GENETIC ALGORITHM BASED BUILDING FORM OPTIMIZATION STUDY FOR NATURAL VENTILATION POTENTIAL

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ABSTRACT

Building form is one of the most critical factors influencing natural ventilation potential in an urban context, and thus has a significant impact on building energy consumption. This paper describes a genetic algorithm based building form optimization methodology that could respond to urban wind environments and achieve the highest natural ventilation potential. To accomplish this goal, scripts in Rhino Grasshopper were developed. The scripts employed a CFD simulation program to evaluate the pressure distribution on the investigated building's façades. A genetic algorithm was used to optimize the building form that led to a higher natural ventilation potential. The methodology introduced in this paper would provide designers with more information regarding natural ventilation, allowing for a better-informed decision-making process in the early design stages. The paper also provides a case study demonstrating the process and possible issues with the methodology.

INTRODUCTION

Energy consumption of the building and construction sector accounts for around 30-40% of total primary energy use worldwide. Consequently, this sector contributes a great deal to energy pressures and other environmental issues such as greenhouse emissions and global warming. (Luis P.L., Jose O. and Christine P. 2008.) Due to the projected growth of the global population from 6.5 billion in 2005 to approximately 9.0 billion in 2035, the negative ramifications of consumption are likely to increase. (Manish K. D., José L. F.S., Sarel L. and Charles H. C. 2010.) This dilemma has resulted in greater demand for buildings with higher energy performance, leaving designers with significant responsibility.

There are three main strategies for increasing building energy performance: improving energy system efficiency, using free energy resources, and reducing building energy load – the last of which is highly integrated with design. (Zhiqiang Z. and James S. M. 2014.) Natural ventilation was introduced as a promising method for reducing heating and cooling loads if the outdoor microclimate falls within the comfort zone. Studies indicated that natural ventilation could be used to reduce energy consumption in residential buildings by up to 40% as compared with air-conditioned buildings. (Orme M. 2001; Camille A., Qingyan C., and Leon R. G. 2003.) Additionally, there is further mounting evidence that occupants in naturally ventilated buildings tend to accept higher indoor temperatures than those living in air-conditioned spaces. This higher tolerance raises further the potential for energy savings through natural ventilation. (John F. B. 1992.) Thus, natural ventilation, which has been applied in design for decades, should continue to play an important role in designing for a sustainable future.

In recent years, many building simulation tools were developed to assist researchers in gaining a better understanding of building energy performance. There are five main modeling technologies widely used today – building energy modeling, computational fluid dynamics (CFD), lighting modeling, life cycle assessment, and building information modeling. (Zhiqiang Z. and James S. M. 2014.) Building energy modeling is the main technology used in this field, while computational fluid dynamics is critical in analyzing the potential of natural ventilation to improve building energy performance. With the help of simulation tools, researchers can, ideally, explore the anticipated energy consumption of any design.

Barriers do still exist between simulation technologies and design. The simulation results were in most cases difficult for designers to understand and translate into design optimization. This study illustrates a methodology for optimizing design based on simulation results – with the aim of maximizing natural ventilation potential – that could serve as an example of interpolation between design and simulation tools.

METHODOLOGY

Integrated Design with Simulation Tools

To tackle this issue, both designers and building simulation specialists have conducted researches in recent years.

Some designers turned to case studies to explore integrating the design processes with simulation tools. Jorgensen, Clarice and Shady all performed case studies on design competitions or workshops to ilustrate how design decisions could and should be influenced by simulation tools to achieve better energy performance. Jørgensen explained several key design decision-making processes and how simulation aided these processes. (Jørgensen A. M., NielsenB M. W. and Strømann-Andersen J. B. 2011.) He recorded design processes in detail as well as simulation processes and found similarities between different participants. Clarice conducted a similar study with a design workshop, in which she analysed all design decisions and identified common patterns based on qualitative social science research methods. (Clarice B. S. 2013.) Furthermore, Shady performed a sensitivity analysis on different decision-making processes for better performance robustness on energy analysis. (Shady A., Andre D. H., Elisabeth G., Jan L.M. H. 2013.) All of these studies were attempting to conclude the most critical decision-making process in design with the help of simulation tools, which would be beneficial for other designers.

