COMPUTATIONAL MORPHOGENESIS APPLIED TO THE CHURCH OF LONGUELO

Reflections upon a possible parametric interpretation of the original design concepts

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Abstract. Before the introduction of NURBS-based CAD software and optimisation, the design of form-resistant structures was based on the use of either experimental tools (physical form-finding) or analytical surfaces, and architects were challenged in the articulation of spaces from the intrinsic characteristics/rules of structural forms. An outstanding example of this kind is provided by the Church of Longuelo, which was built by architect Pino Pizzigoni in Italy, between 1961-1966. It was conceived as composed by two major elements – an irregular frame and a set of shells suspended to it. The entire design process was based on the calculation of the frame on which the shells have been just added as a dead load. This paper presents one possible way to redesign the church parametrically. Comparison with the original design is not performed at the final formal level, which can logically differ, but around the concepts behind the project. The aim is to show how current digital design and optimisation tools are affecting the way architects design. But, at a higher level, the purpose is also to highlight where conceptual design is now taking place in the process.

Keywords. Parametric design, optimisation, computational morphogenesis, Pino Pizzigoni, Church of Longuelo.

1. Introduction

The term ‘parametric’ was born in the world of mathematics to define all those “equations that express a set of quantities as explicit functions of a number of independent variables, known as ‘parameters’” (Weisstein 2003).

Its architectural transposition was introduced by Luigi Moretti during the Forties and indicates a consistent system of elements and relationships
among them, which is founded on the construction of topological rather than metrical spaces.

The world of forms reveals itself to us through the differences between one form and another. [...] Differences are the inevitable, intransgressible flashes of reality and of the forms; they are the forms. [...] A non-elementary form is constituted by a group of differences that are themselves connected by relationships that express and oblige their order and sequence. The complex of these relationships is the structure of a form, which can be expressed in the abstract as a complex of pure relationships (Moretti, 1957).

The term ‘parametric’ identifies the only invariant of each and every design process with the potential of standardisation in digital design (Aish, 2005). Through parametrics, digital technology is changing into a resource for conceptual design, which is used to formulate problems in a different way and construct resolution tools and strategies in an interactive manner.

This paper aims to highlight this phenomenon by means of parametrically redesigning the historical case study of the church of Longuelo, by architect Pino Pizzigoni (1961-1966). Before the introduction of NURBS-based CAD software and optimisation, the design of form-resistant structures was based on the use of either experimental tools (physical form-finding) or analytical surfaces, and architects were challenged in the articulation of spaces from the intrinsic characteristics/rules of structural forms. The presence of an existing project permits a clear comparison between design processes and shows where conceptual design is now taking place.

2. The church of Longuelo

Pino Pizzigoni designed the church of Longuelo, near Bergamo, in Italy, between 1961 and 1966. This is generally considered his most relevant project based on shell structures. His interest for shell and spatial structures started after the Second Post War. First, he built a few prototypes of hyperbolic paraboloids and umbrellas in a field of his own property. Then, he applied that experience to the roof design of some schools and factories around Bergamo (Deregibus and Pugnale, 2010).

The church spans over 900 square meters, for 18 meters top height. It is conceived as a double-reflectional symmetrical room made of four identical quarters. Each quarter is made of 5 reinforced concrete hypar shells and a beam frame. Figures 1 and 2 show, respectively, an external and an internal view of the church.
2.1 ORIGINAL DESIGN AND CONCEPTS

Pizzigoni’s archive is currently located in the public library of Bergamo “Angelo Mai”. It can be assumed from the documents found that Pizzigoni based the design of the church of Longuelo on three main propositions:
1. The use of hypar shells
2. The Möbius ring
3. The tent pitched by God (Figure 3).

Geometrically speaking, four hypar-surfaces are joined together in the shape of a ring and then topologically transformed into a Möbius strip. A fifth hypar is placed between the other ones in order to give strength to the overall configuration. The use of hypar shells offers several spatial configurations for the proposed frame. Moreover, the topology through which he arranged the hypars, allowed the architect to put to practice the concept of Möbius ring as well. Another feature related to the hypar is that the internal space results in a single, smooth surface that echoes the concept of the tent pitched by God, metaphorical / biblical concept described by the gospel of John (Deregibus and Pugnale, 2010).

In order to better understand Pizzigoni’s design, a three-dimensional model in Rhinoceros® of the church has been developed. Free bars of the frame have been explicitly avoided in order to focus on the spatial complexity provided by the shells (Figure 4). Now, by focusing on a single quarter, it is possible to understand how the geometry of the shells works (Figure 5).

*Figure 3. The three concepts behind the project of the church: hyperbolic paraboloids, Möbius ring, the God tent (Pizzigoni Archive, scanned by C. Deregibus and A. Pugnale).*
3. Computational morphogenesis of the church

According to a classical engineering approach, the church would now be optimised to verify the accuracy of the original structural design and, therefore, the extent of Pizzigoni’s expertise and intuition. Such a process generally starts from a parametric definition of the existing geometry, as it was conceived by the architect - no design is involved, but just a form-improvement of a well-defined structural layout is performed.

In this Section, a different approach is shown. The aim is to use parametric design and optimisation to define a computational process of morphogenesis, in which conceptual design is highly involved.
3.1 DESIGN OF THE PARAMETRIC MODEL AND OPTIMISATION

As mentioned before, three main concepts led Pizzigoni towards the final design of the church: (1) the use of hyperbolic paraboloids, (2) the Möbius ring and (3) the God Tent.

The parametric model of the church is here defined from such concepts rather than referring to the built geometry. This permits the optimisation algorithm to generate new spatial configurations of the church, and therefore it allows morphogenesis to take place.

