OFFICE BUILDING DESIGN IN HONG KONG ISLAND THROUGH SHAPE OPTIMIZATION

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Abstract. Dealing with crucial decision-making process has led to the development of many different methods of multicriteria assessments, especially optimization methodologies. This work is mainly focused on the integration of advanced computational design and digital methods, to design a complex building shape resulting in a performance-based approach through optimization methodologies. The project consists of the design of a skyscraper in Hong Kong Island made through parametrically controlled shape and evaluated respect to light and wind to reduce Urban Heat Island phenomena and enhance liveability. The aim is to find out a unique methodology that can be applied to different cases by making small adaptations regarding the parametrization and the parameters involved. The design is divided into two stages that need to arrange the methodology at different levels throughout the workflow. For this reason, it is mandatory to adapt inputs to the algorithm according to the goal. The result is a skyscraper placed in the financial district of Hong Kong, which has both the features of a Grade A Office building and can mitigate the UHI effect thanks to its particular and optimized shape.

Keywords. Shape optimization; Computational design; Genetic Algorithm; UHI effect; ventilation.

1. Introduction

Designers can use several techniques to discover an “optimal” solution including parametric analysis, genetic algorithms, multi-objective optimization, and even “passive” optimization. “Passive” optimization is what many designers are doing by creating three or four options, mentally testing them against past experience, and then intuitively determining a “best” solution; but in most of the cases it leads to an inaccurate prediction; moreover, it is not easy to consider more than one variable at the same time. For this reason, the most efficient method consists in the use of parametric analysis coupled with a genetic algorithm.

In their article Sun Lee, Ki Jun Han and Jae Wook Lee, compares the conventional “passive” approach, which depends on a designer’s sense of judgment with the approach which uses genetic algorithms, to create optimal indoor lighting conditions by adjusting louvre shapes and window patterns. (Lee, et al., 2016).

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Martins, Adolphe and Bastos searched for the adaptation and evolution of existing building stock blocks into 'positive energy' neighbourhood, by adjusting urban morphology elements. The optimization of solar energy incident on building outer surface is proposed, aiming at enhancing local energy production and minimizing potential solar gains. (A.l. Martins, et al., 2014)

Y. K. Yi and A. M. Malkawi explain the workflow of their research about optimizing building form; they introduce new methods to control building forms by defining a hierarchical relationship between geometry points to allow the user to explore the building geometry without being restricted to a box or simple form. Their methodology succeeds in generating an optimized site-specific building form by integrating advanced simulation and optimization algorithm. (Kyu & Malkawi, 2009)

It is impossible to reduce the environmental factors that impact a building to a single parametric relationship. The factors that affect a building, its envelope and its ability to serve as an effective system of climate control, are multi-dimensional. Parametric simulators can aid in understanding variation in environmental performances of a single parameter but are unable to optimise adequately all the involved factors. As a consequence, in building design, commonly, there is more than one objective function for optimization, then a multi-criteria optimization problem arises.

Genetic Algorithm is different from other optimization algorithms because it requires no skilled mathematical knowledge and is easy to apply. It aims to obtain superior genes via multiple generations, which is similar to a biological evolutionary process. The basic idea is to generate a new set of designs (population) from the current set such that the average 'fitness' of the population is improved. Thus, a superior 'gene' provides a more optimal shape. (J.T.Jin, et al., s.d.)

This paper proposes a computational approach for the design of the shape of an office building in Hong Kong Island. This approach offers an optimized workflow that focuses on two stages: first on the plan optimization and secondly, the location of six sky gardens is carried out. To implement a Pareto curve, it is fundamental the use of visual programming language with a 3D modelling tool for the improvement of passive design practices by showing alternatives and optimizing parameters. The different methods are tested and implemented by Grasshopper together with its plug-in dealing with both building simulations (*Ladybug, Honeybee, Eddy3D*) and genetic algorithms (*Galapagos* and *Octopus*).

2. Methodology

2.1. CONTEXT ANALYSIS

The first step in the design process is to analyse the environment to have clear what issues must be solved and what possible strategies can be implemented in the building. This becomes even more important talking about Genetic Algorithms. The role of the designer is fundamental to change the building's features and goals according to the specific site and problems.

Despite being a highly competitive global city, a leading financial centre and an attractive tourist destination; Hong Kong only has moderate performances in terms of liveability and innovation, which must be enhanced. Particularly the problems of Urban Heat Island and quality of spaces are addressed.

The temperature difference within urban areas compared to the surrounding countryside is known as the 'Urban Heat Island' (UHI) phenomenon and the main causal factors for this must be considered.

