

# Integrated design of a large span roof: a parametric investigation on structural morphology, thermal comfort and daylight

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## Abstract

In this paper we present a case study of using parametric modelling to achieve performance oriented design. The design subject of the case study is a wide span roof, which is part of a larger ongoing project in Bologna (Italy). The use of renewable resources available on site has been a key aspect of the project. Here we focus on passive reduction of summer overheating and on daylight. For these tasks a parametric model has been developed. Three project scales are being discussed. At the large scale, parametric variations of the overall shape of the roof are investigated in relation to cooling through ventilation; here the parametric model allows for the generation of both different configurations of the roof, including its structural morphology, and variations of its structural tessellation. At the medium scale, the integration of openable modules is investigated in relation to air extraction for cooling; with respect to this, the parametric model allows exploring openings based on variations of size and distribution. At the small scale, various options are explored for the cladding system, in order to reduce the direct solar gain while still allowing the income of indirect natural light; and the parametric model has been used to investigate the configuration of self-shading modules and their integration in the structure. The advantages in design process and the current limits of the parametric modelling approach used here are discussed.

*Keywords:* performance-oriented design, integral design, passive solar concepts, parametric modelling, large modular structures.

## 1 Introduction

In this paper we discuss the support provided by parametric modeling in the design process of a large roof in Bologna (Italy). Parametric modeling is an increasingly popular digital technique in architectural design processes and is being more and more widely used in practice and education. Presenting the generic potential and limits of parametric modelling is out of the focus of this paper and this subject has been discussed before (i.e. Aish and Woodbury, 2007); however its capability of representing both geometrical entities and their relationships is hereby recalled as the key potential of this technique. Geometrical entities in the model are structured in a hierarchical chain of dependencies; independent parameters acting as variables can be included in the chain to describe a range of variability; assigning different values to the independent parameters produces different instances of the model. This is a measureable advantage that enables the designer to quickly generate alternative design solutions; however it requires the structuring and abstraction of the design process beforehand (called parameterization process) following rigorous criteria to explore the solution space

of the model by evaluating the generated alternatives and identifying the suitable ones. Based on this framework, we relate parametric modeling to performance oriented design, specifically referring to the solar energy control and structural morphology of the roof. The factors affecting these two aspects were used as keys to parameterize the model of the roof in three different project scales: large, medium and small; furthermore the solution spaces of those parametric models were explored and evaluated based on the performances of the roof.

In the first section of the paper we introduce the overall project that includes the roof and provide deeper insights into the performance targets that are required. The second section relates the architectural geometry of the roof with the investigated performances and presents the parametric model for the three scales of the project. In the last section, we discuss the conclusions of the case study and further work by referring to potential and current limits of parametric techniques.

## 2 The UNIPOL project in Bologna and the Vela Roof

The large span roof subject of this paper is part of an ongoing project in Italy referred to here as the UNIPOL Project. The project is a large intervention on a 45.000 sqm plot in the periphery of Bologna (Italy) and it develops an area for services. More specifically, three building blocks enclose a public square: a high-rise office building, a hotel, and a system of lower buildings for shops and services. The latter are referred to as the Piastra. The office tower is a 130 meters high building located in the North side of the area; the hotel faces the South direction, with a floor extension of approximately 6.000 sqm; the Piastra is between them, with a surface of 5.000 sqm including shops, restaurants, and a fitness. The outdoor space semi-enclosed by these buildings forms a square at the ground floor level. This square has an underground multilevel parking structure underneath and is partially covered by a large roof, the Vela, resulting in a semi-outdoor public space open along the sides. The overall area is illustrated in Figure 1, showing the concept developed by the architectural office. Currently, the office tower is under construction; the Hotel, the Piastra, the Vela roof, the square and the parking place are in an advanced stage of design, with the call for tenders being open. The architectural process is lead by Open Project Office; the structural design is lead by Prof. Massimo Majowiecki and his office; by focusing on the Vela roof, an interdisciplinary group at TU Delft was involved in the design process as part of a PhD research project on performance oriented architectural geometry for large modular and adaptable structures.



Figure1. Concept developed by the architectural office [images courtesy of Open Project Office, Bologna].

