PARAMETRIC DESIGN OF THE VELA ROOF

*A **case** study on performance oriented exploration of design alternatives*

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Abstract. The paper presents a case study, in which parametric modeling has been used to explore the geometrical design alternatives of a large span roof. Explorative criteria are oriented to the use of on site energy resources, with specific focus on the mitigation of summer discomfort. After broadly presenting the subject, specific emphasis is given to the role played by the (parametric) geometry.

1. Introduction

In this paper, parametric modeling is discussed as a support for the design of large roof structures. Due to the increased request for representative structures and for spaces to be used independent of weather conditions, contemporary cities increasingly integrate public covered spaces, such as shadowed squares and streets, courtyards, historic commercial galleries and other examples of semi-outdoor urban spaces. Roof structures for such spaces are often designed based on aesthetics, structural performance and economics. However their impact on the microclimate underneath the roof and of the surrounding area is large and is an aspect to be taken into account during their design process. The use of parametric design is discussed as a support with respect to this specific aspect.

2. The use of on site energy resources in the design of large roofs

Improving the thermal comfort using on site energy resources contributes in limiting the dependence on traditional fossil fuel resources and imported energies. Aiming at that, both active and passive systems should be considered. The design of semi-outdoor spaces, and more specifically of large roof structures covering or partially sheltering them, can consider both. Concerning active technologies, opportunities should be considered for example in relationship to large surfaces often exposed to the sun, depending on their geometry, orientation and surrounding elements. The integration of photovoltaic solar collectors in the roof of the Masdar Headquarters provides a meaningful example of active energy-oriented use of large structures, meant in this case to provide the energy necessary for the construction of the buildings underneath (Nader, 2009). When looking instead at passive systems, large roofs play a key role in the interaction between the built system they are part of and the surrounding environment and climate factors. Even more than for active technologies, passive design requires emphasis on the concept of an entire system whose energy behavior is based on interrelated aspects. In fact, the interaction between the built environment and climate factors is largely influenced by the thermal mass in which the heat is accumulated, stored and dissipated, making use of thermal inertia to stabilize the temperatures; by the solar energy transmission, absorption, reflection of the elements on the site; by the airflows occurring in the area due to natural wind as well as created by the built environment; by the presence of vegetation and water, like the ancient irrigation techniques integrated in the Moorish courtyards, through which evaporative cooling takes place; and by other aspects. Both ancient and contemporary architecture, including instances from vernacular and traditional buildings, show how the interrelated effects of these aspects can be used for climate comfort purposes. The energy behavior resulting from these interconnected aspects is subjected to large influences coming especially from two key factors of the built system: its geometry and its material properties, which both highly condition each of the mentioned aspects. This directly includes the geometry and the material properties of large roof structures, whose role in the described system should not be underestimated. The understanding of the role of large roof structures on their surroundings is a key issue which needs to be actively considered during the design and includes for example influences on the airflows in the area and on the solar gain of the spaces underneath. While traditional design approaches tend to face energy related aspects in an advanced stage of the design by delegating most of the expectations concerning performances to material properties, in this paper we stress the importance of the geometry, toward a performance oriented geometry, as briefly introduced in the next section.

3. Performance oriented geometry

In traditional design approaches, a given geometry is often expected to fulfill energy performance requirements mainly based on its material properties and technical construction systems. This leads to an inverse computing of the material properties that are needed in order to satisfy the expected performances. While such energy related inverse computing is commonly applied in an advanced stage of the design process, it is rarely used to address early design choices concerning the geometry of the project. The exploration of geometrical alternatives is a fundamental practice in design; driving this exploration based on performance evaluations is the nature of performative design. The concept of performative design refers to the generation of the shape as a process directly driven by the simulations of the related performances and on their evaluation based on a comparison between the intended and the analyzed performances. Feeding back the results of such evaluative process in the shape generation influences the design process toward performance improvements. Referring to solar energy related behaviors, a clear example of inverse computing for performative design is offered by the dome of the Louvre Abu Dhabi museum. The structure has been designed with special attention to the daylight underneath, by determining the perforation ratio of the roof based on performance oriented design intentions, such as the perception of the light, the variations of light and temperature levels and the user's comfort (Tourre and Miguet, 2009).

In line with this approach, this paper discusses a case study whose design process integrated performance evaluations at an early stage to explore geometrical alternatives of the project. The case study focuses on the "Vela roof," a large span roof in Bologna (Italy). Its design process used parametric modeling as a key support to explore performance oriented geometry. Both the project and its design process are introduced in the next two sections.

4. The Vela roof

The case study of the Vela roof forms part of a larger project, referred to here as the UNIPOL Project, currently under construction in Bologna (Italy). An interdisciplinary academic team studied the large span roof with specific focus on the use of on-site renewable energy resources. The relevance of the geometry is considered a key aspect of the design process and, in order to explore geometrical design alternatives, a parametric model was developed at various scales of the project.

