Building Arrangement Optimization for Urban Ventilation Potential Using Genetic Algorithm and CFD Simulation

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Abstract

In this study, we developed a computation-al fluid dynamics (CFD)-based method to optimize the arrangement of buildings for urban ventilation potential at the conceptual design stage and demonstrated its application in a case study. For CFD-based optimization, three calculation components must be assembled: an optimizer, a geometry/mesh generator, and CFD solver. The optimizer solves the optimization problem, which comprises design variables, objective functions, and constraints functions. The geometry/mesh generator creates a building geometry (i.e., vertices, faces, and cells) that satisfies the design variables generated in the optimizer, converts them into a mesh file compatible with the CFD solver, and assigns the boundary condition. The CFD solver is used to calculate and return the value of the objective function to the optimizer. In this study, the local kinetic energy (KE) of the target area was employed as the objective function. KE is a parameter that is used to precisely evaluate the convective effects of the wind and is calculated from the turbulent components and the averaged velocity components. The results showed that genetic algorithm enables the developed method to provide options to designers that less negatively affect the urban ventilation potential of the surrounding area.

Keywords

Building shape, Urban ventilation, Urban design, Optimization, CFD simulation, Genetic algorithm

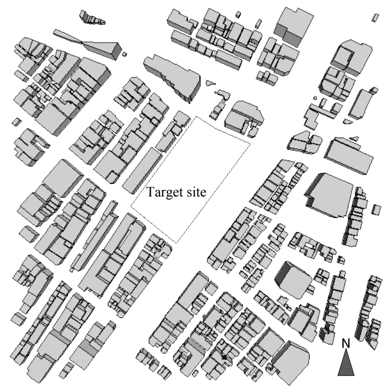
1 Introduction

At the conceptual design stage, there are many opportunities to improve the building performance in terms of the urban ventilation potential and the building energy consumption. For example, the building orientation and massing are typically determined early in the design process and have a significant impact on the environmental performance [1]. During this stage, in order to select the more valuable design, many alternatives are generated and evaluated by any indices for performance assessment. In this sense, many studies have examined building shape optimization with regard to the relationship between the building morphology and energy consumption [2-4], but little attention has yet been paid to the relationship between the building morphology and urban ventilation potential. In this study, therefore, we developed a computational fluid dynamics (CFD)-based method and demonstrated its ability to optimize the building arrangement for urban ventilation potential at the conceptual design stage.

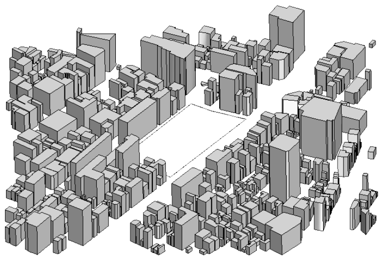
Most current research into the shape optimization for building performance has revolved around a single building. Previous studies have considered a wide range of building shapes, from simple geometries such as a box and polygon to atypical geometries with irregularities. Horikoshi et al [2] and Tuhus-Dubrow and Krarti [5] examined polygons such as rectangles, trapezoids, crossed. Yi and Malkawi developed their own building shape representation method and enhanced a variety of building shapes [3, 4]. These papers are invaluable works of references for an engineering approach to building shape optimization. However, these researchers did not consider the fact that a designer will not accept a plan derived purely from an engineering perspective, no matter how rational. Thus, this study was based upon the premise that the building shape is the domain of the designer. We focused on building arrangement, which is practical engineering support for site-specific building planning. In this paper, we describe how our methodology allows the generation of an optimized site-specific building arrangement through CFD simulation and a genetic algorithms (GA) and present a case study.

2 Outline of Case Study

The target area for the case study covered a densely built-up area of approximately 500 m × 500 m in Tokyo, Japan. Figure 1 shows the current status of the target area. In the first step, a renewal plan was developed with regard to the central district of this area (target site in Figure 1). In this case study, the designer had finished the conceptual design (massing only) and was considering how to reduce the negative influence on the urban ventilation potential through the building arrangement. Table 1 lists the details of the entire target area. Table 2 lists the information on the three masses proposed by the designer. In the second step, CFD-based optimization was carried out to determine which building arrangement maximized the urban ventilation potential.



