A FASTER MULTI-CRITERIA OPTIMIZATION MODEL TO PARAMETRIC FACADES FOR DAYLIGHTING AND THERMAL PERFORMANCE

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ABSTRACT
In the Performance-based design method the 3D model is connected to computational simulation processes and an optimization process is associated with a specific design problem. This work addresses the design of facade solution, which have problems associated with the architectural programing formulation, interoperability with the architectural 3d model, and slow computer simulation processes. The objective of the paper is to present a simplified strategy for faster optimization processes of shading devices and window solutions based on thermal performance and daylighting requirements for an entire year in Sao Paulo, Brazil. The multi-criteria optimization model integrates three performance indexes: solar radiation in the window plane in hot periods, UDI (useful daylight illuminance), and area of the shading devices. The computational model is based on the Radiance two-phase method that was up to 10 times faster than the Daysim based methods. The process uses parametric modeling through Grasshopper, and presents a solution sensitive to complex geometries and choice of glass to assist the performance-based design process. It was performed 10 generations of simulations. The optimized solutions were evaluated and presented a gain that reach 62% in the reduction of material proposed for the shading devices.

Key words: parametric design, shading devices, glass, façade, optimization.

1 INTRODUCTION

This paper discusses the façade design within the context of the performance-based design. For this reason, the introduction is divided into two parts: the design of solar control in facades and the performance-based design method.

1.1 Solar control design on facades

One of the main elements related to the efficiency of buildings is the façade design. It is the skin that filters and promotes the interaction between the interior and exterior of the building. During the process of its conception, one must understand the environmental patterns, observe the incident climate, and propose solutions that take advantage of benefits of climate and avoids bad situations (OLGYAY, 1963). The façade is composed of opaque and transparent elements, closed and open. The opening is the element that promotes the greatest connection between the external and internal environment.

The main effects of solar radiation inside the environments are heating and lighting. Its benefits are associated with the well-being, and health of occupants. Daylighting and external contact are understood as the most beneficial effects associated with openness (AL HORR et al., 2016; DOGRUSOY). The daylight offers benefits through the openings, but also has a conflicting characteristic. It is difficult to approach, since it is intended to take advantage of daylighting, visuals and contact with the outside, and at the same time, to protect the building from overheating caused by the contact with solar radiation and over brightness (BOUBEKRI; BOYER, 1992; RUCK, N., et al, 2000).

The research differentiates two types of solar control devices: solar control glazing and shading devices. The aspects explored are thermal and daylight performance. Solar control glazing solutions act on direct and diffuse radiation as a "filter". In general, they allow the entrance of direct radiation to cross the interior of the building and act homogeneously for different times of the day and year (REZAEI, 2017). Shading devices can be internal or external, static, or dynamic. Shading devices have their performance associated with their shape, the way it is attached to the façade and the internal environment, forming an optical set. They act primarily in the modulated protection of direct radiation and in the admission of diffuse radiation (KISCHKOWEIT-LOPIN, 2002; KIRIMTAT, 2016). Each of the elements has a distinct and complementary contribution to solar control and daylight admission. The thermal and daylighting performance associated with the solar control solution should consider both elements.

1.2 Performance-based design

The design method that integrates modeling and performance strategies is known as performance-based design. Designates the exploration of computational simulations to assist solutions and geometry generation associated with an objective(s). Performance-guided models differ from the traditional process because performance indicators are the key guides of geometry generation, that is directly connected to computational simulation processes. The design team would have quick returns on solution performance and can also incorporate an optimization process that performs alternative evaluations in the modeling system (EVE LIN, 2014, AL-MASRANI 2018).

The adoption of this approach is growing due to the evolution of computer processing, creation of rapid simulation interfaces integrated with modeling tools or with processes in the cloud, creation of programming interfaces, such as the visual programming language (LPV) and development of optimization tools focused on the design process (KHEIRI, 2018; LUCA, 2019). The parametric and optimization process associated with simulation can be controlled by the design team, being scientifically based solutions, which reduces subjectivity (AISH, 2011; ØSTERGÅRD; et all, 2016).