### 2.1 Performance oriented design of the Vela Roof

The Vela roof is a large span structure of approximately 65x65 meters. It is meant to protect some of the outdoor public spaces from climatic factors and at the same time provide an iconic sign within the architectural project. One of the architectural requirements concerns the visibility of the office tower from the spaces underneath the roof. By focusing on the technical requirements of the roof, two are the main performance-related aspects which have been dealt with in more depth: its structural behaviour and its influence on the thermal comfort and daylighting of the spaces underneath. The structural performance has been tackled by the structural engineers; the details of these studies are

outside the scope of this paper and the focus is instead given to the geometrical aspects of the structural morphology. Furthermore, the roof is expected to have a large influence on the thermal comfort and daylighting of the covered spaces. These two aspects and even more their combined design were a crucial issue; and their relations with the structural geometry are direct. Preliminary studies on these aspects can be found in a previous publication (Van Timmeren and Turrin, 2009).

Deeper insights on the climate aspects are provided by the analyses of the local climate, based on EERE statistics data (EERE, World Wide Web reference). Specifically, the local climate is characterized by high annual thermal excursion (about 22C difference between the coldest month, January, and the warmest, July), limited wind speed and absence of dominant wind direction, high air humidity and little precipitations. In such a condition, possible summer overheating under the roof has been identified as the most critical risk. Preliminary calculations made on a reference roof's shape and materials confirmed the risk of highly uncomfortable thermal conditions. In order to improve this critical situation a wide range of investigations has been made during the design process of the roof. Strategies for improving the thermal comfort involve a large set of combined systems for heat gain reduction and passive cooling, among them increasing and controlling the air flow, reducing the direct solar radiation and the mean radial temperature of the roof, using thermal mass and evaporative (adiabatic) cooling for reducing the maximum temperatures. Not all of them are being discussed in this paper; the following sections focus on air flow for cooling and reduction of solar gain as the ones directly related to the architectural geometry of the roof. When investigating the architectural geometry, structural morphology needed to be taken into account. In order to favour a design process that enables to integrate them in an overall approach, a parametric model has been developed and is being presented in the following sections.

### 3 Three scales of performance oriented architectural geometry.

Different possible configurations of the overall roof's shape have been explored for increasing and controlling the air flow for cooling. This has been investigated with respect to two possible air-flow drivers: wind and stack effect, which are both directly affected by the large scale geometry of the roof. The investigations on the medium scale of the project focused on the integration of openable modules for air extraction; while at the small scale, various methods for reducing the solar gain have been explored by analyzing different options for the cladding and shading system. The first two project scales are briefly presented, while a deeper description is provided for the last one.

#### *3.1 Large and medium scales performance-oriented architectural geometry*

Large scale geometry has been explored for possible uses of cooling through wind-driven ventilation by mean of using the on-site air drafts; and for heat extraction through stack effect driven ventilation by mean of increasing the height of the structure. In order to investigate the use of wind-driven ventilation for cooling, CFD simulations have been performed to analyse the air flow on site. Although the location has little wind and no a dominant wind direction, the simulations show that the built environment creates some enhanced wind speeds. In order to make effective use of these draughts, their speed should increase under the roof. Shape variations were investigated to locally induce Venturi-effects that would result in increasing the air speed in the direction of the created negative-pressure areas. Among the boundary conditions given by the architectural concept, the curvature of the roof is the key factor. On the other hand, the thermal stack effect is driven by buoyancy, which increases when increasing the height of the extraction point. This explains the relevance of the investigation of both aspects with respect to the overall shape (Figure 2).

In the parametric model, the overall shape of the roof is described through a NURBS surface. This one can be modelled through a set of independent parameters corresponding to the Cartesian coordinates of the NURBS control points. While exploring different curvature options, the structural

morphology was taken into account. The model assumed as conditions the preliminary studies conducted by the engineers (see acknowledgements) by favouring the selection of a double-layered space truss. At this stage, an external triangular-based layer and an internal triangular and hexagonal-based layer were preferred. This structural geometry was parameterized in a flat starting configuration of a square surface and modelled based on a dependency chain by describing the position of the top layer's nodes on the surface, using UV coordinates. Specifically, a two dimensional point array was set and the number of rows defined as an independent parameter,  $n$ , to regulate the density of the grid (Figure 2). Based on the top layer, the bottom layer nodes were created at a parametric distance  $d$ ; top, bottom and diagonal bars were added. The resulting double layer system is variable in density, which means the structural tessellation can be explored based on different sizes of the pattern modules; and it still remains consistent when modelling the NURBS surface for different roof's shapes. Changing the roof curvature influences the convergence angle of the bars in the nodes. This is a critical point which has been approached by adding a parametric factor to stretch the tessellation in either one or both its main axes. A second parametric factor allows sliding the tessellation on the surface in order to search for suitable edge configurations. This process is described in more depth in previous publications (Turrin et al., 2009). Based on this, the roof configurations expected to be suitable for cooling air-flows were identified. Those were however conflicting with other design requirements, such as structural stability in case of wind storm and proportions of the roof height to its surrounding. These latter criteria lead the decision making process for the final roof's shape.

