Simulation and optimization in free-form buildings: energy consumption reduction from the early stages of the design process

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Abstract

The use of second skins in buildings can reduce their energy consumption by reducing the use of air conditioning and regulating the natural illumination. In traditional orthogonal-shaped buildings, a shading pattern is applied to each face. However, in free-form shaped buildings, usually the same pattern is applied to the whole façade, that can lead to a reducing on the energy performance of the building, compared with the use of different patterns. In free-form buildings, rules-of-thumb can't be used to predict the shading devices, for they weren't developed for this kind of geometry. In those cases, there's the need to use computational simulations. In this work, computational simulations with parametric modelling and genetic algorithms were used in the beginning of the design process (mass study) for high-rise buildings, aiming on reducing energy consumption. In this method, the building's façade was subdivided in several faces, in order to apply different patterns, reducing heat gains and thus the use of air conditioning, while considering the natural illumination of each face. This method was compared with other optimization methods (orientation, implantation and shape). In the design experiments carried out, the methods allowed modifications at the beginning of the design process, as part of the creative exploration, resulting in a better performance of free-form shaped buildings.

Keywords: free-form, optimization, simulation, shading, performance, design process

1. Introduction

In the last few years, there's an increasing concern regarding the use of natural resources and energy, leading to movements and discussions related to sustainability. In the area of architecture, this led to the creation of manuals, certifications organizations, use of computational simulations and the use and experimentation of new technologies and materials.

When dealing with traditional orthogonal-shaped buildings and simple forms, it's easy to calculate, for example, its solar thermal gain. Rules-of-thumb and sustainability manuals are focused in those kind of geometries, considering the building as a parallelepiped. A good example is that the building orientation; usually, it's preferred for the building to be positioned so that the widest façades will face the north and south. Those kinds of rules-of-thumb, however, can't always be applied to more complex geometries [1], making it necessary to use computational simulations during the design process [4]. By using computational simulation together with parametric modelling, the design solution will be more efficient than traditional methods and may result in a more complex and dynamic solution [7][10]. During this optimization process, together with the simulation and parametric modelling, the genetic algorithms are widely used, for they usually give a satisfactory result in a shorts period of time.

Those methods can be used in several phases of the design process, from the early stages to the last ones. When used in an advanced phase of the design process, or even after the major decisions (such as shape or orientation), the simulations are limited to the building geometry and pre-determine components [4]. Even though the use of simulations in those stages allows verifying the building's performance, there isn't much room for changes – or they are rather expensive. This is a very limited way of working with simulations, maintaining a gap between the simulation's result and how they are incorporated in the architectural solution [4][6][9].

By using this method since the early stages of the design process, it's possible to generate a more responsive architecture, with integrated solutions between the design and the building's performance. Two of the main aspects that can be simulated since the first stages of the process are its thermal performance and natural illumination. Both affect directly the building's energy consumption, by determining the energy spends with HVAC systems and artificial lighting.

This work presents the use of computational simulation with parametric modelling and genetic algorithms in the early stages of the design process (mass study) of high-rise complex-shaped buildings, focusing on the reduction of the building's energy consumption. The optimization methods used on the design experiments presented are based on the building's energy spent with HVAC systems and artificial lighting.

2. Methods and parameters

For any optimization process it's important to define the method and parameters used, according to the stage of the design process, the project limitations and goals, aesthetic factors, location and climate. In this work, the main optimization methods for energy consumption reduction during the mass-study phase were tested. As the design exercise site was located in Sao Paulo – Brazil, the simulations carried out used the specific weather file (.EPW) for that region. The model was developed in Grasshopper for Rhinoceros, using the plugins Galapagos (genetic algorithm), Diva (connects Grasshopper and Energy Plus) and Giraffe (geometry discretization and model preparation, see "7.Acknowledgments" for more information), with simulations on Energy Plus.

2.1 Optimization methods

In the literature, four main types of optimization methods were found: implantation, orientation [11], shape variation [8] and shading [1][3]. Each method focus in different parameters, therefore, they have different restrains and influences on the overall result.

