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Periodic 3D model to optimize urban shapes for solar radiation

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Abstract. *Solar radiation is a significant input for energy and light in buildings, and its access depends highly on the shape of the city. Theoretical test cases – blocks, canyons, courtyards – are common in the study of the solar exposure of an urban fabric. This paper presents a geometric formalization of a district as a periodic fabric composed of a repeated urban cell. This definition allows us to evaluate solar radiation considering replica of the studied district as solar masks. An example of optimization using an evolutionary algorithm to find an optimal set of block heights for direct solar access at different dates is then presented. The results show patterns that clearly illustrate the relation between sun path and optimal urban design for solar energy potential.*

1 Introduction

In order to respect itself and the engagement it recently took in Paris at the occasion of the conference of the parties of 2015 (among others), the world community will have to double its efforts to reduce greenhouse gases emissions and, for its high contribution to the latter, energy consumption.

The building sector is known to represent a significant energy consumer [Pérez-Lombard, 2008]. Furthermore, this sector has a high improvement potential, for it is possible to reduce drastically the use phase energy consumption of a building through efficient construction methods (thermal insulation, mechanical ventilation), and a right adaptation to the climatic and geologic properties of the land.

In this context, solar radiation should be constantly taken care of in architecture for its various aspects: thermal passive energy, daylighting, solar and thermal panels, for the useful part, but, on the other side, risks of overheating discomfort, and intensification of the urban heat island.

In the literature, the relation between solar radiation and the urban shape is studied on one hand by simulating and comparing realistic or existent district [Compagnon, 2004; Sarralde, 2014]. On the other hand, various studies simplify the city by canyons [Kanters, 2012; Strømann-Andersen, 2011; Krüger, 2010; Van Esch, 2012], blocks [Ratti, 2003], courtyards [Muhaisen, 2006] or typologies of houses [Hachem, 2011; Hachem, 2013] in order to link solar access to general morphological parameters of the city: aspect ratio, height, density, granularity. Furthermore, the use of optimization have recently increased in the field, exploring wider sets of geometric configurations of buildings [Kämpf, 2010; Vermeulen, 2015; Vermeulen, 2013].

When evaluating the solar potential of a district, the urban context (surrounding buildings) plays a role as masks, and reflectors if the reflections are taken into account. It seems logical to consider this border as part of an optimization or design problem: a “good” configuration of the district must avoid casting shadows on pre-existing buildings when solar energy and daylight is needed.

In the case of a study of new buildings in a real district, the border can be logically defined by the surrounding buildings and masks. Nevertheless, in order to study the sun capture of theoretical shapes, several situations exist:

- the district is located in an open environment, and the masks are neglected;
- an arbitrary urban context is considered: for example, all the surrounding buildings are set at an average height;
- urban context is randomly generated on the basis of the typology of the same district [Cheng, 2006].

In the second case, the choice can prevent generalizing the results: why would the buildings to be optimized have varying heights and not the context?

In the third case, the influence of a context consisting in buildings of random heights should also be evaluated. But again: the random context, even if it represents a diversity more in line with the variability of the optimized buildings, is not a general case.

These remarks motivate the use of a new geometric description of the district as a regular urban fabric whose basic element, called “cell” is subjected to optimization. Therefore, the urban context is homogeneous with the sub-area of interest: these are copies of it.

A description of the urban cell for solar radiation simulation is described in the next section. An optimization test case for maximizing direct solar radiation on a set of blocks is then presented and some results are shown.

2 Definition of the Urban Cell

We call urban cell a delimited urban area with buildings that can have parameterized heights or properties. From this definition, a periodic urban fabric can be defined as the infinite repetition in each direction of the urban cell. This repetition generates solar masks which will vary in the optimization process in a similar manner as the cell itself.

In the present work, we illustrate the urban cell with a representation of the city as blocks of varying height centered on parcels. However, its definition could be successfully derived in a variety of urban shapes that observe translation symmetries (canyons, courtyards).

The cell is associated with the representation of a block area on a rectangular grid. It is composed by n_x x n_y locations. The cell is then repeated on the sides as masks. An example of cell dimensions of 3x3 is shown in fig.1.