4.1. PASSIVE IMPROVEMENT OF THE SUMMER THERMAL COMFORT

The UNIPOL Project consists of an intervention on a 45.000 sqm plot located between a city by-pass and a suburban area. The architectural process was led by Open Project Office and the structural design by Massimo Majowiecki and his office. Spanning in scale from the urban level to the detailed design, the project includes three building bocks enclosing a system of urban spaces. These latter are partially covered by the Vela roof. This is a large span structure of approximately 65x65 meters, offering a multilevel sheltered area faced by shops, services and offices. Since the spaces enclosed by the Vela are supposed to buffer between indoor and outdoor, the demands for the thermal comfort are less strict than what is expected for fully indoor spaces. The main task can be summarized in a simplified approach that aims at mitigating the worst thermal conditions, avoiding uncomfortable conditions of summer overheating and mitigating cold winter conditions and uncomfortable daylight. Referring to passive strategies, passive cooling for summer time and passive solar heating for winter conditions are therefore both considered, which together will contribute in achieving the thermal comfort with a lower need for imported energies. The analysis of the local climate conditions allows identifying the relative potentials and contributions of both. As shown by the EERE (2009) statistics data, the local climate in Bologna is characterized by high annual thermal variation of about a 22°C difference between the coldest month, January, and the warmest, July; limited wind speed and absence of a dominant wind direction; high air humidity and little precipitations. In such a condition, possible summer overheating under the roof was identified as the most critical risk. As a consequence, the work presented here focuses on the assessment of the risk of overheating in the summer and offers guidelines for improving thermal comfort in this season of the year.

The very first conceptual design developed by the architectural office was assumed as a starting point and various strategies for improving the summer thermal comfort were investigated, involving a large set of combined systems. These included the use of thermal mass in the spaces underneath the roof and in the surrounding buildings; the reduction of the solar energy absorption factor of the roof and the integration of inner coating devices for reducing the long wave radiations from it; the use of vegetation and water for adiabatic cooling both underneath the roof and on its top surfaces; the increase of ventilation in order to achieve cooling effects; the reduction of the direct solar gain of the spaces underneath the roof. Based both on the simulated effectiveness of these strategies and on evaluations related to other factors considered in the design process, the integration of openings for ventilation, the reduction of the solar absorption, the use of adiabatic cooling and the reduction of the transmittance of solar heat through the roof are the strategies which have been integrated in the final design, with increasing order of importance.

4.2. THE USE OF PARAMETRIC MODELLING

The geometry of the roof proves to have a large impact especially on the control of the airflow for cooling and on the reduction of solar gain. In order to explore geometrical design alternatives, parametric modeling was used. Parametric modeling allows representing both geometrical entities and their relationships, which are structured in a hierarchical chain of dependencies established during the preliminary parameterization process. The independent properties of the model are usually expressed through independent parameters, and their variations generate different configurations of the model. By making use of this potential, three project scales were parametrically explored. At the large scale, parametric variations of the overall shape of the roof were investigated in relation to cooling through ventilation and here the parametric model allowed for the generation of different configurations of the roof, including its structural morphology and variations of its structural tessellation. At the medium scale, the integration of openable modules was 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. Although variations in the geometry of the roof and the integration of large openable systems have not been integrated in the final design, the support provided by parametric modeling demonstrated great potentials in investigating both the large and medium scale of the project. A detailed presentation and deeper discussion of these aspects can be found in previous publications (Turrin, 2010). At the small scale, various options were explored for the cladding system, in order to reduce the direct solar gain while still allowing the income of indirect natural light. This aspect is presented in the following section.

5. Performance oriented parametric design of the cladding system

Preliminary calculations have shown the importance of both reducing the direct solar radiation transmittance of the roof and its solar energy absorption in order to mitigate the summer thermal discomfort. With respect to these subjects, the roof properties have been formulated based on an inverse process to meet the thermal design intentions. Specifically, the solar energy transmittance (g-value) of the roof was required not to be higher than 0.35 and the energy absorption to be limited as much as possible. The total amount of solar energy that is transmitted through the roof depends on the percentage of transparent and or translucent elements and on the g-value of these elements. In order to achieve a suitable g-value, the roof's transparency was required to be lower than 30%. An opacity higher than 70% should be achieved through light colors in order to reduce energy absorption. When trying to fulfill such requirements based purely on the material properties of the cladding, it is possible to achieve the desired reduction of thermal discomfort. However the resulting daylight factor of the spaces underneath the roof is too low if compared to the daylight requirements, for which a minimum light transmission of 0.3 was prescribed. The problem was approached by extending the inverse computing process used for the material properties to the geometry of the cladding; and exploring cladding systems allowing three-dimensional variations in geometrical configurations. Special attention was given to ETFE pneumatic cushions due to their potentials in acting as a 3D system. In such a system, the different layers of the pneumatic cushions can be customized to control the energy transmission based on various material properties and also on different three-dimensional configurations. Among the various evaluated alternatives, here we present a static system based on a customized shading pattern, North-South oriented. In this system, the orientation of the pattern of each ETFE cushion is studied to block direct solar radiation and allow the income of indirect light. Parametric modeling was used to explore variations of the system, aiming at maximizing the reduction of the g-value and increasing the indirect daylight transmittance.

