Transformations on Parametric Design Models

A Case Study on the Sagrada Familia Columns

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Abstract: This paper presents a research in progress in the development of parametric models for generation of complex shapes, and introduces a methodology for exploration of possible designs generated from a single model. The research presents a case study on the designs of the Spanish architect Antonio Gaudi, and takes on the fundamental rules of form generation of the lateral nave columns of the Sagrada Familia temple in Barcelona. A parameterization schema is presented as a fundamental tool for design exploration, which allows the reproduction of the original shapes designed by Gaudi, and the generation of a large set of new designs.

1 INTRODUCTION

Parametric modeling (PM) CAD systems, which until recently were high end commodities in the architectural domain, are becoming standardized tools to aid the design process in academy, practice and research. Initially intended for the aeronautical industry, parametric modeling systems are making their way into the architectural domain since they provide a powerful framework for conception of design, allowing the description of multiple instances and possible designs from a single modeling schema. PM systems are challenging the traditional use computer systems for representation of designs to intelligent models capable of interacting and responding to local and global variables imposed by the environment and by the designer at will. Parametric modeling systems pose a challenge to expand the design process beyond current limitations of traditional CAD systems by:

- Offering more flexibility to design parts and assemblies of complex nature;
- Provide reliable systems to test instances of designs from a single model;
- Expand design exploration of at the initial stages of the process.

PM requires rigorous thought in the process to build a model that is appropriate for the needs of the designer and a very sophisticated structure. Even though this task can be time consuming, a good parametric model has the advantage to provide a solid structure that will act as a container of information of the design history.

Furthermore, the model can be flexible enough to be constantly evaluated, revised, and updated if different components are added, changed and deleted, within the same structure of the PM.

2 PARAMETRIC MODELS

A parametric model is an abstract representation of a system or event in which some elements of the system have attributes (properties) that are fixed, and some attributes that can vary. The attributes that are fixed are called explicit, and attributes that are subject to change are called variables. Explicit attributes become variables through parameterization, a process that defines which components of the model will vary and how the variation occurs. Variables can also be constraint to a particular range of values. The variables can be independent, were the variable can have any value that is assigned to have, or they can be dependent, in which the value of the variable is related or linked to the value of another entity of the model.

Parametric modeling is the process of making a geometrical representation of a design with components and attributes that have been parameterized. Parametric design is the process of designing with parametric models or in a parametric modeling setting.

2.1 Instances of a Parametric Model

The principal advantage of a parametric model is that it allows a level of flexibility to perform transformations that would result in different configurations of the same geometrical components. The different configurations are called instances of the parametric model. Each instance represents a unique set of transformations based on the values assigned to the parameters. As a result, variations on the design are obtained by assigning different values to the parameters that yield different configurations. In simple terms, a parametric model allows the designer to perform changes and reconfigurations of the geometry without erasing and redrawing

2.2 Scope

The scope, number of design instances that a parametric model can generate, will depend on a balance between the parameterization schema, the constraints and degrees of freedom of the parameterized components, and the geometrical model representation. Together they will determine the size of the design space allowed by a parametric model.

The parameterization schema will determine which are the attributes subject to parametric transformations, in other words which components of the model will vary and which components of the model will be fixed. The step value assigned to the parameters, along with the constraints, will determine the increment in which the parameters can vary.

The representation type of the geometric model will determine if topological transformations are allowed. In the case of a circular shape, unless a different representation is chosen, the shape will always remain a circle. If instead of a circle we had chosen to use four arcs, the resulting shape will have generated all kinds of ovals and ellipses including circles as well.

3 PARAMETRIC MODELS FOR THE COLUMNS OF THE SAGRADA FAMILIA

The singular character of the work of Gaudi is the result of a sophisticated geometrical manipulation of simple forms derived from his own observations of nature. Gaudi's design rules are based on the architects' intuition and interpretation of natural forms rather than scientific knowledge of mathematics and geometry. The geometry of the columns of the nave of the temple is the result of the studies that Gaudi performed between 1915 and 1923.