The model is generated by means of Grasshopper®, a Rhinoceros® plug-in that allows the definition of parametric systems and their visualisation in real-time.

3.1.1. Boundary conditions, design variables and solution domain

First, the symmetrical and centrical layout of the original church is preserved. The parametric model is therefore based on a single quarter of the church, which is subsequently mirrored twice.

Second, each quarter of the original church is composed by five hypars, four of which define a Möbius ring. The topology of such a ring is preserved by the parametric model, but the position of the fifth hypar becomes a design variable. Three different edge conditions are possible for this hypar, as shown in Figure 6.

Figure 6. Four hypars define a Möbius ring and their topology is preserved. A fifth hypar can be placed in three different positions and is a design variable of the optimisation problem.
Figure 7. Eight points define the geometry of a quarter of the church. The coordinates of the points are design variables and their solution domain is shown here.

Third, the structural frame is determined by the edges of the hypars, and the geometry of the edges is controlled by acting on the coordinates of eight nodes. Defining the solution domain of such coordinates is a key point (Figure 7). A bounding box that embraces the volume of a church quarter is defined and acts as the overall domain for positioning the eight nodes. Four nodes are further constrained to the upper part of the box to generate a closed roof (R₁, R₂, R₃ and R₄); two points are retained to the lower part of the quarter to define the connections with the ground (B₁ and B₂); the last two points are kept into the middle part of the quarter (M₁ and M₂).

Defining a parametric model of the church in this manner involves design. Therefore, this is only one of the possible ways to interpret the concepts by Pizzigoni, and has a purely illustrative scope of what ‘parametric thinking’ stands for.

3.1.2. Fitness function and penalty functions

Optimisation is here used as a source of inspiration. The aim is to develop the church design through the generation of a wide spectrum of geometries, which perform efficiently in structural, spatial and functional terms. In order to do so, multi-objective optimisation is used.

Structural behaviour is the first performance. Nodal vertical displacements of the church frame are calculated by means of the FE solver Karamba, a Grasshopper® plug-in which was developed by Clemens Preisinger with Bollinger+Grohmann (Preisinger, 2013). Karamba is chosen because permits to rapidly connect geometric and structural models within a single parametric environment, i.e. Grasshopper®. Applied loading refers to the original calculations provided by Pizzigoni (Deregibus and Pugnale, 2010).
Spatiality and functionality are then considered together as the second performance criterion. The idea is to calculate the maximum amount of space covered by the structure with no intermediate supports. Without this function, the algorithm would tend to reduce the structural frame size towards unusable dimensions.

Galapagos, a ‘black-box’ Genetic Algorithm implemented in Grasshopper®, is used to perform the optimisation. Genetic Algorithms (GAs) are meta-heuristic search algorithms based on the mechanics of natural selection and natural genetics (Coelho et al., 2014). They provide a robust and flexible tool to solve complex problems and their meta-heuristic way of exploring suitable solutions seems to be particularly helpful in architecture – designers generally benefit from comparing several sub-optimal outcomes rather than converging to a single optimal one.

Multi-objective is pursued through the aggregated fitness function \( F(1) \). Such a function aims to minimise nodal displacements (2) while the area covered by the shells is maximised (3). For both criteria, solution domains are normalised.

\[
F = c_1 F'(dz) + c_2 F'(A) + P \tag{1}
\]

\[
F(dz) = \sum_i (dz_i) \in \mathbb{R} \quad \rightarrow \quad F'(dz) \in [0; 1] \tag{2}
\]

\[
F(A) = [A]^{-1} \in \mathbb{R} \quad \rightarrow \quad F'(A) \in [0; 1] \tag{3}
\]

The optimisation process also includes a penalty function \( P \), in order to prevent self-intersections between shells. Two weighing coefficients, \( c_1 \) and \( c_2 \), are finally applied to treat the performance criteria equally.

4. Design through optimisation: reflections

The GA was run multiple times to increase the amount of geometries generated through optimisation. Figure 8 shows a comparison among configurations with similar performance but very different shape. In Figure 9, a further reduction to five representative solutions is proposed to provide full details for each of them. For these, views of the church interior are also rendered (Figure 10) to understand the spatial quality they offer. The geometrical variety given by the external axonometric views is not reflected by the spatiality of the internal perspectives, which look very similar to one another. Similarity is given by the position of the fifth shell edges, which is shared by the five selected geometries. Structurally speaking, they are all very efficient, but the quality of the interior spaces is much lower than in the case of the original design, where light is brought in creating a kind of clerestory.
Figure 8. Variety of shapes generated by the optimisation process. Fitness decreases (improves) from top to bottom but is comparable among geometries in the same row.
Figure 9. Five geometries with different shape but comparable and very low fitness.
5. Conclusions

When applied to historical case studies, optimisation is generally used to verify the accuracy of the original structural design, and therefore the level of the architect’s expertise and intuition. No design is involved, but eventually a form-improvement of a well-defined structural layout is performed.

In this paper, a different approach has been shown.

First, a parametric reconstruction of the church has been defined starting from the original architect’s concepts rather than on the built form. This has shown only one of the possible ways to translate Pizzigoni’s ideas into a system of topological relationships.

Second, optimisation has been used as a source of inspiration. The definition of a suitable fitness function has been fundamental to list priorities for the church design (such as structural performance, covered area, etc). A GA has been run several times in order to explore a wide spectrum of possible solutions, but mainly to appreciate how the initial settings (boundary conditions, design variables, solution domain, etc) might affect the algorithm outcomes.

References