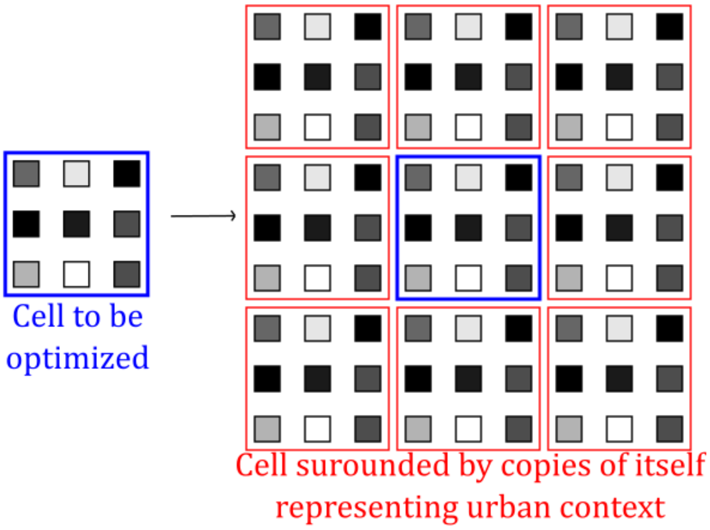

Figure 1. Example of urban cell. Grey level represent building height

When using a periodic definition of a district, a building whose height increases also generates masks around it whose proximity depends on the size of the cell. The influence of the masks regarding the sun exposure of a building decreases with the distance. Thus, the dimensions of the cell is *a priori* likely to influence solar energy that can capture a building, and can be an interesting parameter with which to play. To give an example of generated periodic fabrics, urban cells of dimensions 2x2, 3x3, and 4x4, reproduced to form 7x7 buildings districts, are shown in Fig.2.

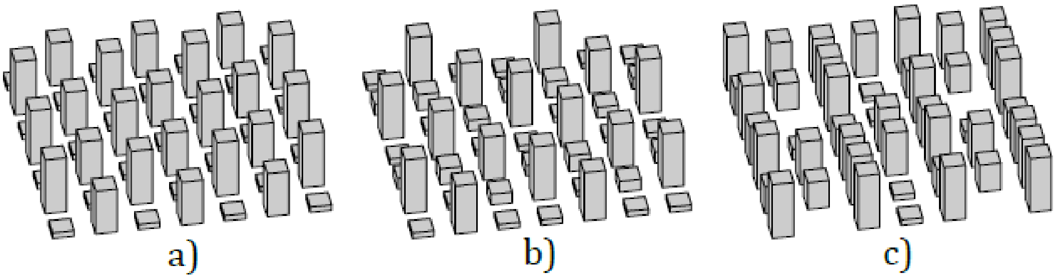

Figure 2: Examples of cells of dimensions 2x2 (a), 3x3 (b) and 4x4 (c)

3 Optimization Methodology

3.1.Geometry and parameters of the optimization test case

We consider a cell that takes the form of a square grid of parcels of 20 x 20 m in the center of which are arranged square base buildings of base 10 x 10 m. Each building may consist of 0-to-10 floors of 3 meters height. The vector of variables to be optimized is constituted of the integer number of floors x_i of building i.

$$\vec{x} = \{x_1, \dots, x_{Nbuilding}\}$$

The cell representation presupposes regularity of the urban fabric. Also, to consider whether some urban cells are better than others, different optimization tests are performed by varying three parameters:

- Three periods of interest are considered: 21 December (winter solstice), March 21, which is equivalent to September 21 (equinox) and June 21 (summer solstice). Solar radiation at the summer solstice is actually undesirable, and the radiation at the equinoxes, which brings a lot of energy to buildings because of a low sun in the sky, is also associated with risk of overheating. However, these dates are included to illustrate the reaction of the shape of the district to different geometries of solar radiation. The resulting optimal shape for direct energy maximization in summer should be considered as layouts to avoid.
- The volume of built area, which ranges from 33%, 50% and 66% of the maximum volume, where the maximum volume represents the overall built volume when all buildings are 10 floors high.
- The cell size may vary from a grid of 2 x 2 to 6 x 6.

In order to compare districts with comparable total building envelope, a constraint is imposed on the total volume to be built.

