshop for cultural heritage recording, Corfu, Greece, pp 58-64.

Fuchs, A., 2006: Outils numériques pour le relevé architectural et la restitution archéologique, PhD thesis, nov 2006, Université Henri Poincaré, Nancy, France.

Havemann, S. and Fellner D.W., 2004: Generative Parametric Design of Gothic Window Tracery, *Proceedings of the Shape Modeling International*, Genova, Italy.

Palladio, A. 1965: The four books of architecture, traduction Isaac Ware, Dover publications, 1965.

Mueller P, Zeng G, Wonka P and Van Gool L, 2007: Image-based Procedural Modeling of Facades, ACM Transactions on Graphics, volume 26, number 3, article number 85. pages 1-9. Proceedings of SIGGRAPH 2007

Remondino, F., 2003: From point cloud to surface: the modelling and vizualisation problem. In proceedings of ISPRS International workshop on vizualisation and animation of reality-based 3D models, Tarasp-Vulpera, Switzerland.

Viollet-le-Duc E: 1967, Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle, Editions. De Nobele, Paris.

References from websites:
GML 2008, http://www.generative-modeling.org (accessed 12 Jan. 2008)

Maya software: http://usa.autodesk.com (accessed january 2009).

Photomodeler software: http://www.photomodeler.com (accessed january 2009)

Trimble : http://www.trimble.com (accessed january 2009)