The implantation method looks for the best implantation on the site, based on a grid of points equally distributed. During these tests, one meter was used as spacing unit. Setbacks and the shape of the site were also taken into account, so all the points in which the building would be outside the limits are excluded from the optimization (Figure 1).

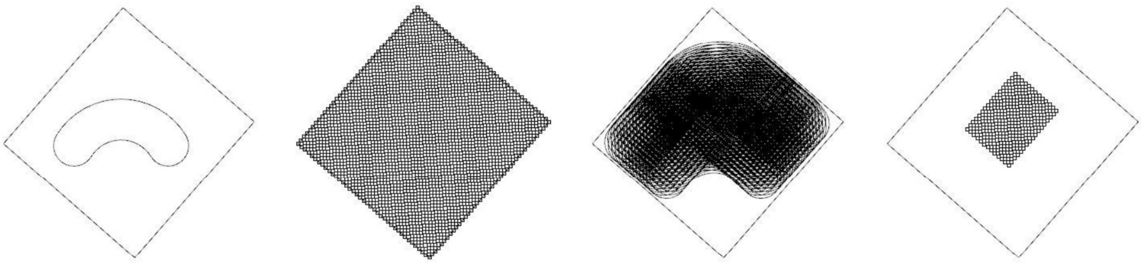

Figure 1: Point selection: site and base profile, site subdivision, distribution of base profile on site and selection of points for implantation optimization.

The second method, orientation, is based on rotating the building in search for the best solar orientation. It was allowed for the building to rotate from 0 to 359 degrees (resulting in 360 different orientations).

For the shape variation, the parameters used may vary according to the parametric construction of the geometry. The maintenance of the building's height and number of floors, as well as the area of the floors are indicated to be used as guidelines in the chosen of the parameters. As the optimization will look for the reduction on the energy use for artificial light and HVAC systems, by using parameters that will influence in the aspects cited, the algorithm will just try to reduce de building's dimensions, consequently, reducing the amount of energy spend. In this particular case, the top profile of the geometry was able to vary its position on the X and Y axis, as well as rotate. This will be explained in more details on the item 3.2.

The last method, shading, consists in applying a second skin to the building's façade, in order to control its solar gain and natural light. Usually, the same pattern is applied to each façade in orthogonal buildings; however, complex-shaped buildings may not have such defined façades. In this kind of geometry, after its tessellation, each faces that compose the geometry may have a slightly different tridimensional orientation. At the same time, it would be quite time-expensive to define a specific shading ratio for each separated face: if there were a thousand faces and ten different shading ratios, it would mean 10^{1000} possibilities. However, it's possible to separate the faces in groups according to its tridimensional orientation and, to each group, apply a different shading ratio.

The shading ratios possibilities for this exercise were defined as 70%, 40% and 10% of shading. As for the faces groups, first they were separated according to its cardinal orientation (considering eight possibilities in the XY plan, each with a interval of 45°) and vertical orientation (considering six possibilities, each with a interval of 30°, being three positive - from 0° to 90°- and three negative – from 0° to -90°). This way, there would be 48 groups of faces and 3 possible shading ratios, resulting in controlled number of possibilities. This reduction was quite important to match the dynamics of the early stages of the design process, focusing on an easier and faster optimization.

2.2 Simulations and genetic algorithms

As cited, the models were prepared using the Giraffe plugin and sent to Energy Plus through Diva, to carry out the simulations. For the simulations, brazilian technical standards were used for internal gains, minimum and maximum values for internal temperature and illumination. Surrounding buildings were also considered due to their shades.

From the simulations, were extracted the information for: zone lights electric energy, zone ideal loads zone sensible heating energy and zone ideal loads zone sensible cooling. The heating and cooling energy were added, resulting in the HVAC energy spend. First, it a simulation of an initial concept of the building was carried out. After that, for each simulation, its result would be compared to the results of the initial concept model.