Gaudi initially proposed a helicoidally shape column, like the salomonic columns from the renaissance. However, Gaudi considered that the single twist was visually inappropriate, since it produced a visual perception of a weak column that could be squashed or deformed. The visual imperfection of the single twist column which bothered Gaudi for a number of years was solved by the use of two rotations. This methodology, which has no know precedents in architecture, is the result of eight years of work and experiments and Gaudi's interpretation of the helicoidally growth present in trees and plants.

3.1 Generation Procedure

Gaudi's novel solution consisted in the use of two opposite rotations of the same shape, once clockwise and another counter-clockwise, much like superimposing two opposite twisted columns on top of each other. The process of double rotation of the columns is better explained graphically, to shows the generation process of a square column, known as *the column of 4*. Figure 1 shows a square shape extruded along a vertical axis with a 22.5 degree rotation. Figure 2 shows the same procedure with a negative rotation, known as a *counter-rotation* of the same square shape. When the two shapes are superimposed and a Boolean intersection is performed, the resulting shape is the actual column of 4 as develop by Gaudi (Figure 3). Even though Gaudi did not have knowledge of how Boolean intersections are done in a computer, the resulting shape from the Boolean intersection is analogous to the actual column originally designed by Gaudi, which simulates the techniques used by the plaster modeling process (Burry 1993, 54).

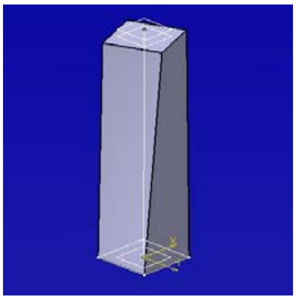

Figure 1 Rotation

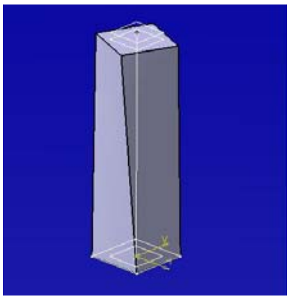

Figure 2 Counter-Rotation

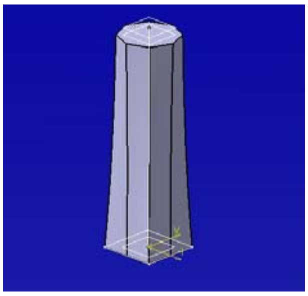

Figure 3 Intersection

The columns on lateral nave of the Sagrada Familia nave follow the same procedure, where the only variations are the initial shape, the height of the column, and the rotation degrees.

3.2 Reconstruction of the Column Model

The work started by the reconstruction of the columns knots of the lateral nave of the Sagrada Familia. The rectangular knot (Figure 4) was selected as the main model for the parametric exploration. The first challenge was to find a suitable modeling procedure that will yield an accurate representation of the knot. The modeling system we chose did not have the appropriate tools to reconstruct the knot shapes according to the counter rotation procedure prescribed by Gaudi. This initial challenge called for alternate ways to represent the column knot. After a series of experiments it was found that using a bottom (initial) and top (final) shapes of the knot and filling the space in-between with a blend surface algorithm, the resulting form will generate the knot shape that was visually equivalent to the original plaster model by Gaudi. Figures 5 and 6 show the parametric model of the column and the knot and the comparison with the plaster model by Gaudi.

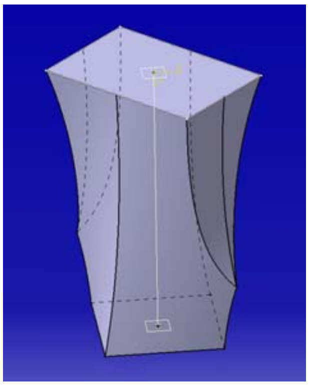

Figure 4 Column Knot

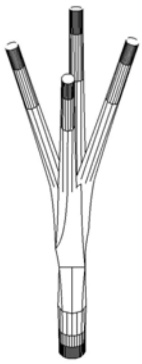

Figure 5 Parametric Model

Figure 6 Original

Figures 7 through 10 show the sequence for the generation of the parametric model. The first stage was to create the top and bottom figures and locate them in parallel planes at a distance equivalent to the height of the column knot. A pair of top-bottom figures was created for each rotation. This wireframe model is called the parametric skeleton (Figure 7). A surface fitting algorithm was applied to each pair of top-bottom shapes producing both the rotation and counter-rotation shapes (Figures 8 and 9). The two generated shapes were used to perform the Boolean intersection that generates the knot shape (Figure 10). Although this procedure of blending between two shapes was not described by Gaudi, nor any other researchers and scholars, the resulting columns were not only geometrically accurate, but also visually correct when compared to the original Gaudi models.

