URBAN FORM OPTIMIZATION FOR THE ENERGY PERFORMANCE OF BUILDINGS USING CITYSIM

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ABSTRACT

The energy efficiency of the urban texture relies notably on the buildings' form, which characterizes its capability to take profit of the solar potential as well as its loss of energy through the envelope. Therefore, the general layout at the district scale has a significant impact on the global energy balance in a dense built environment, where the relative position of the adjacent buildings generate shadowing and inter-reflection on a large part of the incoming solar radiation.

In the current work, an urban energy simulator named CitySim is used together with a hybrid evolutionary algorithm. The physical model within CitySim features the computation of shortwave radiation including reflections, longwave radiation and a nodal thermal model for the building energy flows. The complete simulation leads to a rather precise evaluation of the annual heating needs, defined as the objective function to be minimized at the district scale. An existing district in Paris is taken as case study: the Bercy park front. Its buildings are disposed in several blocks surrounding courtyards with openings on the park's side (south-west). This district is recent (1994-2005) and located in a dense area of seven stories buildings. In its original design, the access to sunlight was taken into account by the planner, thus the initial intuition of the architect is compared with optimized configurations.

The paper describes a case of urban form optimization, with the formal description of the variables, constraints and objectives of the problem and the definition of the geometrical case for Bercy Front Park. The optimization variables focus on geometrical properties such as the height of the buildings and glazing ratios. The thermal properties of the building (insulation, glazing type) are set in accordance with the French standards of the thermal regulation (RT2005). The urban layouts resulting of the optimization process are analyzed and discussed.

Keywords: Urban form optimization, evolutionary algorithm, urban energy simulation, CitySim

INTRODUCTION

The use of simulation tools for the energy balance evaluation leads to a better understanding of what are the most important features of a good urban layout. The most common methodology consists in comparing different urban layouts considering one criterion, e.g. minimize the energy needs. In this context, combination of these tools with numerical optimization methods appears to be an efficient way to search within a large space of possible configurations those that best suit a given objective. Results are expressed as a set of values for each of the optimization variables which can be related to geometric and architectural characteristics (height and form of buildings, glazing ratio), materials properties (insulation, glazing), or building systems specifications for heating, cooling and HVAC [1]. Most of the building optimization studies involves genetic or evolutionary algorithms to search for optimal solutions [1].

In the specific field of urban planning, the solar potential is a common criterion for design, either treated geometrically [2], by parametric studies of urban layouts [3], or by using optimization methods [4]. It has been shown that a significant improvement in the annual solar potential can be achieved compared to standard intuitive configurations [5]. While playing an important role in the solar transmitted energy, the design of windows is usually treated separately as a optimization problem in itself: glazed areas better transfer heat by conduction but allow the transmission of solar radiation which has an impact on daylighting, heating and cooling needs [6][7].

The present study describes a case of shape optimization at the urban scale based on the geometric parameterization of an existing district in Paris. The optimizer uses an evolutionary algorithm (hybrid CMA-ES/HDE) developed with the purpose to achieve urban optimization [8]. The annual energy needs for heating are defined as the objective function to be minimized. The evaluations of these needs are performed with CitySim, a software designed for the simulation of the energy fluxes at urban scales [9]. The cooling needs are not taken into account since they are not significant under Paris climate, assuming the possibility to open windows and to use blinds.

In a first optimization case, the heights of buildings forming a block are defined as optimization variables. The optimum configuration, obtained after the optimization process, is compared with the original layout with respect to their heating needs. An analysis of a set of good urban configurations is then performed with the aim to characterize the design subspace ensuring low heating demands. Finally, the glazing ratios of the four main block orientations are set as optimization variables together with the building heights to compare the importance of these two characteristics on the design subspace obtained.

METHODOLOGY

Optimizer

The optimization process is treated using an evolutionary algorithm developed as part of a work on urban shape optimization [8].