When combining two or more factors in an optimization process, the solution can be considered multicriterial [5][6], which means that the result may not present the best result for one or more factors independently, but will present the optimal solution for their combination. In multicriterial optimizations, it's also possible to determine a weight for each factor, in order to give one or more factor more importance. During this work, both factors were considered with the same weight. In this case, two strategies were used for the multicriterial optimization. In the first one was based on comparing the artificial light energy and HVAC energy with the ones from the initial concept model, finding a Light Factor and HVAC Factor. They were then multiplied one by the other, resulting in the Total Factor. The second one was based on adding the artificial light energy and HVAC energy, resulting in the Total Energy spend. This was then compared with the Total Energy of the initial concept model.

For both strategies, the genetic algorithm (Galapagos) was used. For each method, the genome for the algorithm was the varying parameters described earlier (site points location for implantation, rotation for orientation, position and rotation of the top profile for shape variation and the shading ratio for each group for shading). The fitting for the algorithm vary according to the multicriterial optimization strategies, being the Total Factor or the Total Energy. In all optimizations, the initial population was of 10 individuals, with 5 individuals per generation, aiming on the minimization of the fitting parameter, therefore, reducing the energy consumption of the building. In some cases, the number of individuals for the initial population or for each generation can be higher, however, for the experiments carried out it leaded to similar results of bigger populations, within a shorter period of time.

3. Design exercise

The building was considered as an office building with open plan. Its occupation was considered as 0.1 person/m². The internal gain by equipment and artificial lights was considered as 24w/m². The minimum illumination was of 500 lux. The minimum temperature was set as 20°C and the maximum as 26°C, without any natural ventilation. Standard glasses were considered for the windows, without any internal shading device.

3.1 Site

The site chosen for the design exercise was located in São Paulo/SP, one of the most important capitals of the country due to its economic and international importance. The city presents a historical process of verticalization, with eleven out of twenty tallest buildings of the country. One of its principal avenues is Avenida Paulista, with a high density of tall buildings. With 50x50 m, the site chosen is surrounded by tall buildings up to 90m, so that the surroundings of the building would influence its thermal gain (Figure 2).

Figure 2: Site at Avenida Paulista, Sao Paulo/SP, Brazil

3.2 Initial concept

In this design exercise, it was consider that the buildings should be, at least, taller than the tallest building in Brazil, which is the Millennium Palace, with 177m. The height of the building was stablished as 210m, so that it wouldn't influence much in the surrounding buildings. In terms of its geometry, the building should be asymmetric, with double-curvature and allowing self-shading. These guidelines were determined in order to maintain the level of complexity of the geometry, despite of its parametric variation. The base of the building was determined by two concentric arcs, united by semicircles. The top of the building had the same topological shape, varying its dimensions, as well as its position and rotation. The base and top profiles of the building were interpolated, generating its shape (Figure 3).