3.2.Solar radiation simulation and objective function

The objective function to be maximized consists in the overall direct irradiation on the urban cell on a one-day period by clear sky conditions, at the latitude of 50° N. The simulation uses a sky model developed by [Liu, 1960], and later adapted by [Campbell, 1998]. The shadows are computed at each time step by projections methods. This solar energy simulator has been formerly used for related optimization problems [Vermeulen, 2015].

The time step for solar radiation integration is set to 30 minutes.

In the present definition of the urban cell, the urban context is assumed repeated infinitely while, in practice, it needs to be limited in a balance between computation time and accuracy. For this purpose, a calculation radius is determined in which the context will be generated independently for each building. For example, for a cell of 3x3 blocks, treated with a radius of representation of six, nine urban geometries will be created, each having at its center a building of the cell and six rows of buildings repeating the cell in each direction.

3.3.Optimization method

An evolutionary algorithm is used for the optimization of the urban cell. It is based on a population of individuals (here: districts) which is evolved along generations to improve the value taken by the objective function [Eiben, 2003]. The structure of the optimization algorithm is presented in Figure 3.

The algorithm is fully described in [Vermeulen, 2015]. It showed a good ability to converge for similar parameterizations of districts. The main features of the algorithm are summarized below.

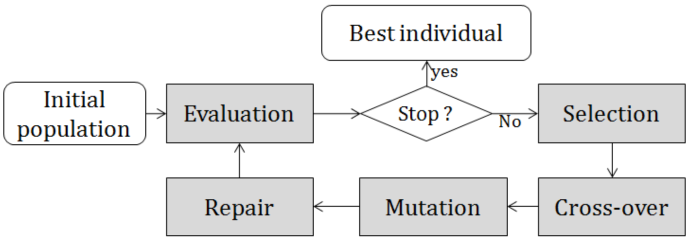

Figure 3. Structure of the evolutionary algorithm

As a selection operator, we use a ($\mu + \lambda$)-*Evolution Strategy* [Beyer, 2002], which means that the μ best individuals regarding the objective function are selected to be “parents” and to generate λ offsprings. The selected individuals are kept in the population for the next generation.

The crossover operator has to combine two admissible configurations to provide two offsprings satisfying the volume constraint and showing better performance. With the μ selected parents, $\lambda = 2\,\mu$ offsprings are created. A classical one-point crossover is performed: the vector of heights of the two parents are cut and exchanged. The cutting point is chosen randomly.

The mutation function consists in moving a building to an empty parcel. If there is no empty parcel, the building either exchange location with another building, or is destroyed and its volume distributed on existing buildings. The mutation over the parameters is performed over the district with a probability of occurrence set to 0.7 on the population of offsprings, which means 70 % of the newly created districts through cross-over are mutated.

The crossover cut point is selected randomly, so the resulting configurations have no reason to satisfy the volume constraint. To correct this, a repair operator has been implemented. This operator modifies the values of height, and thus increases the diversity in the population. Two types of corrections are used: the distributed correction evenly distributes or removes the difference between created district and desired built volume uniformly on all buildings; the localized correction adds or removes volume to a single building until one of its bounds is reached, then the latter is achieved to other random positions until the volume constraint is respected. As low populations are used, it is important to maintain the diversity. Therefore, the reparation operator applies randomly one of these two rules.

4 Results

Three optimization tests were run for each density, cell size and calculation date. A radius of calculation of 7 is used in all cases (seven rows of buildings generated in each direction around the evaluated building), which may require various replications of cells in each direction. The population of districts for the optimization process is set to $3(4+6c)$, where c is the cell size. Finally, it should be noted that the surface energy shown in buildings is the average over each facade. The figures of the next sections include the representation on one cell without its context, and a plan view with the cell repeated once in each direction. These representations are therefore different from the geometries generated for the calculation.

In the following, comments on results are given separately for the effect of calculation date, density and cell dimensions on the features of the best patterns found.