Assuming the resulting overall roof's shape, investigations were made on the medium scale for integrating openable modules within the roof structure; specifically, various locations and dimensions of openings were evaluated. Using the modular structure as a reference, the parametric model generates a surface including hollow modules with variable distribution and dimensions. However, preliminary numerical analyses have shown as the ventilation rate air exchange underneath the roof is not relevantly affected by an open roof area smaller than 200sqm; openings of acceptable dimensions have therefore no relevant effects on the thermal behaviour of the spaces underneath the roof. As a consequence, this option was no further investigated and the openings' morphology not developed.

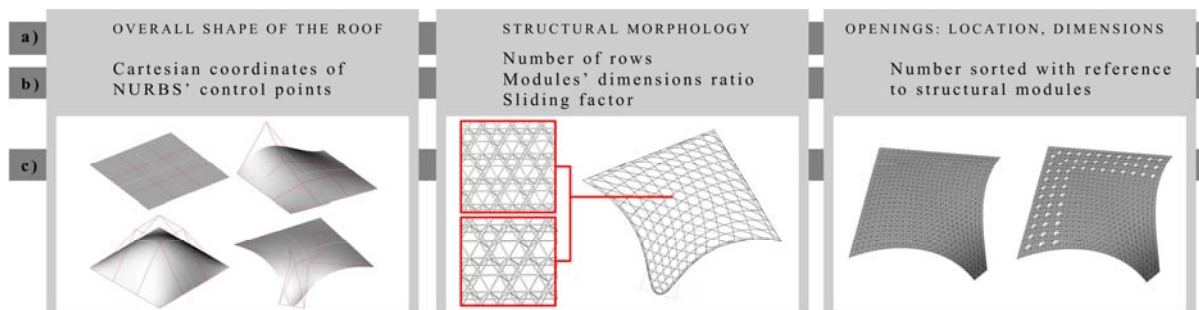


Figure2. Matrix of a) design exploration tasks; b) independent parameters; c) examples of instances

### 3.2 Small scale performance-oriented architectural geometry

Within the given roof's geometry and based on preliminary calculations, limiting the roof's solar energy transmission resulted the most effective measure to improve thermal comfort in summer. Particularly, preliminary calculations shown the need of a solar energy transmission (g-value) of maximum 0.35; to fulfil this requirement, the transparency of the roof was reduced by introducing a high percentage of opacity (higher than 70%). On the other hand, sufficient daylight illumination was required not only for the square underneath the roof, but also for the indoor spaces facing the square. This leads to the need of a minimum light transmission of 0.3. Based on numerical analyses of these factors, different cladding options have been compared with respect to solar gain, daylight and costs. Specific attention was given to serigraphed glazed panels and ETFE pneumatic cushion cladding

systems with printed patterns; based on numerical results, this latter was chosen. Its key advantage was identified in the 3D geometry of the ETFE pneumatic modules; by acting as a 3D system in fact, the shading capacity was possible to be highly customized by allowing better performances. Particularly, two different shading methods were analyzed: a static north-south oriented printing on a two layer cushion and an adjustable system for a three layers cushion with a movable middle layer. This latter has the top and middle layers with complementary printed patterns; the middle layer can flip from a middle or bottom to a top position; the system results in a totally opaque state when the movable layer coheres with the top layer. Differently, the first system allows a shading effect based on its static geometrical properties. In this case, each ETFE cushion is studied to block the direct solar radiation by allowing the income of indirect light and the system is based on the orientation of the shading printed pattern; a similar principle has been used for the ETFE roof of the Dolce Vita Tejo in Lisbon. According to the analyses which have been made, both these systems performed satisfactory; particularly, among all the analyzed systems, they provided the best ratios between the g-value and the daylight transmittance (Figure 3a). By comparing the two, the adjustable system performed slightly better, but the increased level of its technical complexity (especially when used on the curved parts of the roof) was not balanced by comparable benefits. The static system was thus chosen and further developed based on thermal and daylight analyses of parametric variations of this typology.