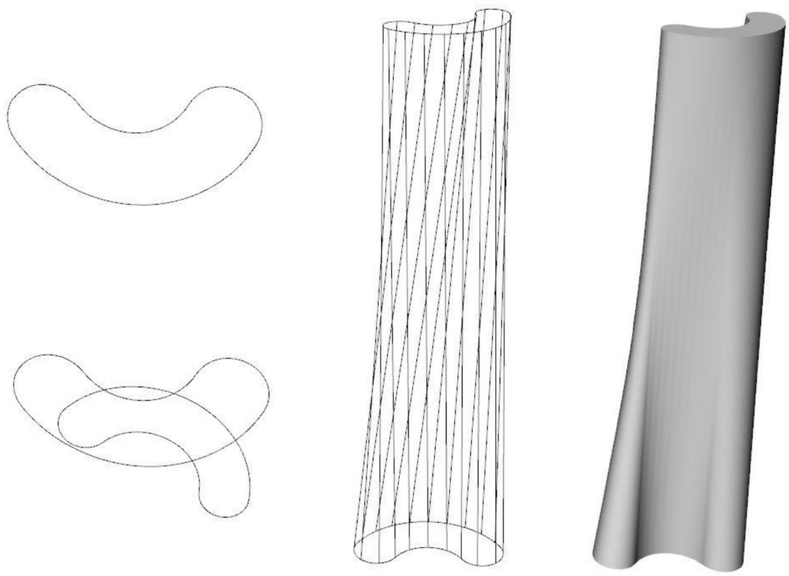

Figure 3: Building's geometrical construction: base profile (to the left on top), base and top profiles (to the left on the bottom), curves interpolation (on the center) and final geometry (on the right).

In order to follow the determined guidelines, both for the position and rotation of the top profile, restrains were determined. For the position, it was determined a variation from 0 to 10m in the X axis and from 10 to 40m in the Y axis. For the rotation, it was determined a variation from 150° to 210°. The initial concept had a rotation of 210°, with a translation of 3m in the X axis and 22m in the Y axis (Figure 4).

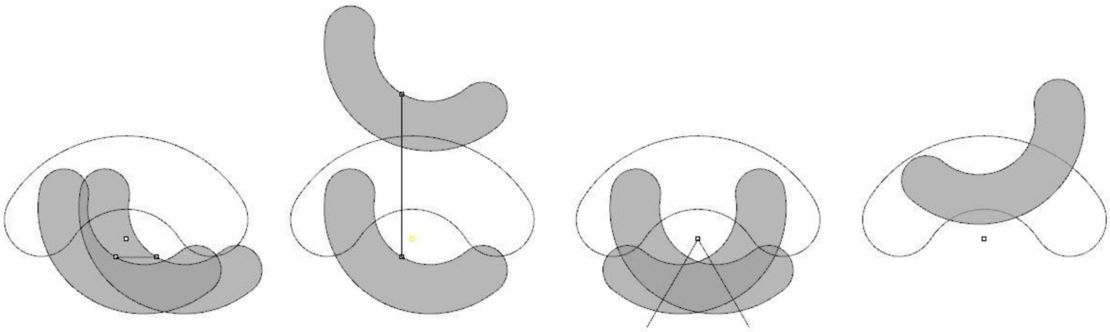

Figure 4: Shape variation: translation on X axis (left), translation on Y axis (center left), rotation (center right) and initial shape (right).

4. Results

The optimizations were carried out with the two strategies cited and compared with the initial concept model results. The first table (Table I – Optimization through total factor) shows the results for the optimizations which the Total Factor (highlighted in grey) was used as fitness function. The second table (Table II – Optimization thorough total energy) shows the results for the optimizations which the Total Energy (highlighted in grey) was used as fitness function. The resulting geometries for both strategies can be seem at figures 5 and 6, respectively.

	Light ()	HVAC ()	Energy	Energy (0-1)	Light Factor	HVAC Factor	Total Factor
Initial concept	57,614	1,271,800	1,329,414	1.000	1.000	1.000	1.000
Implantation	55,757	1,277,600	1,333,357	1.003	0.967	1.004	0.970
Orientation	52,661	1,331,700	1,384,361	1.041	0.914	1.047	0.957
Shape variation	43,438	1,023,000	1,066,438	0.802	0.754	0.804	0.606
Shading	73,032	1,037,500	1,110,032	0.835	1.267	0.839	1.063