(a) Top view



(b) Perspective

Figure 1. Target area

Table 1. Target area properties

Properties	Value
Total area	250,000 m^2
Number of buildings	607
Mean building height	29.33 m
Mean building plan area fraction	35.06 %
Mean floor area ratio	342.66 %
Target site area	16,712 m^2

Table 2. Building masses properties

	Building1	Builidng2	Builing3
Height	80 m	24 m	12 m
Floors	20	6	3
Floor height		4 m	
Plan area	1,600 m^2	3,500 m^2	2,700 m^2
Total floor area	32,000 m^2	21,000 m^2	8,100 m^2

3 The Computational Method

To develop the CFD-based optimization, three calculation components must be assembled: an optimizer, a geometry/mesh generator and a CFD solver. The optimizer solves the optimization problem, which comprises design variables, objective functions, and constraint functions. The geometry/mesh generator creates a building geometry (i.e., vertices, faces, and cells) that satisfies the design variables transferred from the optimizer, converts them into a mesh file compatible with the CFD solver and prescribes the boundary condition. The CFD solver calculates and returns values of the objective function (see Figure 2). For the CFD solver, we utilized the Star-CCM+ 8.02 simulation engine. MATLAB R2012a was used to implement the representation developed for the GA optimization. The objective functions and constraint functions discussed in the following sections were programmed using m-files. To handle the geometry, we utilized a parametric design program of our own making.

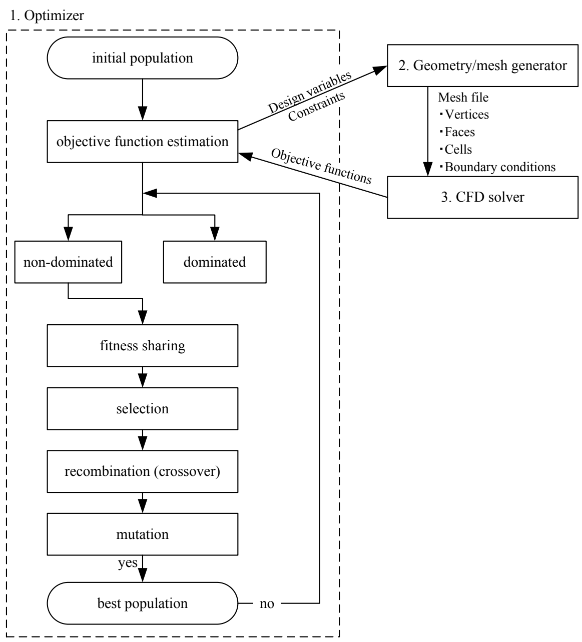


Figure 2. Data flow of a CFD-based optimization

3.1 Building Shape Representation

One of the most important elements of CFD-based optimization is a geometry modeling method to provide a link between the design variables and a mesh file compatible with the CFD solver. In this section, we discuss the design variables that represent the building arrangement.

In building shape optimization, parameters which represent building geometries can be classified into two sets of variables: location-related and architectural form-related variables. However, because the architectural form is determined by the designer in this case study, all architectural form-related variables were fixed. Because the morphological diversity is constrained by this precondition, we can represent building morphology with shorter chromosomes in the GA. This makes the present method more practical.

Figure 3 shows design variables for building1 on the site. The coordinates of the center of the building geometry (C_{x1}, C_{y1}) were used as the location-related variables, and the angle between the axes of the site and building (θ_1) was used as the architectural form-related variables. We can describe the building arrangement by using a total of nine variables (three buildings × three variables).