On the other hand, current simulation tools have some limitations for integrated design. The simulation software and design software cannot share models, and it would require a lot of effort to modify the design models for a simulation tool. Most simulation software requires many boundary condition inputs that are too difficult for a designer to handle. In addition, simulation results and conclusions are barely understood by designers, which creates a barrier for the simulation results to be converted into design changes. As a response to these limitations, some simulation platforms were developed to break through the technical barriers. Benjamin focused on a methodology based on BIM for better communications between different simulation tools to improve design and simulation process speed, accuracy and consistency. (Benjamin W., John H. and Zack R. 2011.) The contributions of the study include building up workflow, data transferring, design integrating, process automating and so on. Meanwhile, Pelken and his colleagues focused on supporting integrated, coordinated and optimized design of buildings and their energy systems, by assisting collaborating architects, engineers and project management teams throughout from the early phases to detailed building design development. (P. Michael P., Jianshun Z., Yixing C., Daniel J. R., Zhaozhou M., Shewangizaw S., Lixing G., Hugh H., Wei F. and Francesca L. 2013; Jianshun Z., P. Michael P., Yixing C., Daniel J. R., Zhaozhou M., Shewangizaw S., Lixing G., Hugh H., Wei F. and Francesca L. 2013.) A few research projects focused on simulation plugins in a 3D-modeling tool to simplify the simulation process and better inform designers with results in a more ocular way. Two examples are day lighting simulation plugin DIVA based on Daysim and energy model simulation plugin Viper based on EnergyPlus. These plugins converted 3D models into simulation models automatically and guided the users step by step through boundary condition inputs, reducing the need for proficiency in simulation software. Results from these simulation plugins were visualized in 3D-modeling software together with the original design so that designers could easily see how their design influenced the building performance. One study showed that designers are better informed with the help of these plugins and could adapt their design based on simulation results. (Christoph F. R., Jan W. 2011.)

Natural Ventilation in Early Design Stage

Studies have shown that integrated design with simulation tools is possible and critical to achieving higher building performance. However all the studies shown either used a simplified model to evaluate the effect of natural ventilation or did not consider it at all. CFD simulation is barely used in integrated design methodology. This is because running reliable CFD simulation is time consuming and requires high proficiency in software.

Progress has been made in recent studies. Recent research illustrated the importance of CFD simulation for natural ventilation evaluation by integrating CFD simulation with building energy modeling. (Bing W., Timur D., Debashree P. and Christoph F.R. 2012.) Another case study was conducted on natural ventilation performance. Chaobin recorded the design optimization process of a natural ventilation improvement for high-rise residential buildings in detail, validated by file measurements. (Chaobin Z., Zhiqiang W., Qingyan C., Yi J. and Jingjing P. 2014.) The paper described clearly three levels for step-by-step optimization of natural ventilation performance, which included community level, floor plan level and room level. Computational fluid dynamics as the main simulation technology used in this research provided a great deal of detailed information on velocity and pressure distribution of wind environment. Yu and Zhiqiang also used computational fluid dynamics to optimize an indoor ventilation system with a multi-objective genetic algorithm. (Yu X., Zhiqiang Z., Qingyan C. 2013; Zhiqiang Z., Yu X., Qingyan C. 2014.) In these studies the HVAC inlet geometry was optimized to target higher air change rates. In summary, CFD simulation software could play an important role in design and the process could be integrated with building energy simulation and design with the help of scripts, which provides a possibility for applying optimization algarithms.

This research project deploys the use of natural ventilation studies in the early design stages. CFD simulation software was used to predict detailed wind environments and it was highly integrated within the design modeling tool, with scripts developed for this research. The study focused on evaluating natural ventilation in the early design stage since it is widely-agreed that the earlier simulation software gets involved, the better it can provide decision-making support with more flexibity in design. Also because of the lack of detailed information in the early design stage, the study would use a relatively simplified evaluation index for natural ventilation potential.