The success of the integrated simulation model is related to the way the analyzed model is generated parametrically. It is essential to plan the logical steps, the flexibility of the 3D model, the selection of variable parameters and the design of system constraints (AISH, 2011; PAPALAMBROS; WILDE, 2000). Performance-based design brings measurable steps to the solution generation process (NGUYEN ET AL., 2014). With programming, initial time and effort may be apparently significant, but the cognitive construction, and the ability to regenerate the model within the design logic, radically generates more possibilities when compared to traditional or non-algorithmic parametric modeling (AISH, 2011; ZHAO; DE ANGELIS, 2019)

The optimization algorithms available in design tools can be classified when to the number of optimization functions and the solution method. As for the number, they can be unicriteria and multicriteria. As for the method can be Metaheuristic or deterministic. In the single-criteria, a single mathematical function guides the optimization process. The result presents a solution determined as optimal. Is the multicriteria functions represents the problem with multiple functions of interest. Thus, there is no determined solution as the best, but a set of solutions presented in a universe of possibilities in order to characterize the problem. Metaheuristic algorithms are nondeterministic models, that is, they follow the simulation step in a random way. Deterministic algorithms use processes that follow a certain direction. The calculations run until the convergence of functions. Disadvantages of using deterministic models in architecture are the complexity of problems. Often functions have conflicting characteristics and may not be likely to be convergent.

Optimization methods should be selected based on the nature of the problem to be analyzed. Methods based on continuous models require functions with linear problems that can be convergent, while nonlinear and discontinuous problems (some of the architectural problems) can be evaluated through free methods such as metaheuristic sums (KHEIRI, 2018).

2 OBJECTIVES

The aim of the paper is to present a fast, interoperable simplified model of optimization processes for materiality and geometry solutions of solar control on facades based on thermal and daylighting performance for the whole year.

3 METHOD

The paper discusses the use of integrated simulation models associated with modeling for the generative design of solar control solution. They are included as sub themes: optimization models, algorithmic modeling. The experiment uses quantitative methods and follows the following practical steps:

I. Study for the climate data reduction in order to reduce the time of simulation.
II. Selection of the base-case and establishment of the parametric model of solar control solution.
III. Formulation of the integrated analytical-geometric model.
IV. Compilation of optimization solutions and discussion.

3.1 Climate data reduction.

An experiment was performed to verify how much it is possible to reduce the climate data without losing the original annual characteristics for daylight simulation, as required for architectural design for nonresidential buildings. Thus, the period between 06:00 and 18:00 of the climate data was considered, also the days were also reduced in three ways:

I. from 365 to 182 days (half of the days of year),
II. from 365 to 121 days (a third of the days of year),
III. from 365 to 91 days (a quarter of the days of year).

It was analyzed the box plot and histograms for Global Radiation, Direct horizontal Radiation, and Diffuse Global radiation. The second option was chosen (II). The figures 01 and 02 shows the box plots, and the histograms for the complete climate data set, and the climate data reduced to a one third of the days for Global horizontal Radiation. For simulations, the reduction of the climate data was automatized using the plugin Grasshopper for Rhino 3D.

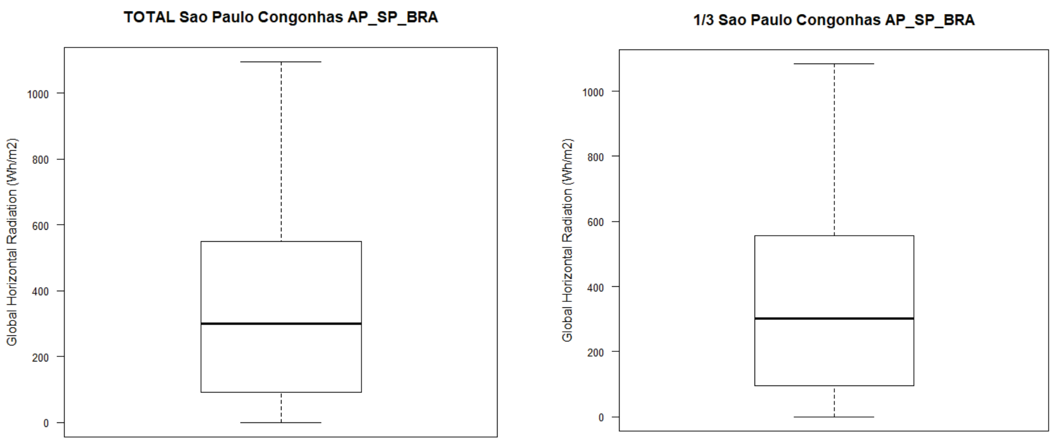

Figure 01. Box plots of Sao Paulo climate data with no reduction (left), and with a an third of the days of year (right).