4.1. Effect of the date

A sample of results for the three considered dates (winter and summer solstice, and the equinox) is presented on Figure 4. One can notice that, for winter solstice and the equinox, the presented optimal configurations show east-west rows of maximum height buildings, while the presented optimal configuration for summer solstice has high buildings on every north-south row of buildings. It has to be noticed that various configurations are nearly equivalent, and the features of the best cells are better observed studying results for diverse cell size and volume. From this study, the results show:

- For the winter solstice, where the sun stays close to the horizon, with solar energy mainly coming from the south, the most efficient urban layouts all have at least one building of maximum height in each north-south strip. It can be observed that rows of high buildings or checkerboard patterns are equally efficient.
- At the equinox, the solar radiation is strong from direction south-east and south-west. The best urban layouts are constituted by east-west rows of maximum height buildings. The checkerboard pattern is not efficient for this date.
- At the summer solstice, the solar rays have low incidence on the facades in the middle of the day and are more potent when the sun is east or west, emphasizing the corresponding facades. All the best layouts have buildings of maximum height in every east-west strip. The checkboard pattern is also efficient in this case.

From these observations, it appears that east-west rows of buildings are the most efficient for winter period, while being very inefficient at the summer solstice.

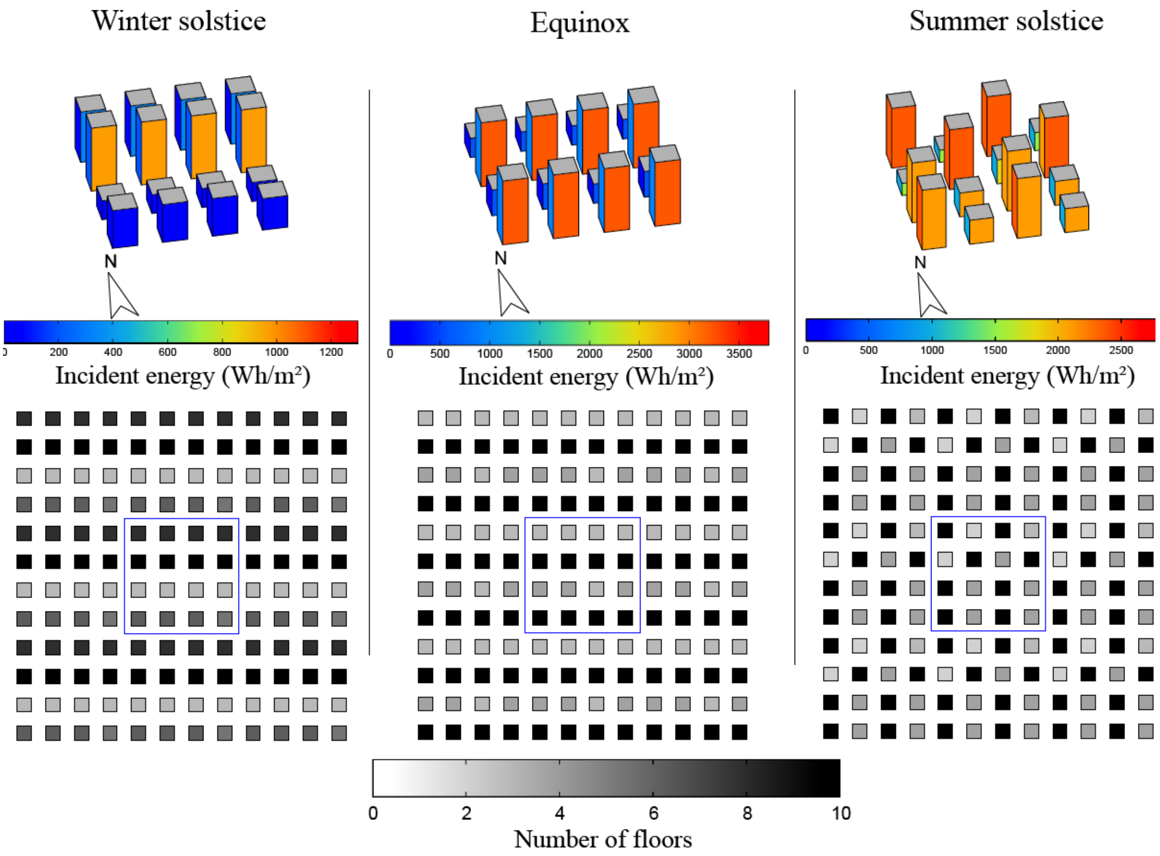

Figure 4. Best urban cells found for solstices and equinox (50° N, cell 4x4, volume=66%Vmax)