Solar exposure, affecting urban radiant temperature, is most directly influenced by building density but also by land-use zoning allocation of the built mass as well as the charter of vegetation cover on open ground. The building density is manifested in the extent of ground coverage, the allowable floor area ratio, and the ratio of the height of buildings to the width between them. This influences the shading of the solar heat during the day affecting gain and radiative heat loss at night due to the related parameter of sky view factor.

An appropriate solution to UHI effect is reached by designing adequate solar exposure, vegetation, natural ventilation; in addition, high albedo or high solar reflectance materials in urban areas can reduce this problem. This can be done at three scales: building group scale, building scale and building component scale.

The case study is located in Murray Road landmark site. It was the first commercial plot to be released in Central since 1996; for this reason, it got the attention of local developers. Henderson Land Development is going to turn the 31,000 sq ft site into a single landmark Grade A office building with around 35-floors by 2022. The car-park is going to be transformed into a "landmark building" in Hong Kong's downtown business district with the contribution of Zaha Hadid Architects, which presented their project last November. Adding a central atrium and sky gardens it is possible not only to exploit cross ventilation for heat gains reduction but to increase liveability and daylight exposure.

2.2. PROCESS DESCRIPTION

To simplify the process, the design was divided into two main phases. First, the plan optimization was conducted and then, when the best plan shape was fixed, the sky gardens' position were parameterized and optimized. The parameters involved in the two phases were different, changing according to the goal of each analysis, but the logic behind the process was the same.

In general, the process is made by the following steps:

1. Develop a geometrical representation connected to the parametrized plan and the fixed height.
2. Run simulations
3. Run again to compare the performances. The more runs are done the more it is possible to understand which variable impact the most.

The whole iterative process is then automized thanks to the optimization component. Reading the results for each trial problems can be highlighted and fixed. At the end of the workflow, it was possible to establish the best methodology and the final most efficient shape.

Before starting the simulation, for both stages, it was fundamental to define the geometry (Genome) and the parameters to test (Fitness), then the analysis process started.

2.3. STAGE ONE: PLAN OPTIMIZATION

To run the optimization component, it was first necessary to parametrize the plan to define the 'Genome' of the analysis. Three different plan parametrizations were tested to find out the one able to stay within the constraints.

Together with the performance-based approach, represented by the optimization workflow, it was fundamental to keep in mind the limitations given by prescriptive Regulations; in fact, the first stage of the parametrization was to check Hong Kong's Standards. According to Sustainable Building Design Guidelines, APP-152 establishes the design requirements regard the continuous projected façade length (Lp), Separation Distance (S) and Permeability (P). (BuildingDepartment, 2016)

Putting together the limits given by standards and design features stated by the designer, the project's constraints are summarized in:

- - Fixed building height: 180 m
- - Fixed floor to floor height: 5 m
- - Building setbacks from APP-152
- - Permeability: min level of 20% per each Assessment Zone from APP-152
- - Maximum and minimum GFA from APP-152

The next step consisted of the parameter's definition. They were assessed considering how these affect the performances of the building and how to implement them on Grasshopper to be linked to the Genetic Algorithm software.

The main features to consider in the early design phases were grouped in daylight availability, sky exposure and natural ventilation. To perform these variables a preliminary analysis permitted to define the best method to implement them in the software. Summing up this preliminary phase, the defined parameters were: hours of sun and radiation, regarding the daylight availability; Sky View Factor and Quality View Factor (view on the harbour) for the sky exposure; and permeability and wind velocity ratio related to natural ventilation.

Moreover, to work with a unique variable instead of different scores for each analysis point, a post-process of the quantities was necessary. *Figure 1* shows an example of radiation analysis on a shoebox, displayed as the value per point on the left and with the coloured mesh generated by *Ladybug*, on the right.

The goal of this first stage was to test different methods to assess which algorithm performs better dealing with multi-criteria optimization. Thus, three methods were carried out, each giving some pros and cons permitting the designer to define limitations and to find a way to solve them and improve the workflow.

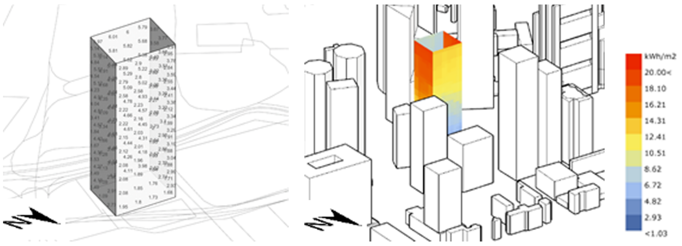

Figure 1. Radiation analysis on a shoebox. Value in each point (left), coloured mesh (right).