For exploring the chosen cladding and shading typology, the parametric model and his hierarchical chain of dependencies were structured by first modelling the generic single ETFE pneumatic module and then propagating it within the structural geometry, on a lower, dependent level of hierarchy. The parameterization process of the system has been done based on two main aspects. On the one side the parametric ETFE feature needed to be generic enough to fit various structural modules different in shape and orientation. On the other side, different variations of the module were to be investigated for the solar energy transmission of the system; and those variations needed to be expressed through independent parameters which act as variables meaningful for the energy transmission. Concerning the first aspect, for each ETFE cushion three key elements have been defined first: the axis of the frame of the cushion; the height of the cushion; and the orientation of the shading system. The frame acts as interface between each cushion and the structure and needs to match the geometry of the structural modules; these latter are polygons defined by the position of the structural nodes. In order to make the ETFE feature fitting various structural modules, a generic polygon built by vertices has been therefore used as the highest entity in its dependency chain. The polygon might have as many vertices as wanted; however previous geometrical studies and discussions with ETFE companies already addressed the choice toward quadrangular polygons and this condition allowed a simplification of the parametric model. On this generic polygon, NURBS surfaces have been built to describe the inflated top and bottom ETFE layers. The height distance between their farthest points is proportional to the polygon span, which is its shortest side. The proportion is based on a ratio stated at 0.24, as required for structural reasons; the identification of the shortest side was simplified based on the known absence of relevant differences among the structural polygons' sides' sizes. The so obtained ETFE layers have a shading printed part, which is south facing for the top layer and north facing for the bottom layer. This condition refers to the North-South direction that remains constant for whatever shape and orientation of the modules. The parametric model represented this condition through a plane East-West oriented and passing through the centroid of the module to subdivide the top and bottom NURBS in four parts. Within the resulting parametric feature, variables meaningful for the energy-transmission of the system were then included. Specifically, the most meaningful geometric parameter has been identified in the angle of rotation of the plane mentioned before around the East-West axis. This angle is referred to here as opening angle and is shown in Figure 3. Its variations directly affect the income of direct solar radiation, by affecting both the solar factor of the system and its daylight transmission. The best balance between a low solar factor and a high daylight transmission has been identified in an opening angle of 60 to 70 degrees.

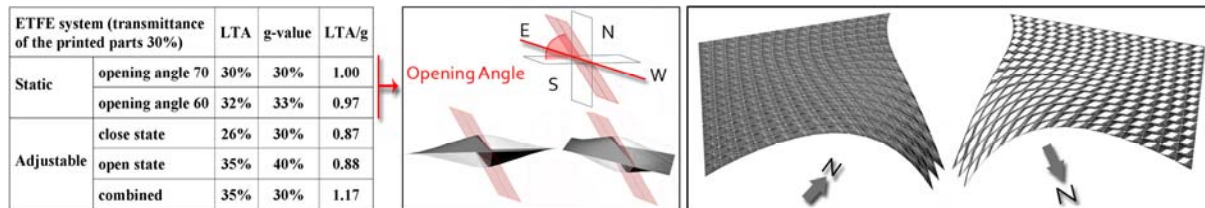


Figure3. a) comparative summary of results for light transmittance (LTA) and g-value; b) parametric model of a single feature of ETFE pneumatic cushion with variable opening angle; c) propagation of the feature on the roof.

## 4 Conclusions

The support given by parametric modelling demonstrated a relevant contribution in the design investigations. When compared to a traditional design approach, a key advantage consisted in automatically generating the alternatives to be evaluated. Concerning this aspect, respectively a current great potential and a possible further development are here following pointed out. On one side, obtaining variations which are meaningful to the performances to be analyzed depends by the parameterization process. Generating alternatives is in fact based on the data-flow from the inputs (independent parameters) to the outputs (3D geometry); and it is driven by the dependency chain of the model. Structuring this hierarchy during the parameterization process required therefore a combination of geometry-related and performances-related expertises and was based on a multidisciplinary team work. The knowledge shared to define the parameterization process is pointed out as an added value of the model. On the other side, the great potential of parametric techniques can increase even more in the future thanks to possible further technical developments. One of them is here following discussed and refers to the combination of parametric techniques with rule-based design. Specifically, integrating parametric modelling with computational supports to allow a more systematic search for performance oriented optimal solutions would guide the currently difficult exploration of large design solution spaces. This issue is currently tackled by the authors and others; and follow up research uses a genetic algorithm optimization system to loop the parametric generation of geometrical alternatives with their performance evaluation process.

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