Provided with the evaluation of natural ventilation potential, a design optimization was conducted based on a genetic algorithm.

In summary, key points of the methodology are listed below and will be illustrated in detail in next section.

1. CFD simulation was used to provide precise and reliable results for natural ventilation evaluation.
2. Design optimization focused on building form within an urban context in an early design stage.
3. An index was proposed to evaluate natural ventilation potential.
4. A genetic algorithm performed the optimization process.

CASE STUDY

The case study was an example of integrated design methodology with CFD simulation for natural ventilation. Current available commercial CFD software was used and detail settings were explained. A high-rise tower design within an urban context was employed as the optimization target, with several design options provided. To evaluate investigated building's natural ventilation performance, one index was proposed in this early design stage. Finally, a genetic algorithm was employed to optimize design. This case study illustrated the integrated design methodology proposed in this research and a discussion on the result is inspiring for future studies.

CFD Simulation

Pheonics 2011 was used in this study as the CFD simulation tool, which is commercial CFD software developed by CHAM in England. (Ludwig, J. C. and Mortimer, S., 2010.) Detailed settings followed the CFD simulation guideline provided by AIJ (Architectural Institute of Japan), which was concluded by several studies on cross comparison of CFD simulation results and wind tunnel experiment data. (Tominaga Y., Mochidab A., Yoshie R. 2008.)

1. Simulation domain size

On the windward side, the building area should be less than 4% of the total domain area. Distance from building to boundaries should be larger than 2 times building height. Distance from building to outlet should be larger than 6 times the length of the turbulence area. Distance from building to inlet should be larger than 2/3 of the length of the turbulence area, which could be calculated according to equation below.

$$R = B_s^{0.67} B_l^{0.33} \qquad (1)$$

Where B_S is the length of the short edge of the building on the windward side, while B_l is the length of the long edge of the building on the windward side

2. Inlet boundary conditions

The boundary conditions of inlet should include velocity U, turbulence kinetic energy k and its dissipation rate ε. The inlet should have a vertical velocity profile, as well as the vertical distribution of turbulent energy, both of which are given by power laws. The following equations are recommended.

$$U(z) = U_s\left(\frac{z}{z_s}\right)^{\alpha} \qquad (2)$$

$$I(z) = \frac{\sigma_u(z)}{U(z)} = 0.1\left(\frac{z}{z_G}\right)^{(-\alpha-0.05)} \qquad (3)$$

$$\frac{\sigma_u^2(z)+\sigma_v^2(z)+\sigma_w^2(z)}{2} \cong \sigma_u^2(z) = (I(z)U(z))^2 \qquad (4)$$

$$\begin{aligned}\varepsilon(z) &\cong P_k(z) \cong -\overline{uw}(z)\frac{dU(z)}{dz} \\ &\cong C_t^{1/2}k(z)\frac{dU(z)}{dz} = C_t^{1/2}k(z)\frac{U_S}{z_S}\alpha\left(\frac{z}{z_S}\right)^{(\alpha-1)}\end{aligned} \qquad (5)$$

3. Turbulence model

In outdoor wind environment simulations, the two-equation model - the Standard *k-ε* model (Oomiyasi, H., et al., 1998. Meng, Y. and Hibi, K., 1998.), is the most widely used turbulence model. However, when simulating the airflow around a single building with the Standard *k-ε* model, the result of the turbulence kinetic energy *k* at the top of building is too great. (Jiang T.F., 2003.) Therefore, the MMK model (Tao W.Q., 2001.) and the Durbin model (Gaskell P. and Lau A.K.C., 1988.) were developed by making a revision on the calculation of the turbulence kinematic viscosity coefficient v_t. The author also conducted a study on comparing the turbulence model with field measurement. (Bing W. and Borong L. 2011.) As a conclusion, the Standard *k-ε* model has an acceptable precision for design application while the Durbin model is recommended for better precision in research. In this study, the Standard *k-ε* model was used.