The tested variables changed throughout the workflow according to limitations emerged during the trials. Going form Method 0 to 3, the number of parameters involved increased and the software complexity with it. Method 0 consisted of a preliminary test on a shoebox, which enables the designer to assess the limitation of the site and critical areas and values to work on. Then, Method 1 was the fastest way to automatically test different orientations thanks to a tool integrated into the analysis components (radiation, sunlight-hours and view analysis), of *Ladybug* itself, which lets the user study the relationship between the orientation of the building and the amount of incident solar radiation or sunlight hours. In this study, it was applied to the Radiation component. It does not permit to test different geometries and the number of orientations is limited to the value input by the designer.

For these reasons, Method 2 involved a Genetic Algorithm using the plug-in *Galapagos*. This software looks for maximising or minimising a variable, resulting in several 'optimized' results displayed in the software's panel. The main problems of this method were related to the parametrization, which exceeded the site boundary, and to the number of parameters considered. These drawbacks were solved thanks to Method 3, both using a multi-criteria GA plug-in (*Octopus*) and changing the plan's parametrization.

The last method was carried out in different trials, in which the change of plan's parametrization and of the number of parameters were necessary.

The fourth, last, trial involved a four-parameters optimization trying to:

- - Maximise Gross Floor Area
- - Minimize Radiation
- - Maximise Sky View Factor
- - Maximise Quality View factor.

Octopus' results were displayed both on a three-dimensional graph and on a parallel one (*Figure 2*) in which the phenotypes were normalized on the four axes. In the second one, it is easier to read the non-dominated solutions, which are represented with thicker and darker lines, tending to minimize their value and to move towards the left of the diagram. The selected solutions are highlighted in yellow, and the corresponding values are reported in *Table 1*.

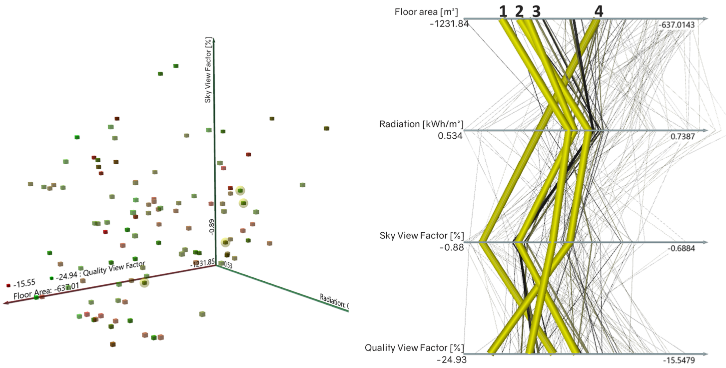

Figure 2. Three-dimensional results' graph (left), parallel axis results' (right) from Octopus. Stage 1.

Looking at these four options, the role of the designer is to evaluate the results, using both his knowledge and comparing them in terms of other useful parameters. In this project, a comparison in terms of natural ventilation on the first three solutions, displayed in *Figure 3*, permitted to assess the final best shape.

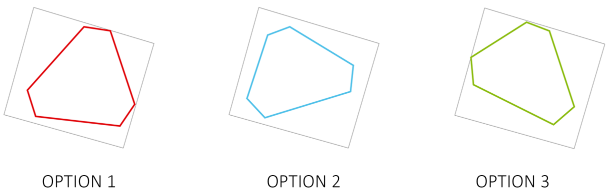

Figure 3. First three best options' plan geometry.

To evaluate which plan configuration can reduce stagnant area and increase the natural ventilation at the urban level both prescriptive and performance-based approaches given by Hong Kong's standard were used. First, referring to APP-152 (BuildingDepartment, 2016) the permeability of each configuration was evaluated. After that, considering the Air Ventilation Assessment Guidelines (AVA), the Velocity Ratios, both at Spatial and Local level were maximised. (Ng, 2009) To evaluate these values, a CFD analysis on the site was run, thanks to the *Grasshopper* plug-in *Eddy3D*.

In *Table 1* the final results are collected to point out that the best plan shape is given by Option 3.

Table 1. Summary of results. Stage 1.