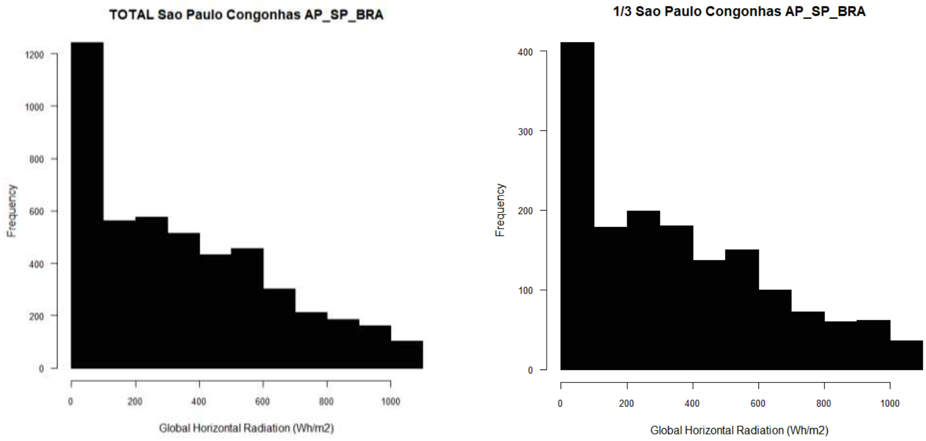

Figure 02.Histograms of Sao Paulo Climate data with no reduction (left), and with a an third of the days of year (right).

3.2 Selection of the base case

The base case is a nine-story building with free plan and structural technical core. It is located in a hypothetical urban context for the city of São Paulo-Brazil; latitude of 23.54 south (figure 03). Each façade has 70% glazed area with a 60% Tvis glass. The parametric model of the shading solution consists of curved balconies up to 2.00m. The solution is established from the combination of five distinct configurations of balcony progressions (in the vertical section of the facade), applied individually to 12 points distributed along the four façades in the horizontal section, as shown in Figures03 and 04. The whole model allows 512 combinations of solutions:

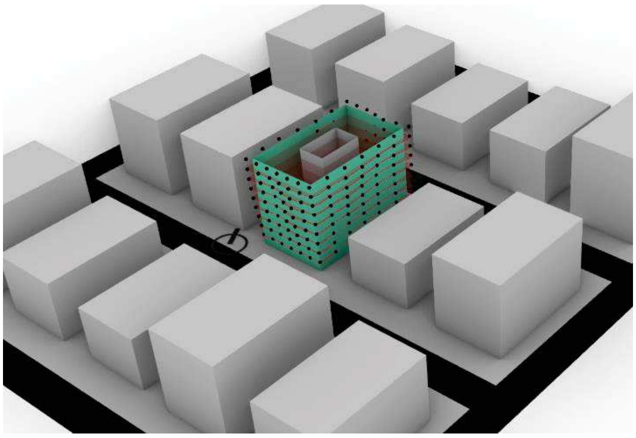

Figure 03. Free plan building, urban surroundings and control points.

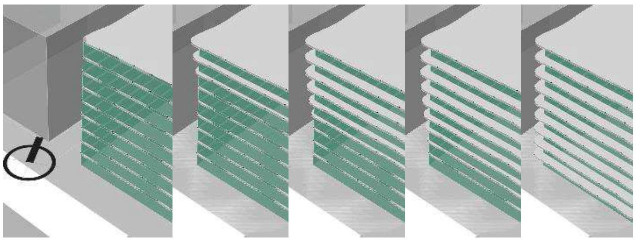

Figure 04. Five possible variation scans settings over the course of the façade for each group of control points.

3.3 Integrated analytical model

The multicriteria optimization model features three performance indicators, one for daylighting quality, one for thermal performance and one for help the design decision:

a) Average UDI (Useful daylight illuminance) for range from 200 to 2000 lux for hours between 07:00 and 18:00 in every day of the year on a work plan at the height of 0,75m.
b) Average daily solar radiation that crosses the glazing system per sensor between the hours of 07:00 and 18:00, for situations with air temperature above 22°C. This indicator is measured in the opening plane on the inside of the building environment.
c) The sum of the area of the balcony (solar protection).