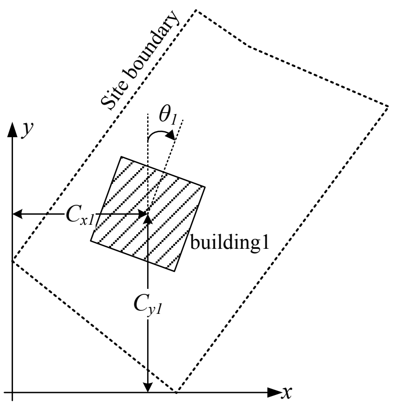


Figure 3. Location-related variables

3.2 Objective Function

The mechanism of movement by the fresh and cool outside air into the target area depends on the turbulent diffusion. Therefore, the urban ventilation potential of the target area may be considered from the perspective of turbulent transport. Thus, the objective function should be an index that represents this turbulent transport performance quantitatively. In this study, we used the local kinetic energy (KE) to describe this performance. This parameter is used to precisely evaluate the convective effects of the wind and is calculated from the turbulent components and the averaged velocity components, as defined in Equation (1) [6].

$$\mathrm{KE} = \frac{1}{\mathrm{V}} \iiint_{\mathrm{space}} \left(\frac{1}{2} (\bar{U}^2 + \bar{V}^2 + \bar{W}^2) + k \right) ds \qquad (1)$$

where KE is the spatially averaged kinetic energy [m^2/s^2], $\bar{U}$, $\bar{V}$ and $\bar{W}$ are the averaged velocity components [m/s], and k is the averaged turbulent kinetic energy of the entire target space [m^2/s^2]

The outdoor wind environment has previously been assessed according only to the flow in the dominant wind direction. However, this approach remains open to debate because the calculation result may change considering the fluctuations in the wind direction. In this study, therefore, we attempted to obtain a more reasonable solution by considering the annual wind distribution in an objective function calculation using Equation (2). We used the hourly measured statistical data recorded over 10 years (from 1991 to 2000) at the Tokyo Meteorological Observatory, which contained the percentage frequencies of the wind direction and the mean velocity by direction. In this study, we categorized the 16 directions into the four cardinal directions to decrease the computing load. Table 4 lists the detailed information of the four wind-direction groups.

$$\mathrm{KE}_{\mathrm{annual}} = \frac{\sum \mathrm{KE}_i \times t_i}{8760} \qquad (2)$$

where i is the azimuth group number (1, 2, 3, or 4), KE_i is the local kinetic energy for azimuth group i [m^2/s^2], and t_i is the time for azimuth group i [h]

Table 4. Categorized wind directions

Group	Azimuth	Mean velocity [m/s]	Time [h]
1	N, NNE, NNW	2.00	3604
2	E, NE, SE, ENE, ESE	2.24	1991
3	W, NW, SW, WNW, WSW	2.60	1728
4	S, SSE, SSW	2.25	1437

Finally, we used the relative $\mathrm{KE}_{\mathrm{annual}}$ ($\mathrm{RKE}_{\mathrm{annaul}}$) as objective function. In this study, we attempted to represent the urban ventilation potential of individual cases by using $\mathrm{RKE}_{\mathrm{annual}}$, which is maximized by the GA process. $\mathrm{RKE}_{\mathrm{annual}}$ is defined in Equation (3).

$$\mathrm{RKE_{annual}} = \frac{(\mathrm{KE_{annaul}})_{individual}}{(\mathrm{KE_{annaul}})_{initial}} \quad (3)$$

Figure 4 shows the initial building arrangement used for the analysis in this study. Since the building height is adjusted for overlapping mass, the total volume of the three masses was equal in every individual case.