To this purpose, a vector of bounded continuous parameters, $\vec{x}$, is defined, encoding the characteristics of an urban configuration. In this scope, a set of values for these parameters defines an individual. A population corresponds to a group of individuals.

$$\vec{x} = \{x_1, \dots, x_n\} \qquad x_{i,min} \leq x_i \leq x_{i,max}$$

The optimization problem consists in minimizing the objective function $J(\vec{x})$, in our case the heating needs, given a parameter space A, ie:

$$\min_{\vec{x} \in A} J(\vec{x})$$

Case study

A district of Paris is considered as a case study: the Bercy Front Park. This district was built between 1988 and 2005 at the site of a former wine warehouse district, southeast of Paris. It is composed of seven stories housing blocks surrounding courtyards (24 m height). The area is bordered on the southwest side by the Bercy Park. Although the blocks were designed by different architects, consistency rules have been established by the architect responsible for the development of the area, Jean-Pierre Buffy. Thus, the blocks adjoining the park have a U-shape closed by two independent blocks, leaving visual openings on the park.

For this study, one single block is considered (Figure 1). To simplify the modeling, the block is discretized into 16 identical buildings around a courtyard (Figure 2). Trees and balconies are not taken into account, although they may have a significant influence on the reduction of solar radiation. The surrounding buildings are modeled in a simplified manner and influence the heating needs calculation. The heights of each of the 16 buildings of the modeled block constitute the parameters of the model, represented by the continuous variables $h_1, \dots, h_{16}$. The vector $\vec{x}$ of the optimization parameters can be written:

$$\vec{x} = \{h_1, h_2, \dots, h_n\}$$

The optimization problem is solved in two steps. At first, only the heights of the buildings are set as variables. Then, four parameters: r_{SW}, r_{SE}, r_{NE}, r_{NW} corresponding to the glazing ratio of the four directions of the block (for every surfaces) - respectively southwest, southeast, northeast and northwest - are added to the optimization parameters.

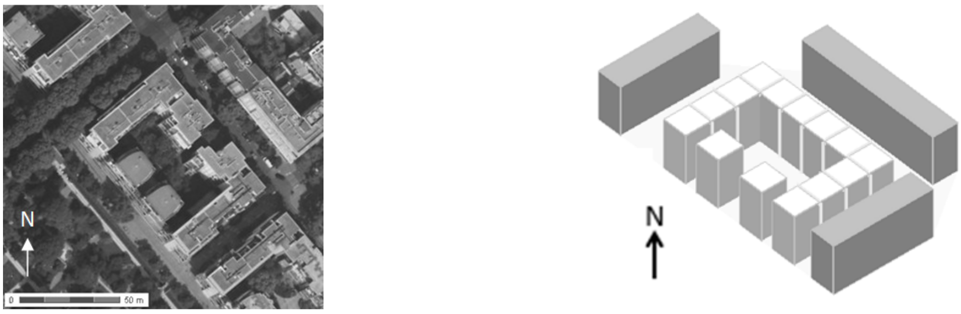

Figure 1: satellite view of the block (source: IGN) and simplified representation

Figure 2: representation of the block discretization with building numbering

Constraints

The Local Development Plan of the city of Paris sets the maximum allowable building height, which, for the studied block, is 31 m. In accordance with the regulation, and to work only with floors of 3 m, each height parameter is bounded:

$$3 \leq x_i \leq 30 \qquad i = 1, .., 16$$

A constraint on the total volume of the block is defined with respect to the volume of the simplified original geometry of the block, V_{built} (Figure **1**):

$$\sum_{i=1}^{16} A_i h_i = V_{built} \pm 5\%$$

In the second optimization case, the glazing ratios, considered as variables, are bounded in order to prevent them from taking extreme values (no windows or fully glazed façades):

$$0.2 \leq r \leq 0.8 \qquad r \in \{r_{SW}, r_{SE}, r_{NE}, r_{NW}\}$$

Heating needs simulation

The annual heating needs are assessed using the software CitySim [9]. It features a nodal thermal model applied to each building. Heat gains from direct and diffuse solar radiation are taken into account, as well as shortwave reflections [10]. Longwave exchanges between the walls are also calculated. The calculations are based on weather data for the city of Paris from Meteonorm 6.1 [11].

The insulation of the buildings is defined in accordance with the French thermal regulation of 2005. Construction details are referenced in Table 1.