4. Numerical Settings

In this study, the total grid number was around 150,000 and the growing ratio of the grid was smaller than 1.3. A grid independent study was conducted. A logarithmic law with roughness parameters was used in solid surface boundary conditions, with a Fully-Rough function for ground and General-Log-Law function for building walls. Steady simulation with a Simple solution algorithm and Quick differencing scheme was used. For each case, 1,500 iterations were calculated before a converged result was achieved.

With all recommendations of boundary conditions, a script was developed to read geometry information from 3D-modeling tool Rhinoceros and then prepare a CFD case file. CFD simulation was then run automatically and the run time for each case was around one hour.

Building Form Design

This study focused on a high-rise tower design within an urban context. A basic building form model with surrounding buildings is shown as Figure 1.

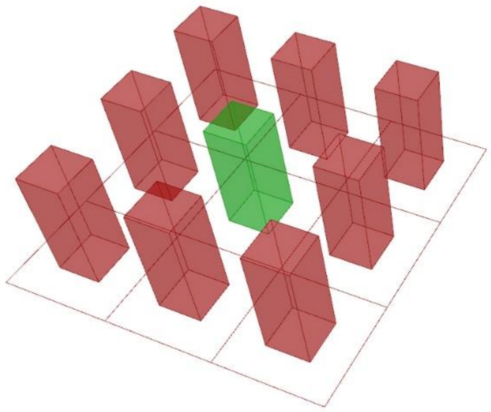

Figure 1 Basic Building Model with Surroundings

In this case study, only the building form was considered as the design target. There were several fixed design conditions as well as several design variables. Fixed design conditions include:

1. Site size

The site was chosen within a city environment, with a grid size of 100m by 100m, which is a typical city-size grid for a modern city central area.

2. Surrounding buildings

The surrounding buildings are simplified to represent an urban context. Each building has a floor area of 40m by 40m, and is located in the middle of the grid. Each building has 30 floors with a fixed floor height of 3.5m, giving each building a height of 105m.

3. Floor-to-area ratio (FAR)

The floor-to-area ratio for surrounding buildings is 4.8. The same number was set as the target for investigated buildings. However, the actual FAR will shift slightly around the target.

Design variables included:

1. Floor width

The floor width was set as a variable with a range of 0 to 100m.

2. Floor depth

The floor depth was set as a variable with a range of 0 to 100m as well.

3. Corner radius

The corner radius was the size of the corner for the floor rectangle, which was set as a variable with a range of 0 to 50m. At the same time, it will not exceed the smaller one between floor width and floor depth.

So far with floor width, floor depth and corner radius, the floor area could be calculated. With the target FAR 4.8, the total building height could be calculated. Then, floor number would be available by dividing building height by the fixed floor height of 3.5m. The floor number would be rounded to the nearest integer and then the building could be modelled.

4. Orientation

The orientation of the building was set as a variable with a range of 0 to 180 degrees from the north direction because of the symmetry of geometries.

5. Twist angle

The twist angle of the building was set as a variable with a range of -180 to 180 degrees.

6. Tilt angle

The tile angle of the building was set as a variable with a range of 0 to 180 degrees.

7. Tile direction

The tile direction of the building was set as a variable with a range of 0 to 180 degree from the north direction.

In summary, the investigated building has seven design variables, which would be optimized by a genetic algorithm for best natural ventilation performance.

Natural Ventilation Potential Evaluation

Typically, evaluating natural ventilation potential requires a significant amount of knowledge of the built environment, as well as experience in different types of simulation software, including CFD simulation, airflow network analysis and building energy simulation. It is difficult for designers to conduct a reliable evaluation of natural ventilation potential by themselves. Current practice of evaluating natural ventilation included five steps, shown as Figure 2.

First, weather data would be analysed and the most critical cases would be identified for further analysis. Second, a 3D model would be prepared and CFD simulations were ran to understand wind environments and pressure distribution on the building façades. After the CFD simulation, the pressure information on façades would act as the input for the airflow network analysis, which would be used to calculate ACH (hourly air change rate) based on the floor plan and window information. In the end, the calculated ACH would be used in energy simulation software to analyse the energy savings through natural ventilation. The process would take a considerable amount of time, resulting in a full report of natural ventilation potential.