Solution	Description	Floor Area [m2]	Total Rad [kWh/m2]	SVF [%]	QualVF [%]	Tot perm. [%]	Tot wVR [-]
1	Octopus: four-criteria opt.	1129.96	9059.27	30.65	22.17	156	0.76
2	Octopus: four-criteria opt.	1061.62	9085.45	30.87	20.17	157	0.85
3	Octopus: four-criteria opt.	1082.39	9150.29	30.55	23.83	163	0.95

2.4. STAGE TWO: SKY GARDEN OPTIMIZATION

A characteristic feature of this design is the presence of sky gardens connecting the external environment with an atrium in the middle of the geometry. The five-storey gardens, which are located at different levels and directions, provide fresh air into the central atrium, which acts as a natural ventilation chimney for the building. Moreover, central atrium and the triangular shape of the building plan help to create a zone with negative pressure, which itself causes the building's natural ventilation.

The second stage of the optimization methodology consisted of the design of the sky gardens' location. Differently from the first stage, the methodology applied was the same (Method 3 / Octopus multi-criteria optimization), but the parameters involved changed from Method 1 to Method 2 due to considerations carried out throughout the process.

The 'Genome' for the algorithm were six sliders corresponding to the height of the sky gardens. These were set according to Regulation's constraints given by the Practice note N.01, regarding green features to be exempted from the GFA. (BuildingDepartment, 2014)

Considering the geometry to design, the first step was to state the parameters ('Fitness') to take into account. Indeed, Method 1 aimed to maximise the radiation hitting on the internal façade to increase the buoyancy effect due to the increased surface temperature, minimizing the external radiation and maximizing the overall SVF. Nevertheless, designing an atrium geometry, the contribution given by the reflected light in the atrium well is fundamental, and a big limitation of *Ladybug* tool is that it does not include the light's indirect component.

For this reason, Method 2 conceived the use of *Honeybee*, which works with Radiance and Daysim tools which better represent the reality. Moreover, a deeper analysis of the internal daylight was carried out executing a dynamic daylight analysis at four significant floors. The parameters involved were UDI (Useful Daylight Index), customized UDI evaluating the percentage of time with lux in a comfort level (office buildings: 300-1000lux) and sDA (spatial Daylight Availability). Lastly, the 'Fitness' parameters for *Octopus* were: Radiation on the internal façade to maximise, and customized UDI to maximise.

Big limitations to this method were given by a series of assumptions taken to design a parametric thermal zone and the time needed to obtain a consistent result. For these reasons the parameters involved were just two, but a longer and deeper evaluation may consider more parameters and a more detailed model containing information regarding all the floors and the precise materials and glass' definition.

Given the parameters and the 'genotype' of the analysis, a two-dimensional optimization was run. The first three solutions, showed in *Figure 4*, were evaluated also in term of sDA, UDI and internal radiation and their coloured mesh helped to identify critical areas of each geometry. An example of the comparison of the four floors behaviour in the three geometries is reported in *Figure 5*; it represents the percentage of time that points are hit by less then 300lux, thus the red area corresponds to the critical one, with poor light exposure.

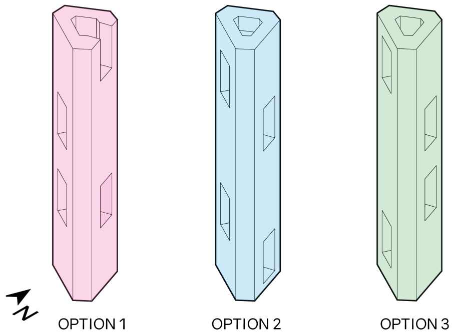

Figure 4. First three best options' sky gardens locations.

These values were also reported in *Table 3* to better compare the results. In conclusion, Option 2 was selected as the best shape and its geometry is reported in *Figure 4*.

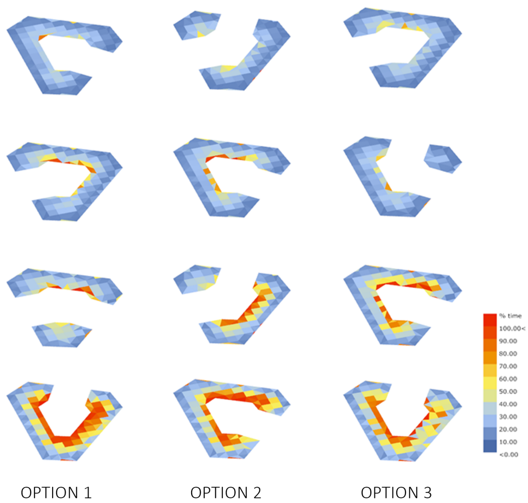

Figure 5. UDI<300lux evaluated at the four selected floors in three best sky gardens configurations.

Table 2. Summary of results. Stage 2.