4.2.Effect of the density

When raising the desired density of the district, each added block will be able to collect less solar energy than the previous one. The effect of the raising density is twofold. Primarily, it raises the maximum overall direct solar energy potential to a certain point where it is capped, as showed in [Vermeulen, 2015]. Secondly, the features of an optimal cell appear sequentially: the features of high density cells are usually composed of patterns already noticeable in the low density districts. Eventually, in the high density cases, some of the remaining volume is located where it is not well exposed, as it can be noticed on the Figure 5.

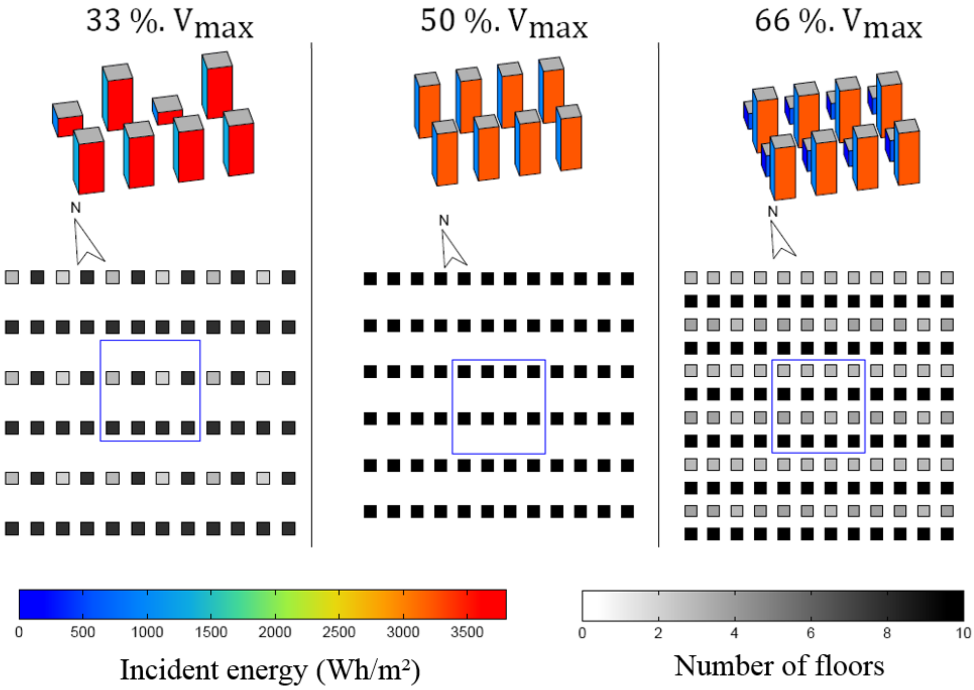

Figure 5. Best urban cells found for built densities of 33 %, 50 % and 66 % Vmax (50° N, cell 4x4, equinox)

4.3.Effect of the urban cell dimensions

The dimensions of the urban cell add more diversity to the possible patterns of district: a 6x6 cell could have all its volume in a limited perimeter of the cell whereas a 2x2 cell will necessarily generate a district with some homogeneity as no 2x2 empty spaces could exist in the resulting urban fabric. Illustrations of optimal results for the winter solstice, for a built volume of 66 % of the maximum volume, for various cell dimensions are presented on Figure 6. The presented configurations have similar objective function value per parcel (respectively 133 kWh, 134 kWh, 136 kWh, 134 kWh and 134 kWh per parcel). The higher diversity granted by the larger cells can be observed.

Further optimization case show that the cell dimensions does not improve the highest radiation per building that can be captured by the district for given conditions of solar radiation and density, However, the largest cells tend to have a lower worst value of objective function per building, for the reason evocated earlier.