The commercial software Star-CCM+ 8.02 was used. The domain height was 500 m, and the distance downstream from the target area was set to be 500 m. Tetrahedral grid cells were generated, and a finer mesh was applied to the region close to the surface and expanded farther away from the solid surface. The minimum grid size near the building was 1 m. Although the total number of cells varied for each case, it was about 11,000,000. All solid surfaces, including ground and building surfaces, were modeled using a no-slip boundary with zero roughness. We used the Reynolds-averaged Navier-Stokes (RANS) model to compare the urban ventilation potential of many design alternatives. Large eddy simulation (LES) and direct numerical simulation (DNS) were beyond the scope of this study because of their very high computational costs, although they can provide more accurate results. As the major purpose of this study was to estimate the relative overall ventilation potential for the urban area under the influence of the new building rather than obtaining the actual information for the target area, we selected the standard k-ε model. Gao and Niu [7] also indicated that the standard k-ε model is sufficient if the emphasis is on the airflow field. Figure 5 and Table 5 present details on the conditions of the objective function calculation.

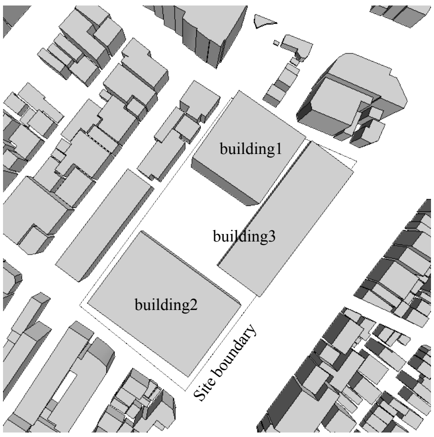


Figure 4. Initial building arrangement

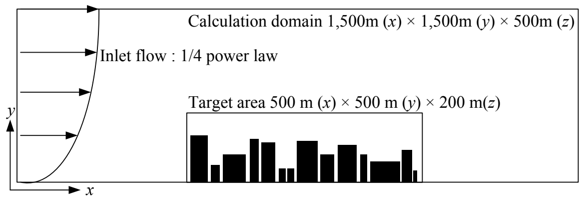


Figure 5. Calculation domain

Table 5. Categorized wind directions

Turbulent model	Standard k-ε model
Inlet	$u(z) = u_r \times (z/z_r)^{1/4}$ $k = 1.5 \times (I/u(z))^2$ $\varepsilon = C_\mu \times k^{3/2}/l$ $l = 4 \times (C_\mu \times k)^{1/2} {z_r}^{1/4} z^{3/4}/u_r$
Outlet	Free outflow
Side, top	Free slip

In Table 5, $u(z)$ is the inlet velocity at height z [m/s], z_r is the reference height (=74.5 m), u_r is the reference velocity, which is the mean velocity for the given azimuth (refer to Table 4) [m/s], k is the turbulent energy [m^2/s^2], I is the turbulent intensity (=0.1) [-], ε is the turbulent dissipation rate [m^2/s^3], C_μ is a model constant (=0.09) [-], and l is the length scale of the turbulent flow [m]

3.3 Constraint Functions

A constraint function specifies a condition that individual cases generated in the GA optimization process must satisfy. In this case study, two constraint functions were employed: all vertices of the building geometry must be inside the given site, and the highest building can be no higher than 100 m. These constraint functions were formularized in m-files as equations that included the design variables, and were inserted into the optimizer modules.

4 Results and Discussion

Figure 6 shows the evolutionary changes in $\mathrm{RKE_{annual}}$ as the calculation progressed. In the early calculation stages, the degree of $\mathrm{RKE_{annual}}$ value change was significant. As the calculation progressed, the degree of change in $\mathrm{RKE_{annual}}$ become insignificant. Although the GA was not completed because of time limitations, the value seemed to be converging at about 1.035. The last generation point where the results converged was composed of 12 arrangements, which was the value set as the population size of GA parameters. These arrangements can be candidates for the designer's choice. This means that the designer will always choose superior designs in terms of the urban ventilation potential if any design in the last generation front is selected. Figure 7 shows one arrangement from the last generation in this case study.