5.1. PARAMETRIC GEOMETRY

The parametric study first focused on a generic single ETFE pneumatic module. This was modeled by taking into account three main aspects: its direct relation with the structural geometry, its orientation with respect to the cardinal directions and the geometrical key factors affecting the transmission of the solar energy.

Focusing on the first aspect, the geometry of the cladding module and the structural geometry of the roof are reciprocally constrained. A double layer space frame was previously chosen as the typology of the structural system based on architectural and structural evaluations. In order to match the ETFE modules with the tessellation of the top layer of the space frame, the parametric ETFE module has been built based on a polygonal frame that acts as an interface between the cushion and the structure. Such a polygonal interface can be built in order to fit different possible structural tessellations allowing applications to different structures. Its potential is great, especially in combination with parametric models of the structure that support the explorations of different structural tessellations. This requires generalizations of the geometry of the cladding modules, but provides advantages in quickly enlarging the solution space of the parametric model. The specific project, however, allowed limiting the parametric solutions to be explored in this phase. In fact, even though at this stage of the process a structure consisting of a bottom layer based on triangles and hexagons and a top layer based on triangles was strongly considered, quadrangular tessellations were shown to be explicitly more effective than the triangular ones when focusing on the shading effects of the printed ETFE cladding. As a result, triangular tessellations were not further embedded in the parametric model and both the space frame and the modular cladding have been developed based on quadrangular patterns only. A quadrangular polygon built by vertices was therefore used as the highest entity in the dependency chain of the ETFE module. Based on this polygon, NURBS surfaces were built to describe the inflated top and bottom ETFE layers.

Focusing on the second aspect, the printed shading parts on the so obtained ETFE layers were modeled by taking into account their North-South orientation. This implied the assumption of an absolute reference that remains constant for whatever shape and orientation of the modules. An external reference, to which the module has been constrained but that remains independent of the geometry of the roof in order to maintain its consistency even in case of rotations and variations of the roof structure, fulfills this requirement. This can be seen as a potential also when applying the modules to different structures.

Focusing on the third aspect, different variations of the module were investigated for the solar energy transmission of the system and expressed through independent parameters which act as variables meaningful for the energy transmission. Among many variables, the most meaningful seemed to be the opening angle between the top and bottom printing. While the printed part of the top layer is constrained to face the South and the printed part of the bottom layer to face the North, the opening angle is the angle of rotation of the top and bottom printed parts around the East-West axis. The variations of such angle affect both the income of direct solar radiation and the daylight transmission, where increasing the angle decreases both. A second meaningful variable was identified in the height distance between the top and bottom layers, in their farthest points. This geometrical property affects the amount of incoming indirect daylight. However, structural reasons constrained the proportion between the height and the polygonal base of the cushion. This implied a proportion with respect to the short side of the polygonal frame, with a ratio of 0.24.

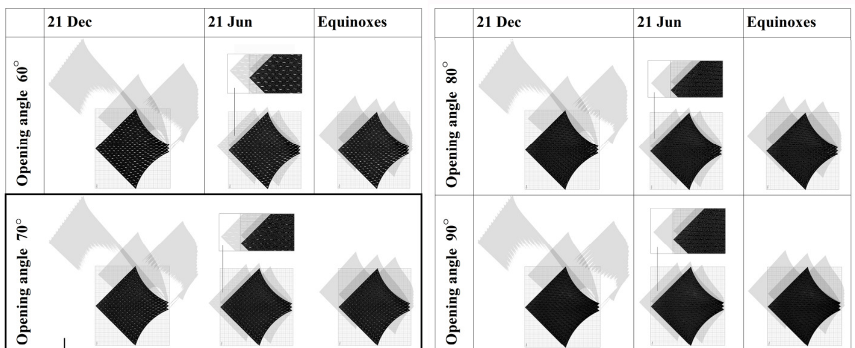
The resulting module was then saved as a replicable feature; in this way, the module could be propagated onto the structural geometry by guaranteeing the relationships with the structural geometry as well as with the North-South direction.