Location	Parameter	Unit	Value
Façades	Wall U value	W/(m².K)	0.36
	Wall solar reflectance	-	0.4
	Glazing U value	W/(m².K)	1.8
	Glazing ratio on all walls (1st optimization case only)	-	0.25
	Glazing solar transmittance	-	0.7
Floor	U value	W/(m².K)	0.27
Flat Roof	U value	W/(m².K)	0.27
	Solar reflectance	-	0.2
Ground	Ground solar reflectance	-	0.2

Table 1: construction details

The air is renewed from ventilation and infiltration, with a coefficient of 0.4 volume/h. Thermal bridges are not taken into account in the calculation, which results in an underestimation of the heating needs. However, the corresponding losses are supposed constant with the geometric parameters (modification of heights), and therefore should not influence optimization results.

RESULTS

First case: optimization of the heights of the buildings only

In a first step, only the heights of the buildings are considered as optimization variables. A total of 5000 evaluations of the objective function are performed in the optimization process.

A decrease of 16.5 % of heating requirements is observed between the worst and the best individual. The best obtained configuration is presented in Figure **3**. The original design was simulated using the same simplified typology (Figure **1**), to ensure a comparable envelope surface and volume. The evaluation on CitySim results in a decrease of 12.1 % of the heating needs between the original configuration and the optimal case.

In order to evaluate the importance of each parameter, a set of good configurations is analyzed, using for this the 5 % best evaluations (about 250 unique individuals). These individuals are all within 2 % of the best individual with respect to the objective function computed with CitySim. For each parameter, a preferential range appears to gather the best configurations. The standard deviations and mean values are calculated for each variable (Figure **3**), giving information on the acceptable range ensuring low heating needs while leaving some flexibility to the urban planner for the design. It has to be mentioned that all the considered individuals have a total volume close to the minimum allowed ($V_{built} - 5\%$).

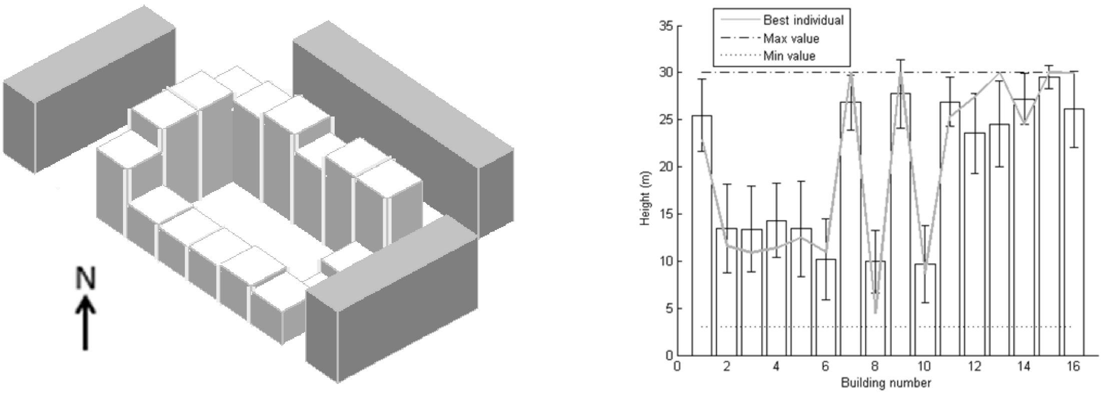

Figure 3: best configuration (left) and analysis of the 5% best individuals: mean values and standard deviations (right)

Second case: optimization of the building heights and the glazing ratios

The combined building height and glazing ratio optimization is also performed with 5000 evaluations of the objective function. The mean values and standard deviations, based on the 5 % best individuals, are shown in Figure 4. It appears that, for the analyzed set of individuals, the standard deviation of the glazing ratios is low relatively to height parameters. For the walls facing north (northeast and northwest) and for the obstructed orientation (southeast), the glazing ratio obtained corresponds to the defined lower bound. Solar gains are offsetting losses only for the southwest orientation which is unobstructed. Nevertheless, the obtained glazing ratio of 0.3 is still much lower than what was actually built (over 0.5). A possible explanation for these generally low values of glazing ratios is the lack of contradictory criteria such as daylight evaluation in the objective function.

The best solution found in this optimization case has a 2 % decrease heating requirements compared to that of the first optimization case, with optimal glazing ratios close to the value set in a first time. The height values of the best individual presents some similarities with the best configuration observed in the case where only heights are optimized (lower buildings to the south side and higher to the north side). Furthermore, the values for most of its parameters fit within the standard deviation around the mean value calculated for the 5 % best individuals of the first optimization case.