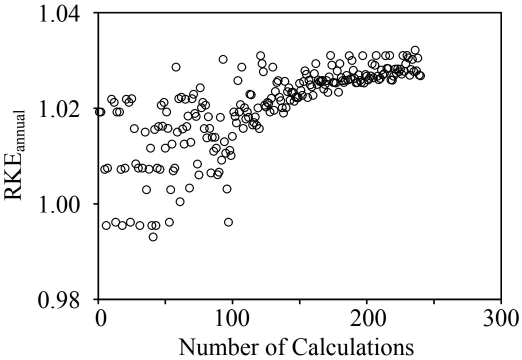


Figure 6. Evolutionary changes in RKE_{annual}

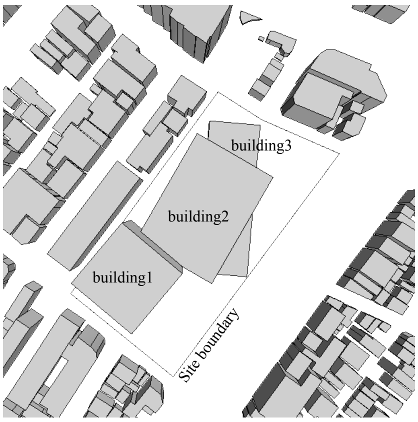


Figure 7. Building arrangement for last generation

Figure 8 shows the initial case (Ini) and last case (Las) for KE in each wind direction. The differences between both cases was up to about 10% with an east wind, even KE of the initial case was larger than the case with the west wind. This led to a small deference in KE_{annual}, of 3.5%. This may seem small when discussing the superiority of different designs. However, this small deference is caused by the fact that KE_{annual} is the volume averaged value of the entire target area (500m × 500m × 200m). Figure 9 clearly shows the differences between both cases, it represents the area in which KE_{annual} became bigger when the initial case was replaced with last generation case. Although the region where KE_{annual} of the last case was larger than of the initial case (marked in black) comprised about 52% of the total area, this was concentrated around the target site.

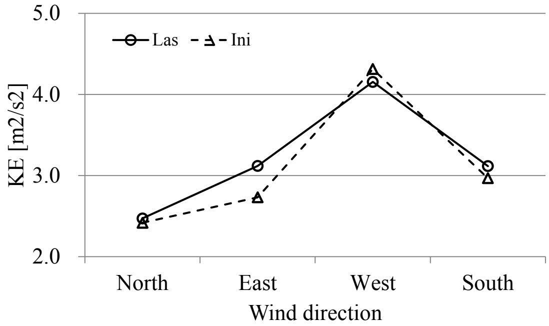


Figure 8. KE of initial case and last case

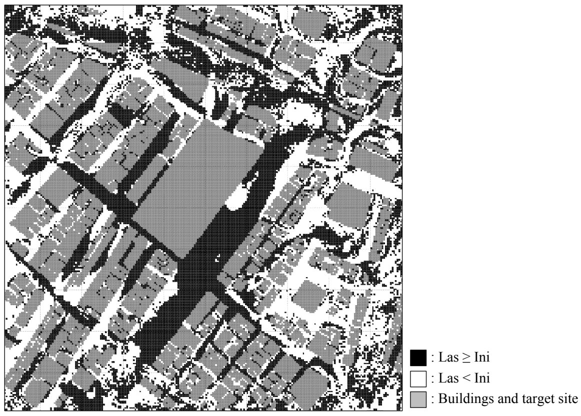


Figure 9. difference of KE between initial case and last case

5 Conclusion

The main purpose of this study was to develop and demonstrate a CFD-based optimization method for building arrangement. This method has three main calculation components: a mesh/geometry generator, CFD solver, and optimizer modules. In this study, we explored the use of GA as the optimization algorithm for performance-based building arrangement planning. In our case study, the results showed that the GA realized a building arrangement that suited the given environment better than the alternative design.

However, a number of problems that remain to be explored. The primary issue is the calculation load. The present optimization calculation was performed in a parallel computing environment. The calculation time to complete 20 generations (population size: 12) was approximately 50 days. In the future, this study will be extended to employ a more time-efficient algorithm to optimize the building shape.

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