The computational model is based on the two-phase method through Radiance, with simplifications described by Subramaniam (2017) and presents an accurate simplified model with processing appreciably faster than Daysim. The optimization process uses a multicriteria and metaheuristic algorithm known as Hype that obtained good results compared to others for similar simulations described by Wortmann, (2017). The proposal uses the Grasshopper, visual script plugin for Rhinoceros 3D and Honeybee+ plugins to connect 3D modeling with Radiance and the Octopus plugin to perform the multicriteria optimization (Figure 05). The balcony has reflectance of 0.7, the roads in urban space 0.1; and the neighboring buildings, 0.4. The Radiance simulation parameters were:

-air 128 -dp 512 -ab 6 -as 4096 -ds 0.05 -aa 0.1 -ad 10000.

To reduce the simulation time, instead of the 365 days of the year, simulations were run for a sampling of 121 days distributed equally in the year. With this, the simulation time was reduced from 45 min for both calculations (Sum of radiation and UDI) in Daysim, to 68 seconds with a two-phase method. Both on a computer with an intel i7 processing.

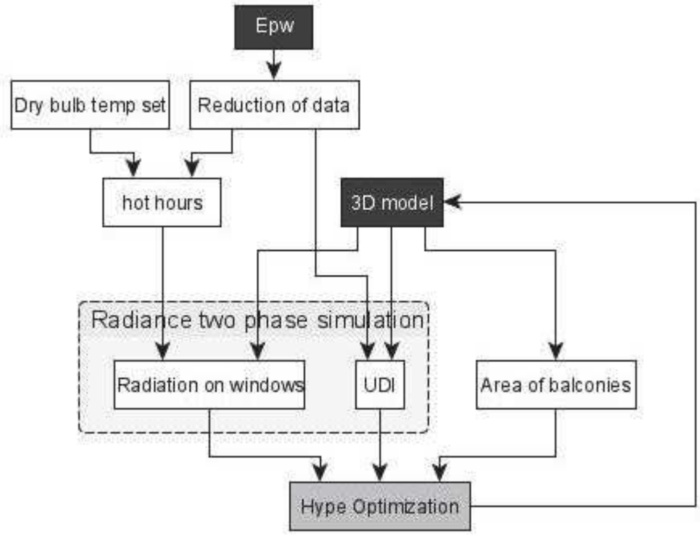

Figure 05. Flow chart of the Grasshopper model.

3.4 Compilation of optimized solutions.

After 10 generations of simulations, ten optimized solutions in the pareto front where selected. A comparison with the extreme solutions were stablished. It was computed the percentage of savings in comparison with the extremes of balcony area solutions, and the percentage of the balcony areas used in the optimized solution. The percentages were stablished considering the equation 1.

$$P_s=100 - [(R_{max}-R_n)/(R_{max}-R_{min})*100] \quad \text{Equation 1}$$

WHERE:
P_S is the percentage of solution [%];
R_n is the optimized solution;
R_{max} is the solution result with the maximum of balcony area;
R_{min} is the solution result with the minimum of balcony area.

The savings where stablished in the equation 2:

$$S = P_s - P_{area} \quad \text{Equation 2}$$

WHERE:
S is the savings compare to the area of balcony used [%];
P_S is the percentage of solution [%];
P_{area} is the percentage of the area used in the balcony considering the maximum [%].

4 RESULTS

The integrated analytical model established evaluation cycles ranging from 65 seconds to 70 seconds per cycle. This time was considered satisfactory. The optimization process considered 10 generations of simulations (approximately 980 simulations) lasting a period of 19 hours total processing. In the end, hundreds of solutions were available for the analysis. The Octopus interface allows an organization of the simulated cases and exportation to a database. It is possible to select a result and visualize the geometric solution on a case-by-case basis using the two graphs: an interactive three-dimensional dispersion plot, or a parallel coordinate diagram (Figure 06 and Figure 07). Figures 06 and 07 shows the graph generated in the 10° generation of simulations. The triangular mesh in figure 05 represents an approximation of the pareto front solutions.