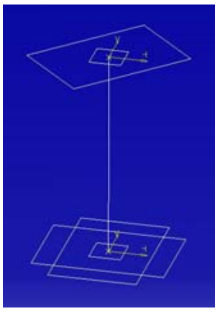
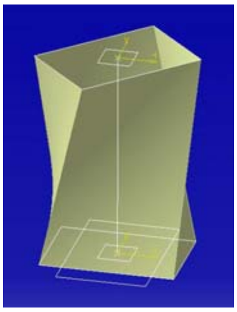
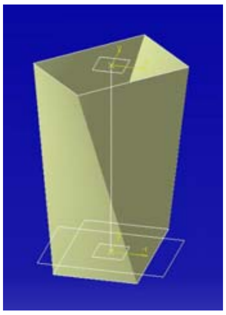
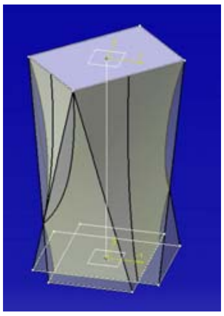

Figure 7 Skeleton **Figure 8 Blend-1** **Figure 9 Blend-2** **Figure 10 Knot**

3.3 Parameterization of the Column Model

The parameterization of the column knot was performed by building a parametric skeleton and implementing surface fitting procedures which generated the shapes for each rotation of the column. This parameterization schema can be subdivided into three parts: The skeleton and primitive shapes, the surface fitting procedure and the resulting shape from the Boolean operation. For the purpose of this paper we will concentrate in the first part of the parametric model, leaving the second and third unvaried.

In the parametric skeleton there are three types of geometrical components: the axis of the column represented by a line, two parallel planes where the top and bottom shapes will be located, and the top and bottom shapes. Each surface procedure is composed of two initial shapes one on the top and one for the bottom, for a total of 4 initial shapes. The parameterization schema only constrains the location of the initial shapes to the top and bottom planes. The planes must be normal to the axis line. The shapes are not constraint and are free to take any kind of geometrical and topological transformations. The parameterized model of the column knot is shown in Figure 11. The same procedure was applied to the column of four shown in Figure 12.

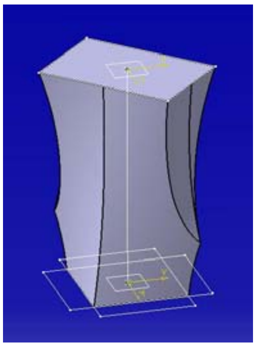

Figure 11 Parameterization of the Knot

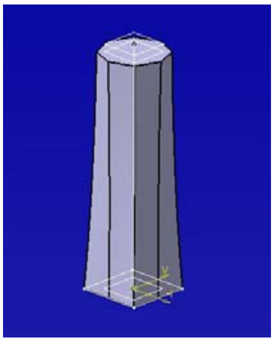

Figure 12 Column of Four

3.4 Transformations of the Parametric Model

The first set of transformations was done to the top and bottom shapes, starting with variations of the proportions of the lower rectangles, to variations on the angles and finally with variations on the four initial shapes. The height of the column, as well as the rest of the parameters remained unchanged through these set of operations. An important discovery was that the topology of the final column would be altered as a result of changing the parameters of the initial shapes, even though the topology of the all the geometrical components of the model remained unchanged. Figure 13 shows different variations of the design obtained from the same parametric model. Other set of transformations included changes in the topology of the primitive shapes. The parametric model allowed topological changes and still maintained the integrity of the surface fitting procedures without breaking the model, or causing geometric problems.