Solution	Description	Tot Internal Rad [kWh/m²]	Total External Rad [kWh/m²]	UDLI [%]	UDI [%]	sDA [%]	Avg Floor Rad[kWh/m²]
1	Octopus: two-criteria opt.	75.73	274.59	31.82	86.83	78.20	16.81
2	Octopus: two-criteria opt.	76.73	269.04	30.51	86.53	99.97	15.60
3	Octopus: two-criteria opt.	77.55	272.17	31.29	86.93	80.28	17.06

3. Results

A final stage consisted of running a CFD analysis for the final optimized shape, to confirm that it permits to increase cross-ventilation along the building atrium. A vertical plane along the main wind direction was considered and the coloured arrows, displayed in *Figure 6* clearly show how this geometry permits to reduce the stagnant areas on the leeward side. The bottom openings help on the windward side facing the prevailing wind direction, while the upper openings help to increase the stuck ventilation.

The result presented contribute to prove the effect of cross ventilation, whose goal is to promote sustainable development as a countermeasure to the UHI effect.

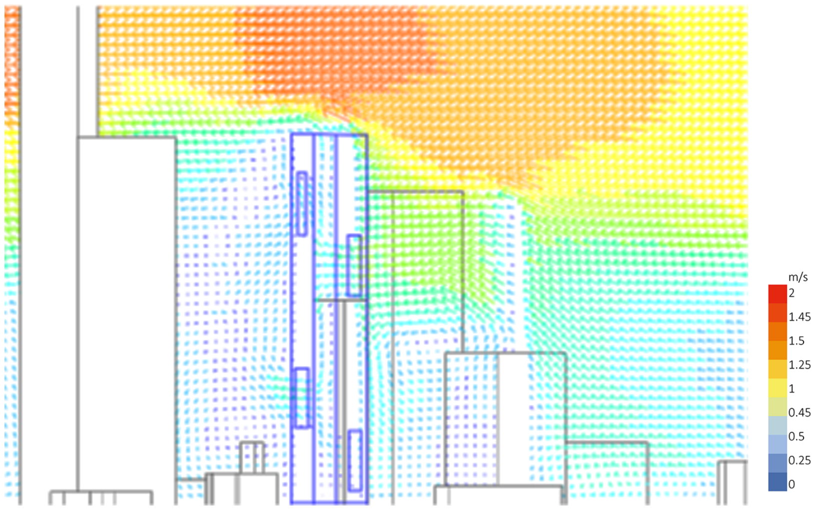

Figure 6. CFD analysis along the main wind direction plane.

4. Discussion

Thanks to the workflow presented it was possible to assess the best shape to lower the UHI effect and increase liveability. The method is a combination of performance-based approaches, given by the Genetic Algorithm, and a prescriptive ones used both to fix the design constraints and, in the last phase, to assess the permeability of each option. The focus of this project was the optimization methodology for both the stages conceiving different constraints.

For each simulation, it was necessary to define the 'Genome' and 'Fitness', that changes with the goal of the analysis. Regarding the first stage, the 'Genome' was the plan shape, including all the parametrized sliders which make it change. The 'Fitness' varied among the different trials. Focusing on the third method, which turned out to be the best one, this involved the use of Octopus plug-in, able to run a multi-criteria optimization.

Especially the second stage was characterized by big restrictions given by the software. These were mainly related to the model definition and the level of detail of the analysis. It was necessary to accept many approximations to make the analysis faster. Nevertheless, these limitations can be easily solved increasing the time necessary to define the model and run the optimization tool. According to the needs of the project, the model can be more or less detailed, and even more parameters can be included in 'Fitness'.

One of the advantages of using *Octopus* is the ability to define multiple objectives that can be evaluated simultaneously. The result, after several iterations, is a pool of optimized design alternatives that meet the objective function set. Nevertheless, although it is a user-friendly method, it cannot be a substitute for the designer. His role is to adjust 'Genome' and 'Fitness' according to the project's needs.

Moreover, these algorithms are not able to assess only one optimal solution. The Pareto curve proposes many non-dominated solutions looking to minimize the fitness parameters involved, but the more criteria are inserted the more complicated is to find out an exceptional solution. On one side it does not help designers in finding a unique solution but it still represents great support in decision-making stages that must be followed by a deeper analysis of the results.

Optimization methods are mainly used in the preliminary design phases of a new building or for building retrofit. If a methodology of sensitivity analysis is applied in the early stages, it is possible to identify the most important parameters about building performance and the expert judgment can be used to simplify the optimization problem and reduce the size of the solutions each space.

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