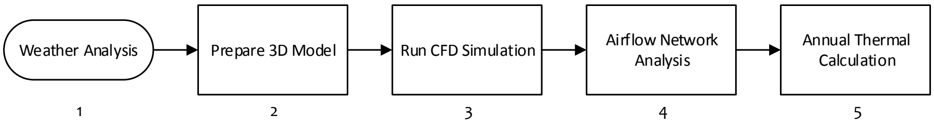

Figure 2 Typical Workflow of Natural Ventilation Potential Evaluation

However, the pressure distribution is not very clear to designers in term of natural ventilation potential. Thus, the highest pressure difference for each floor of the building was used in place of a space distribution. To achieve this, 10 monitor points were set for each floor of the investigated building, located at typical window heights 2m from the floor. Then, the highest and lowest pressure values among the ten monitor points were abstracted from CFD simulation results to calculate the highest pressure difference for each floor. Last, the average value of highest pressure difference for each floor was calculated, which was the final optimization target in this study, shown as Figure 3.

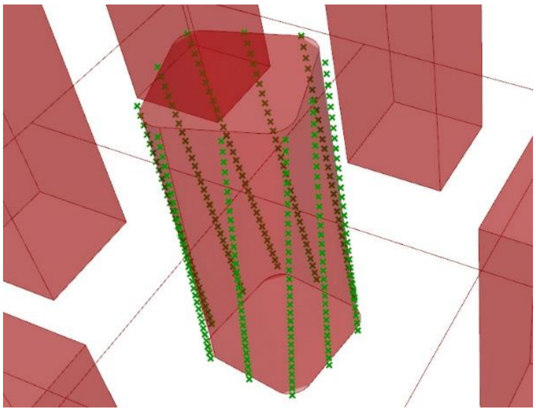

Figure 3 Monitor Points around Target Building

Genetic Algorithm Optimization

With given building form variables, a 3D model of the investigated building could be generated, together with surrounding buildings. Then CFD simulation would be carried out automatically and pressure distribution on building façades would be abstracted. Average highest pressure difference would be calculated as the index for evaluating natural ventilation potential.

In this step, a genetic algorithm was used to optimize the seven design variables, with the average highest pressure difference as the optimization target. The genetic algorithm used in this study is called Galapagos, which is a genetic algorithm component built in Grasshopper.

The Galapagos component took the average highest pressure difference as the fitness, with maximum as the target. With the seven variables, the population was set as 20 and initial boost was set as two times. For each generation, it would maintain 20% of cases and inbreed 80% of cases. In this study the genetic algorithm ran 18 generations before it was manually stopped, and a total of 419 design options were calculated. The optimization process is shown as Figure 4, which ran for around one week.

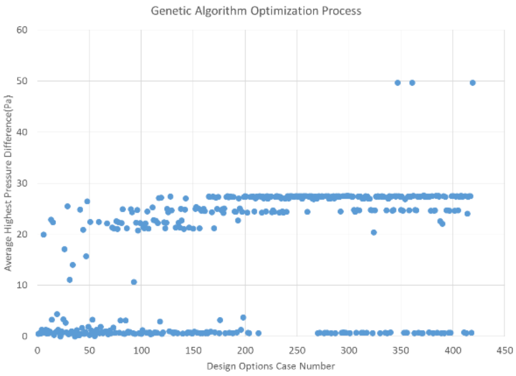

Figure 4 Genetic Algorithm Optimization Process

Result

All 419 target building form options are shown as Figures 5 and 6. Figure 5 placed all models in the order of the genetic algorithm optimization process while Figure 6 placed all models in an incremental order based on the average highest pressure difference. From Figure 5 it is easy to conclude that the geometry did not change much after around half of the optimization process. From Figure 6, more than 50% cases have similar results of the average highest pressure difference except the top three best cases. In one word, the genetic algorithm optimization process provided a stable solution.