5.2. PERFORMANCE EVALUATIONS

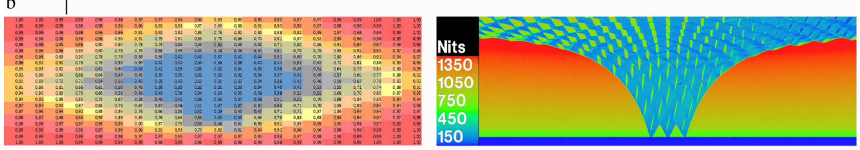
The final parametric model allowed the generation of the cladding alternatives based on different opening angles. The obtained geometrical alternatives were evaluated based on their performances, with a combination of manual and software simulated calculations, in reciprocal crossed validation, as exemplified in Figure 1.

Average monthly g-value (%) for different opening angles												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Opening angle 40°	26	28	32	35	38	39	39	37	34	30	27	25
Opening angle 50°	24	27	30	32	34	35	35	33	31	28	26	23
Opening angle 60°	23	25	28	30	32	33	32	31	29	27	24	22
Opening angle 70°	22	24	27	29	30	30	30	29	28	26	23	21

a



b



c

Diffuse light transmittance factor; g-value; ratio; average physical equivalent temperature (July)				
	LTA %	**g-value %**	**LTA/g**	**Average PET C°**
Opening angle 60°	32	33	0.97	34
Opening angle 70°	30	30	1.00	33,5

d

Figure 1. Some of the key steps of the performance evaluation process for different opening angles: (a) average g-value; (b) shadow simulation; (c) daylight simulation; (d) comparison between daylight and thermal performances, including thermal comfort assessment in July.

Figure 1 exemplifies the key steps of the process by illustrating some analyses concerning ETFE modules having different opening angles. Specifically, for a transmittance and an absorbance of the printed parts of 30% and 15% respectively, the images show: (a) some results of the investigations on the g-value calculated for opening angles between 40 and 70 degrees, during the year; (b) the shadows (and direct solar exposure) simulated in Autodesk Ecotect 2009 on parametric instances for opening angles between 60 and 90 degrees, during the year; (c) the results of a daylight simulation on a parametric instance for 70 degrees, done in Radiance to investigate the daylight factor (resulting of 35%, reduced to 26% by including the roof structure) and daylight levels and distribution; (d) the final comparison between the g-value and the daylight transmittance and calculation of the physical equivalent temperature to assess the summer thermal comfort, for opening angles of 60 and 70 degrees.

The best balance between a low solar factor and a high daylight transmission was identified to correspond to an opening angle of 60 to 70 degrees (Figure 2).

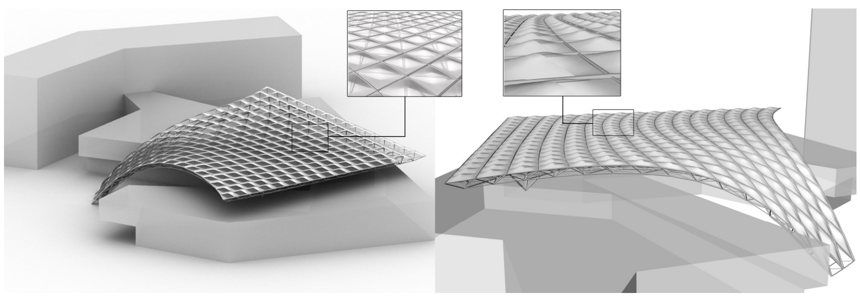


Figure 2. Parametric instance of ETFE cladding, for an opening angle of 70 degrees

4. Conclusions

Throughout the overall design process, the role of the geometry with respect to solar energy performances revealed a high relevance and the use of parametric modeling in supporting the exploration of design alternatives showed high potential. A first key advantage is the automatic generation of geometrical variations, which provides large sets of alternative design solutions. Three aspects of this potential are highlighted here; the first one relates to the importance of visualizing the alternatives; the second one to the emergence of un-conceived geometrical configurations; the third one to the availability of geometrical instances to be analyzed based on simulation software and performance evaluation processes. Each of these aspects does not directly allow a quicker convergence toward suitable solutions, but is meant to increase the potentials for a higher quality of the design. When looking at traditional processes, in fact, time restrictions and other limitations make designers commonly consider only small subsets of the possible design candidates and most design processes explore a relatively narrow range of possibilities (Josephson, 1997). Based on the automatic generation of geometrical variations, the potentials of parametric design have been discussed in direct contrast to this limit. It is also important to recall that such generation effectively supports the process only when the generation includes meaningful design solutions (which mainly depends on the parameterization process), and is properly explored (by searching for solutions that satisfy the given specifications). In this respect, the early interdisciplinary collaborations that are necessary in order to parameterize the geometry as well as select the design alternatives for deeper evaluation must be mentioned as having a positive influence. Finally, based on the described case study, it can be concluded that a larger and earlier integration of parametric techniques in the design process is highly recommendable in order to further make use of their potential, especially when such techniques are more closely combined with performance simulation software and computational search techniques.

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