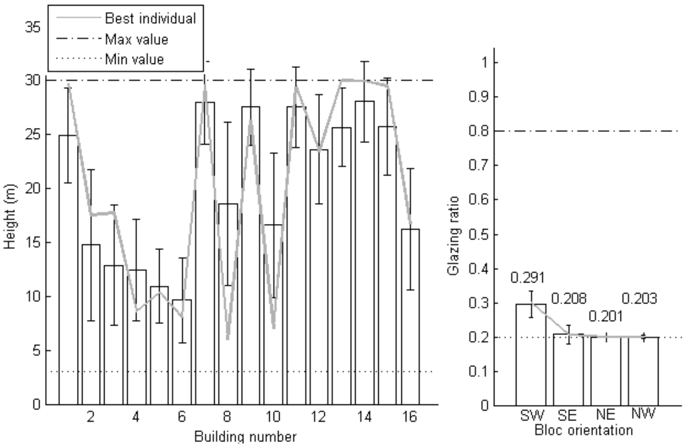

Figure 4: mean values and standard deviations for building heights and glazing ratios

CONCLUSION AND DISCUSSION

A study of urban form optimization was performed by coupling an evolutionary algorithm and CitySim for the calculation of heating needs. A city block based on a district of Paris was used as a case study. For this purpose, the geometry of a block was simplified into elementary buildings of varying height. The optimization initially focused on the heights of the elementary buildings, then on the heights of buildings together with the glazing ratios of the different block façade orientations.

The results were analyzed by focusing on a set of good configurations with respect to the objective function. Thus, it was possible to define a design subspace in which urban configurations have low heating needs. After examining the combined building height and glazing ratio optimization, it was observed that the standard deviations of the glazing ratio parameters over a set of good configurations are lower than that of the height parameters. This could be explained by a higher sensitivity of the objective function to the glazing ratios than to the height parameters.

This study focused only on heating needs, which is the most important part of the energy consumption of residential buildings in Paris. However, notions of comfort, including the visual profit of daylight were not considered and would certainly lead to different results. Future studies might take these aspects into account, possibly in a multi-criteria optimization.

AKNOWLEDGEMENT

The authors would like to thank the Fondation Bâtiment Energie for the financial support to the present work through the project REPA-F4.

REFERENCES

1. Evins, R.: A review of computational optimization methods applied to sustainable building design. Renewable and Sustainable Energy Reviews 22, pp 230-245, 2013.
2. Knowles, R.L.: The solar envelope: its meaning for energy and buildings. Energy and buildings, pp. 15-25, 2003.
3. Hachem, C., Athienitis, A., and Fazio, P.: Parametric investigation of geometric form effects on solar potential of housing units. Solar Energy, pp. 1864-1877, 2011.
4. Kämpf, J.H., Montavon, M., Bunyesc, J., and Bolliger, R.: Optimisation of buildings' solar irradiation availability. Solar Energy, pp. 596-603, 2010.
5. Kämpf, J.H. and Robinson, D.: Optimisation of building form for solar energy utilisation using constrained evolutionary algorithms. Energy and Buildings, pp. 807-814, 2010.
6. Caldas, L.G. and Norford, L.K.: A design optimization tool based on a genetic algorithm. Automation in construction, pp. 173-184, 2002.
7. Wright, J. and Mourshed, M.: Geometric opimization of fenestration. 11th International IBPSA Conference, Glasgow, 2009.
8. Kämpf, J.H. and Robinson, D.: A hybrid CMA-ES and HDE optimisation algorithm with application to solar energy potential. Applied Soft Computing Journal, pp. 738-745, 2009.
9. Robinson, D., Haldi, F., Kämpf, J.H., Leroux, P., Perez, D., Rasheed, A. and Wilke, U.: CitySim: comprehensive micro-simulation of resource flows for sustainable urban planning. 11th International IBPSA Conference, Glasgow, 2009.
10. Robinson, D. and Stone, A.: Solar irradiation modeling in the urban context. Solar Energy, pp. 295-309, 2004.
11. METEONORM v.6.1. Meteotest, 2009.