Table I – Optimization through total factor

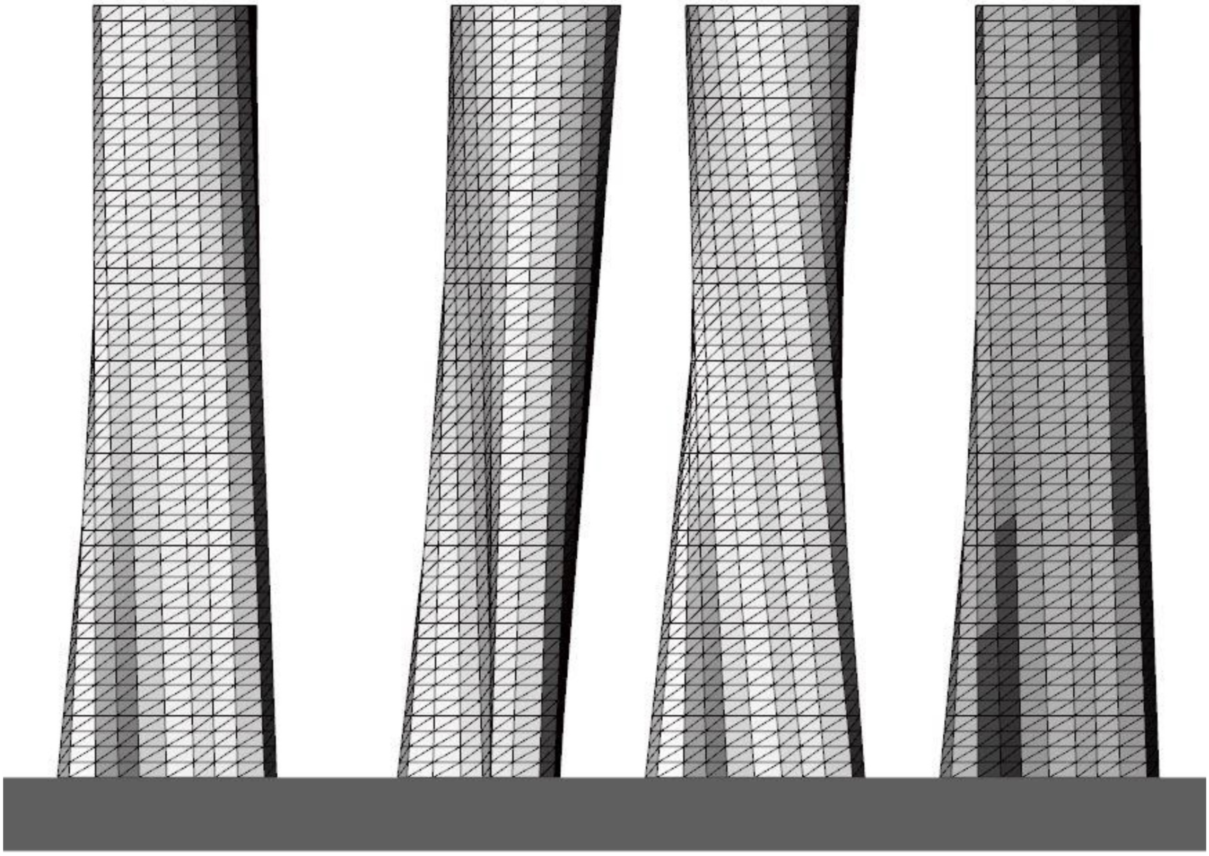

Figure 5: Optimization results by Total Factor: implantation (left), orientation (center left), shape variation (center right) and shading (right), on which the gray scale represents the face shading.

	Light ()	HVAC ()	Energy	Energy (0-1)	Light Factor	HVAC Factor	Total Factor
Initial concept	57,614	1,271,800	1,329,414	1.000	1.000	1.000	1.000
Implantation	58,144	1,251,900	1,310,044	0.985	1,009	0,984	0,993
Orientation	53,689	1,271,300	1,324,989	0.996	0.932	0.999	0.931
Shape variation	52,675	949,783	1,002,458	0.754	0.914	0.747	0.683
Shading	79,772	1,055,900	1,135,622	0.854	1.384	0.830	1.149