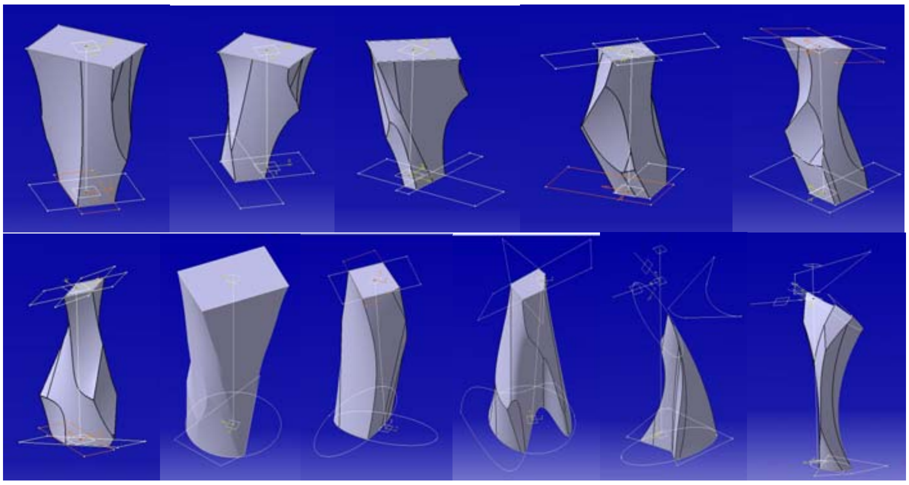

Figure 13 Parametric Variations

4 DISCUSSION

Even though there are four initial shapes, the parametric model does not determine what kinds of shapes are valid. Potentially, there are no limits in which kinds of shapes can the designer use as long as they are closed; therefore the parameterized entities tend to go to infinity, in which case the number of possible designs from this parametric model is infinite. In order to determine a limit number of possible designs it is possible to limit the parameterization of the initial shapes to a certain type. In this case the number of design instances will not only depend on the number of shapes, but the possible combinations among them. This is defined as parametric combinations.

The generation of a parametric model requires a level of thought beyond the representation of a design idea, but provides a very powerful framework for design exploration. In the architectural domain most cases have used applications of parametric models in the context of design development, where most of the design decisions have been made. Which leads to the question of what is parametric design? On the other hand, if it becomes necessary to know in advance what the design is what the role of a parametric model is? Even though the modeling process demands rigorous thinking about the design, the initial assessment of the research proved the potential to use parametric models for design exploration in the initial stages of the design process. Perhaps a well defined parametric model will serve for the purpose of creating designs in a particular language while discarding other that do not fit the criteria.

4.1 Counting New Designs

Since all of the designs obtained were the result of altering only the initial shapes of the parametric model it would be worthwhile to speculate how many possible designs a parametric model can generate. For the column knot, the parametric variations were done exclusively in the initial shapes. Consequently, for the case of the column knot the number of possible designs will depend on the number of shapes and the parameterization of the initial shapes. Additional parameters include, the location of the planes, the direction of the axis, the length of the axis, the surface fitting procedure, which for the set of transformations studied, remain unchanged.

Based on the aforementioned premises, the design space (DS) of the parametric model equals to the sum of number of parameterized entities (PE), and the step value of the parameters (SV), multiplied by the number and type of constraints (CN) which determines the degrees of freedom. The CN is a factor between 0 and 1, where 0 means that the constraints don’t allow any transformations, and a factor of 1 allows infinite degrees of freedom. The representation type (RT) and the ability to regenerate the model (RM) are more difficult to be quantified; therefore they will remain as constants of value 1. The following formula can be derived:

$$DS=(PE+SV)*CN*RT*RM \quad (1)$$

Where the parameterized entities are the four initial shapes; the step value of the parameters is not defined, therefore is zero; and the constraints are not defined, therefore the value is 1. If were to plug-in the values mentioned the formula will be

$$DS=(PE+0)*1*1*1 \tag{2}$$

Therefore the number of designs generated by the model is directly proportional to the number of parametric entities (PE). The presented model showed that is had the ability to generate infinite instances of design from a single parametric model. Although the robustness of the parametric model was mostly dependent on the sets of relations and procedures, it allowed the designer to

If we were to consider that design representations, such as plans, elevations, and 3D models, are geometrical models in an explicit representation, we must conclude that they are subject to parameterization. This proves that there is a great potential for applications in architectural design that has yet to be explored.

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