Finally, the optimal shapes for winter solstice treated in section 4.1 can be analysed on Figure 6, where the cells show diverse geometries but always have maximum height buildings on each north-south strip, sometimes aligned in the form of east-west rows. Furthermore, stair-like shapes descending toward North can be observed, hiding the roofs which are not taken into account in the objective function behind the higher buildings. The plan view helps seeing these: maximum height buildings (black squares) are in most cases followed by one to three buildings of decreasing heights.

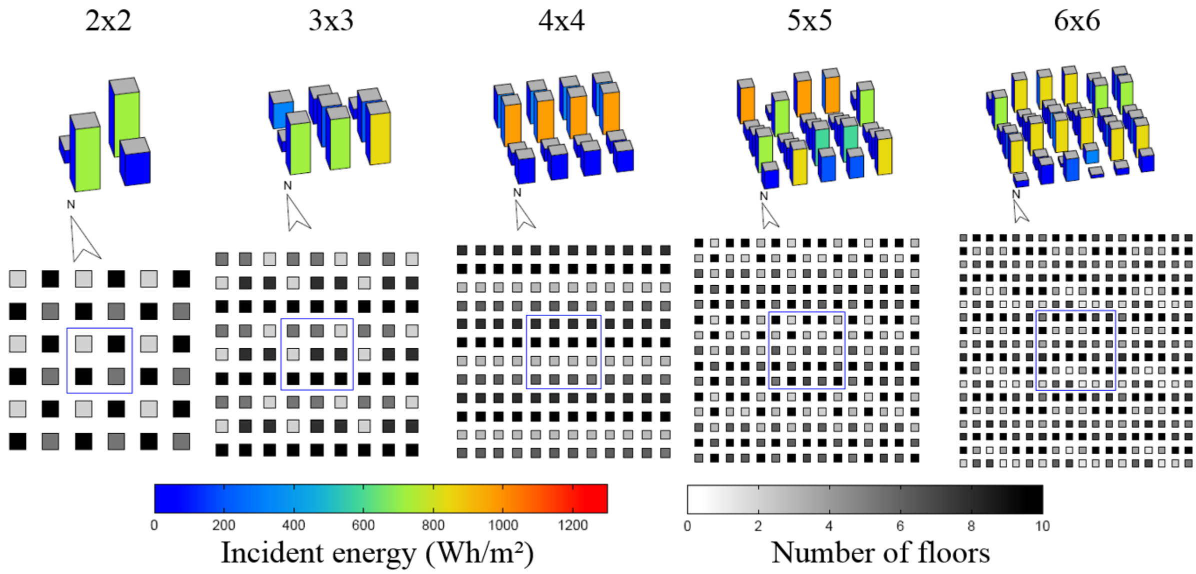

Figure 6. Best urban cells found of dimensions 2x2 to 6x6 (50° N, winter solstice, volume=66%Vmax)

5 Conclusion

The access to solar radiation in dense cities has been the subject of many studies in the last years, due to growing concerns about energy use in buildings and improvement of the simulation tools. Among these works, the study of simplified urban geometries is a common way of searching the general features of a good city regarding some criteria.

The paper presents a geometric description of a simplified district laying on a definition of the district as a periodic fabric composed of infinitely reproduced urban cell. The urban cell definition is then used in a study of optimization of urban shapes for direct solar radiation maximization, where the context of the parameterized district is constituted by reproduction of itself. This way, the boundary effects of having a predetermined fixed context are avoided.

Three optimization conditions are then presented: varying date for solar direct radiation, varying density of the district to be built and varying cell size. The results show that:

- Good urban shapes for winter solstice direct radiation (latitude 50° N) all have high buildings in each north-south strip; for the equinox, the good shapes have east-west rows of high buildings; for summer solstice radiation, the good shapes have high buildings on each east-west strip and small buildings in between to capture solar radiation when the sun is higher in the sky.
- The density has an impact on the overall radiation that can be captured, and optimal low-density patterns can usually be recognized in dense optimal configurations.
- The size of the cell does not influence the maximum direct energy that can be captured with a given built density but grants higher diversity in the set of nearly optimal configurations.

In the study of urban radiation, it is not rare to formulate the hypothesis of a regular district, and the urban cell could therefore be used for further studies of urban shape optimization, with variation on the type of buildings and their parameters, in order to understand better the best features of a good urban shape regarding solar access for local needs and climate specificities.

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