Table II – Optimization thorough total energy

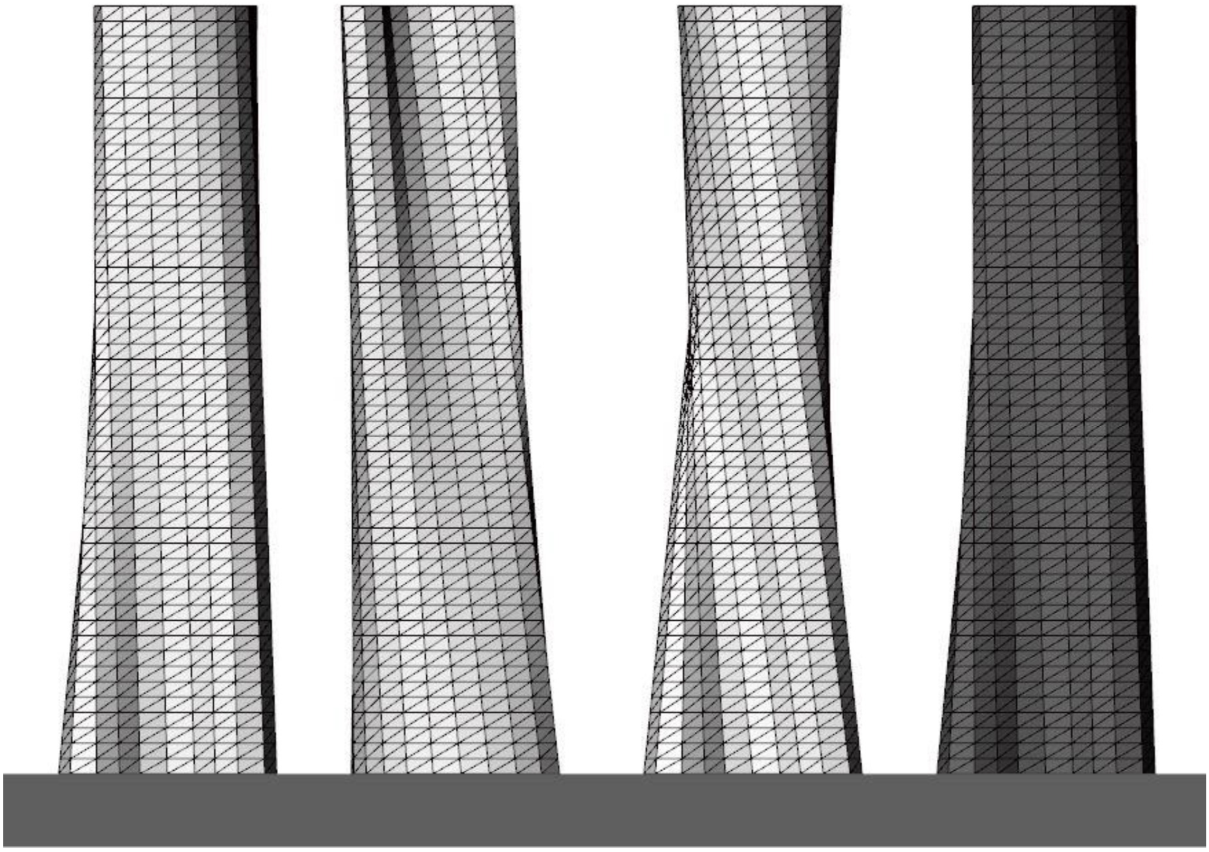

Figure 6: Optimization results by Total Energy: implantation (left), orientation (center left), shape variation (center right) and shading (right), on which the gray scale represents the face shading.

5. Conclusions

As it can be seen in the results, there are differences when using the Total Factor or the Total Energy as fitness function during the optimization process. In the overall process, when using the Total Energy, the reduction on the energy consumption is bigger, however, so is the Light Factor. This can be easily explained by the fact that the energy spend with the HVAC system represents more than 20 times the energy spend with artificial illumination.

When using the Total Factor, in the other hand, the energy consumption reduction is slightly lower; however there is a better distribution between the artificial illumination and the HVAC system. This happens because, when using separated factor for both, the optimization system works with both of them in the same scale. Due to the climate conditions of the buildings site, both factors regulate themselves, for they have the same weight during the multicriterial optimization.