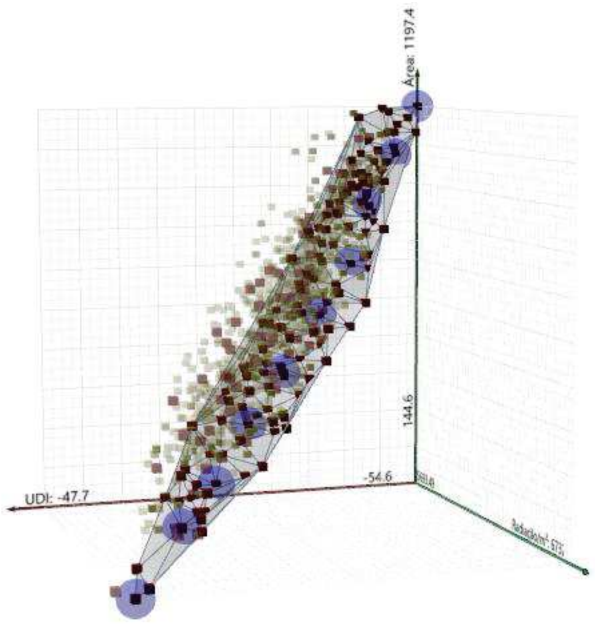

Figure 06. Scatter plot of solutions with ten highlighted solutions in pareto front.

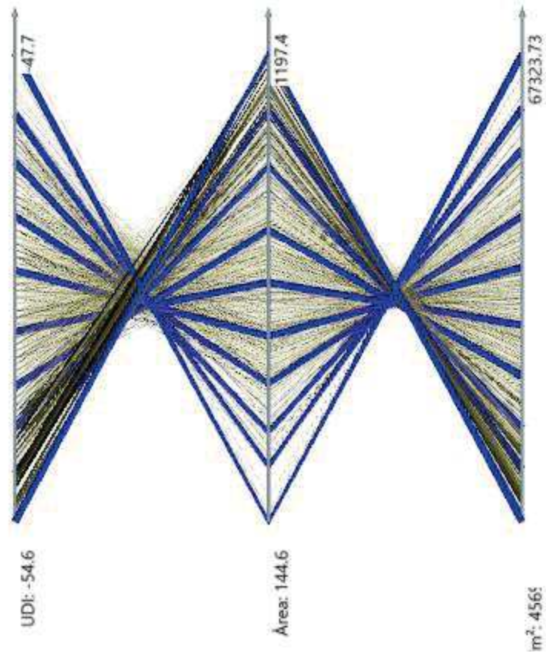

Figure 07. Parallel coordinate graph of solutions with five highlighted.

The solutions with the extreme parameter's combinations were establish. In addition, ten solutions founded in the pareto-front by the optimization algorithm were chosen in order to draw a parallel with the performance-guided design process. That is, to understand the behavior of this specific design problem and select possible design solutions within a universe of possibilities (Table 1). The ten solutions chosen are the combinations marked in yellow in the scatter and parallel coordinate plots (figure 05 and 06).

Table 1 - Results obtained from ten optimized solutions compared to extreme solutions in descending order of balconies area.

Solution	Balcony Area (m²)	Ba%	Average UDI	udi%	Savings	Averag. Radiation (W)	Rad w%	Savings
Rmax	1795,00	100,00	55,30	100,00	0,00	37758,70	100,00	0,00
optimized 1	1197,40	66,71	54,40	88,16	21,45	45702,07	75,82	9,12
optimized 2	1071,10	59,67	53,40	75,00	15,33	48105,81	68,51	8,84
optimized 3	941,90	52,47	53,00	69,74	17,26	49981,34	62,80	10,32
optimized 4	800,60	44,60	52,30	60,53	15,92	52404,97	55,42	10,82
optimized 5	682,30	38,01	52,10	57,89	19,88	54775,80	48,21	10,19
optimized 6	556,00	30,97	51,00	43,42	12,45	57574,35	39,69	8,71
optimized 7	471,60	26,27	50,20	32,89	6,62	59130,45	34,95	8,68
optimized 8	346,60	19,31	49,40	22,37	3,06	62865,68	23,58	4,27
optimized 9	270,10	15,05	48,80	14,47	-0,57	64870,25	17,48	2,43
optimized 10	144,60	8,06	47,90	2,63	-5,42	67270,20	10,18	2,12
Rmin	0,00	0,00	47,70	0,00	0,00	70613,90	0,00	0,00