Villard de Honnecourt : (accessed january 2009) http://villarddehonnecourt.free.fr/carnet.htm
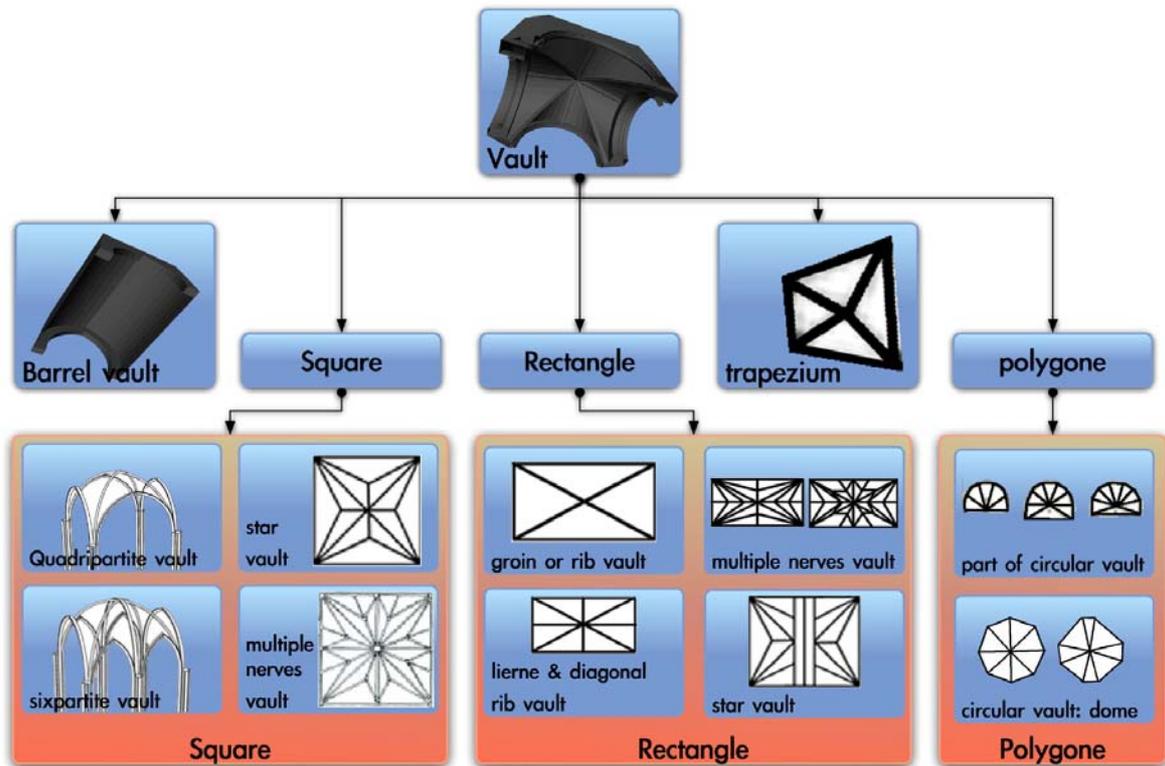
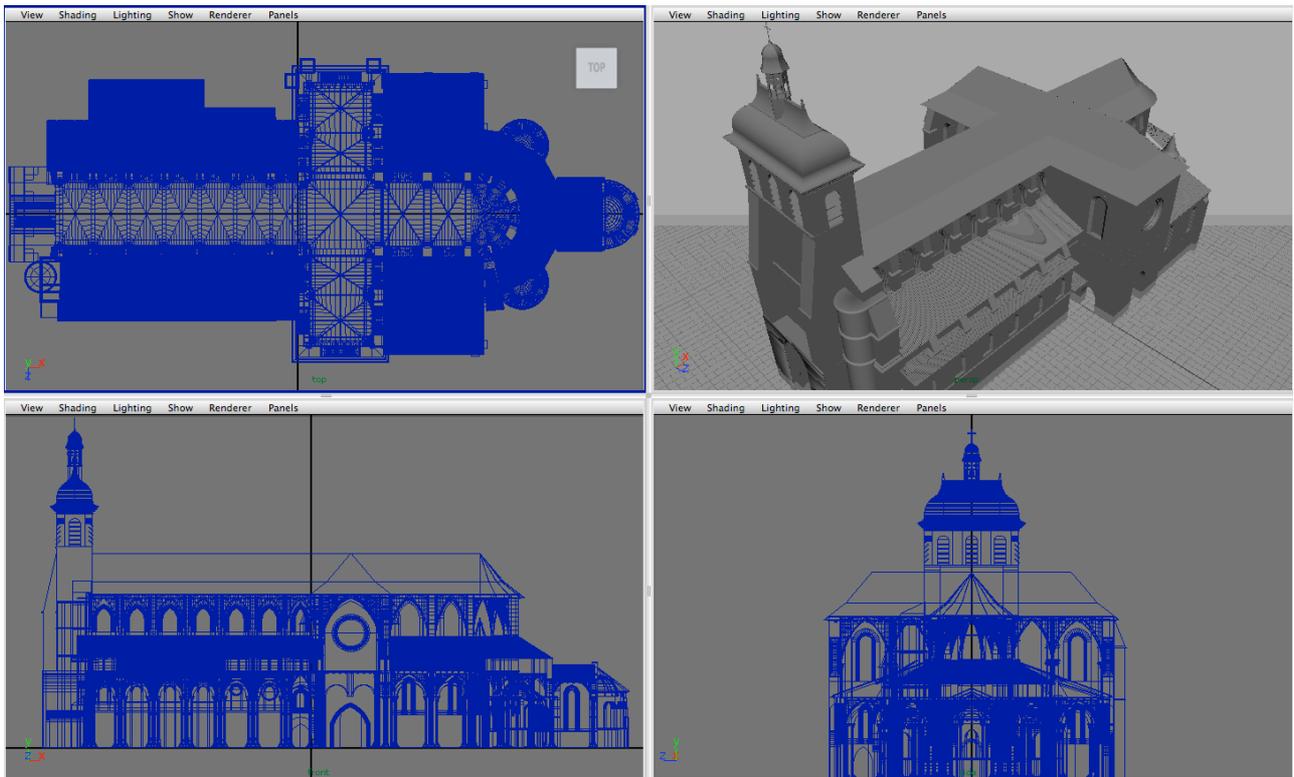Figure 17: Typologic organigram of the vaults.

Figure 18: The entire 3D model of the church has been created with our parametric architectural elements.