Therefore, when using the Total Factor as fitness function, there is a better distribution between the Light Factor and HVAC Factor, resulting in a bigger reduction on the artificial illumination and, consequently, a raise on the use of natural illumination. On the other hand, when using the Total energy as fitness function, the amount of energy spend will be smaller, however the amount of natural illumination will also be.

In both strategies, both the implantation and orientation methods didn't result in a very significant reduction (with a 6.9% of the total factor reduction and 1.5% of the total energy in the best scenario). The second best method was the use of shading, reducing up to 16.5% of the total energy. Although there was an increase on the Light Factor and, consequently, on the Total Factor, the energy reduction is significant. When using shading mechanisms, it's expected that the natural illumination in certain areas will decrease, so that it's expected for the increase on the use of artificial illumination. The best method was the shape variation, reducing both the Total Energy (24.6% of reduction) and the Total Factor (39.6% of reduction). When using the Total Factor strategy, the reduction was more uniform on both factors, and even when using the Total Energy strategy, there was a decrease on both factors.

The correct orientation is part of some well-known rules-of-thumb, however it was demonstrated that, for this geometry, it was inefficient. This doesn't mean that the orientation isn't important in all complex geometries; it means that those rules-of-thumb were not developed for this kind of geometry and, therefore, are not applicable. To ensure the best orientation for a complex-shaped building and to know their influence, simulations will be needed.

In this case, the best method was the shape variation. The strategy used will depend on the objective of the building: reduce its energy consumption to its lowest or reduce to a fine quantity that will provide a better environment for its users. As for the shading, it could be applied together with the shape variation method. Although it may not present the best energy reduction factors, it may be important for other aesthetic and architectural reasons, so it's important that his shading have the best distribution in order to reduce the energy consumption of the building.

6. Final considerations

For the last decades the architecture is going through deep changes, not only in geometrical meanings but from the design process to the building materialization. Those changes allowed for the architecture to explore the geometrical space, its use and sensation that it may cause, expanding the architectural possibilities. With those new possibilities, also new concerns may emerge; the building performance is one of them. As this work showed, it's possible to use computational tools and methods in order to achieve a better performance for the building. In this case, it was possible to reduce the building's energy consumption with the use of parametric modelling, computational simulation and genetic algorithms, in a multicriterial optimization system.

When comparing both the strategies used (Total Factor or Total Energy as fitness function), it's possible to inquire if it's preferred the ultimate performance for the building or just a good performance with a better environment for its users. A building with excellence performance may not be consider a good piece of architecture, if there are other subjective factors that the optimization system was unable to grasp. However, a building with a low performance can't also be considered as good architecture, for it won't be good for its users. Therefore it's possible to conclude that a building with good performance is not a synonymous of good architecture, however good architecture always has a good performance. The optimization methods are important and should be used in order to achieve a better performance, however the architect must analyse if there's a need to search for the best performance or if there's a solution that may not result in the best performance for one or more aspects, but in the overall (including subjective factors) will result in a better architecture.

It's also important to emphasize that, for this design experiment, the orientation and implantation methods didn't result in a significant change in the building's energy consumption, but they may be significant in other geometries, sites and climates. The same goes for the shape variation and shading; the impact of both on the energy consumption may change in other geometries, depending on the geometry, its limits, varying parameters and other factors. Therefore, the best way to understand the implications of each method on the geometry is to carry out with the simulations and optimization processes described in this work.

To conclude, in this work it was possible to demonstrate the importance of the use of simulations and optimization processes in order to achieve a good performance for complex-shaped geometries. The methods described focus on its use during the early stages of the design process, taking advantage of the creative exploration possibilities of this phase, and leading to better performance architecture.

7. Acknowledgments

This research is part of a master degree dissertation [2], in which the plugin Giraffe was developed. The plugin is available at the site < http://lapac.fec.unicamp.br/index.php/people/filipecampos/ >. We would like to thanks LAPAC/UNICAMP for the support and FAPESP for funding the research.

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