The results show optimized solutions with savings that reach 21% for daylight quality results (table 01) and 11% for radiation results. The highest scores were obtained in the solution 01 and 05. The solution 05 presents 62% of balcony area reduction, with a good preservation of the performance requirements. When the optimized solutions approximate the extreme cases, there is a decrease of the solution savings (Figure 08). Depending on the design exigence, various solutions can be considered. In this case, preferably closer to the center of the plot. It is possible that a larger number of generations could find better solutions than those listed.

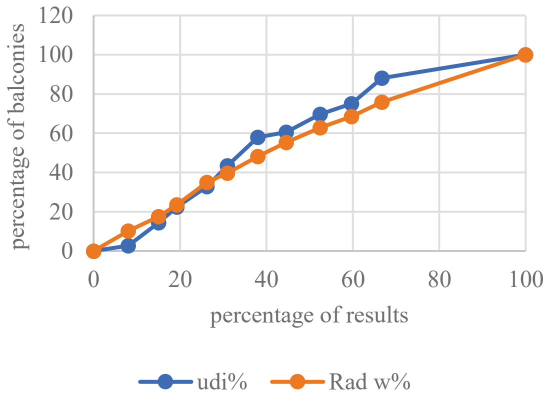

Figure 08. Percentage of results compare with the percentage of balconies.

Figure 09 demonstrates 25 solutions found in the pareto front by the optimization process as representative of the problem, starting with the solutions with performance indicators with lower value up to the with higher values between the established performance combinations. The solutions reunited demonstrate the design possibilities and can be evaluated in a design team considering the greatness of the values found in simulations, thus being able to help design decisions using sustainability strategies as a basis.

In the proposed base case, possibly the solutions of optimized balconies added to the use of glass with visible transmission of 0.60, will still not be sufficient to health the periods of excessive illumination and entry of solar radiation, and another combination of glass, or use of internal shading could be considered. Figure 10 demonstrates the solution that was chosen as desirable for the proposal in this experiment (indicated in table 1 as optimized solution 05).

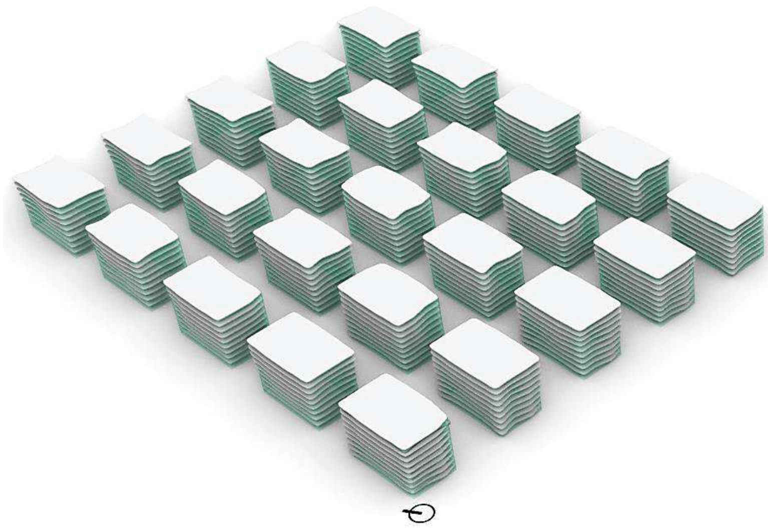

Figure 09. 25 solutions optimized in the pareto front organized in order of balconies area.

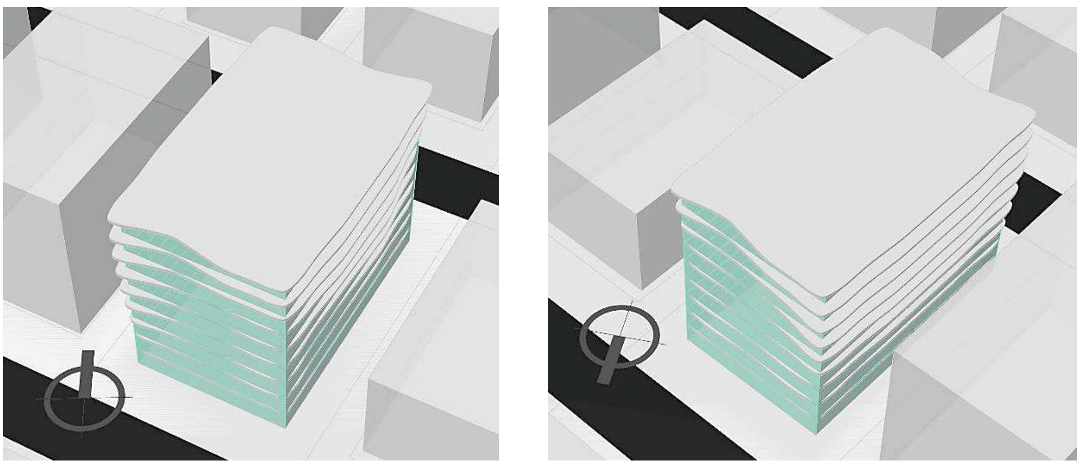

Figure 10. Optimized solution 05.

5 CONCLUSIONS

The experiment shows the applicability of the performance-based design method, the use of optimization in the design process; and proposes a faster method for façade designs with regards to thermal and daylight performance when compared to daysim based models. Through optimized solutions it is possible to reduce associated costs, establish complex solutions where the rules of a desirable aesthetics combine with performance indicators. The parametric model integrated with simulation improves the understanding of possible gaps associated with the range of solutions established, that is, the process helps to understand the behavior of the universe of possibilities and values of magnitude possible to obtain during the design process.

The proposed integrated parametric model fulfilled the research objectives by presenting simulation up to ten times faster than with Daysim. The performance indicators explored allow the classification of solar control solutions based on daylighting and thermal performance requirements (quantitative analysis). In addition, there is a qualifier of the solution, the indicator of the balcony area (qualitative approach). This can be used as a qualifier of the solution in order to help the final choice. The qualitative approach can change according to the design solution analyzed. The model is sensitive to changing glass, and complex geometry solutions. The results presented are compatible with characteristics of the climate of São Paulo, Brazil. The magnitude of results is compatible with the specific problem of the design (base case), being in this case, associated with the influence of the urban context, orientation and a specific climate, compatible with the complexity of the design process.

The optimization algorithm worked for the proposed purpose. It is a good option for situations with a large number of variations of simulation parameters, making it impossible to establish an analysis with all possible combinations. The evolutionary process searches for representative cases in the pareto front and characterizes the general behavior of possible combinations. As a disadvantage, it can be pointed out that due to the random characteristic at the beginning of the optimization process, it is not a guarantee that some simulations such as extreme situations will be simulated. For this reason, it is interesting to compute extreme situations when considering the use of evolutionary optimization algorithms to improve the characterization the optimized solutions. The tool chosen, Octopus, was considered satisfactory because it condenses all the results in interactives graphs, allowing interaction with the geometric parametric model in real time. It was considered a good option for use in the context of the project guided by performance.

The two-phase method presented satisfactory performance for simulations. The reduction of the days of the year for annual analyses made it possible to reduce the calculation time significantly, falling from 270 seconds to 68 seconds per simulation. The speed allows you to perform more analysis cycles in less time, compatible with the requirement of the design process. 19 hours of simulations enables the consideration of hundreds of design possibilities. This can make the use of simulation advantageous, when compared to the traditional design process. The reduction of annual data combined with the use of the two-phase method was considered a good option for dynamic daylighting simulations for the first stages of design.

Next steps provide for the inclusion of a glare metric, and also for the replacement of the radiation model for one that computes the transient cooling thermal load. In future steps, it is intended to use the model presented by ISO 13790. The method presents a simplified calculation model that has undergone a validation process for early design stage analysis as presents Corrado; Mechri; Fabrizio, (2007).

It is understood that the performance-based design method has been up coming and is not common in today's design efforts. However, the evolution of simulation tools, modeling and digital manufacturing processes allow to generate complex geometry models through performance principles, being a premise of sustainable design. It is a recommendation of the author, research that indicates improvements, descriptions of models, processes, selection of problems, and formulation of parametric models in order to gradually demystify these processes.

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