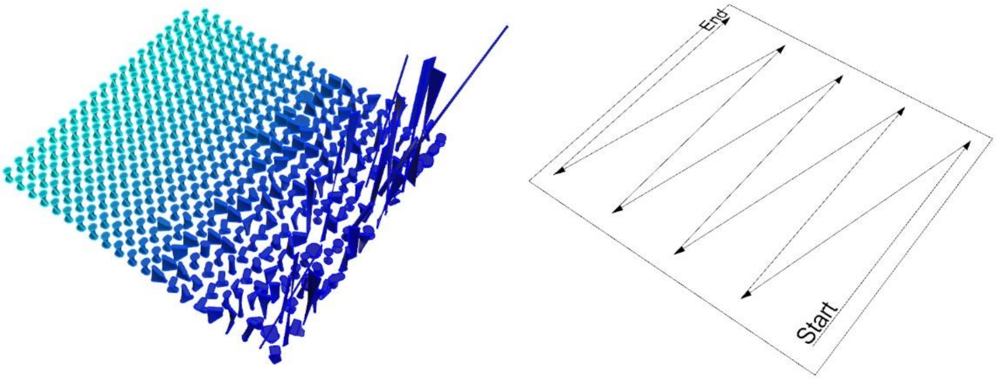

Figure 6 Building Form Options Ordered and Coloured by Optimization Process

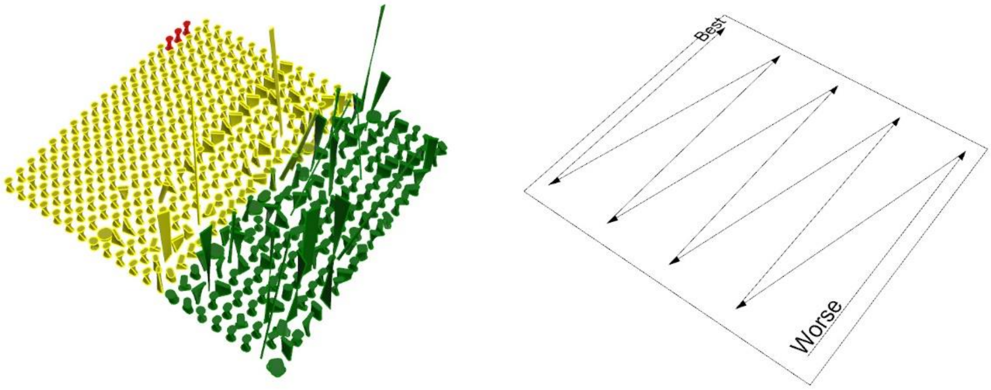

Figure 7 Building Form Options Ordered and Coloured by Optimization Target Value

As shown in Figure 6, the top three design options have much higher target values compared with other cases. In these three cases, the average highest pressure difference is around 49.65Pa while the other cases have a highest value of 27.59Pa. Validations were conducted on the three design options by running CFD simulations again manually. All three cases gave a result of the average highest pressure difference at around 27.5Pa, from which conclusion could be made that these top three design options may be caused by numerical error.

The design optimization result is shown as Table 1 and Figure 7 together with CFD simulation result.

Table 1
Genetic Algorithm Optimization Result

DESIGN VERIABLES	VALUE
Floor Width	42m
Floor Depth	53m
Corner Radius	42m
Orientation	10.8°
Twist Angle	-104.4°
Tilt Angle	5.4°
Tile Direction	72°

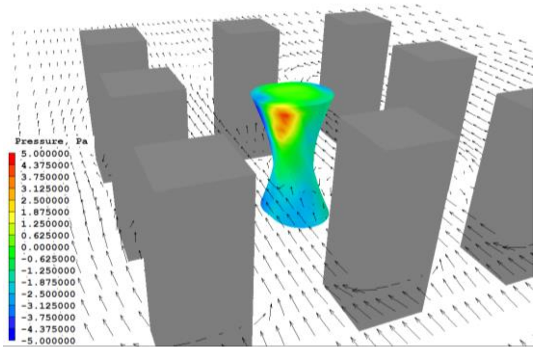

Figure 7 Optimized Building Form

As we can see from the pressure distribution on building façades, the pressure is evenly distributed because of the twist and round shape of the building itself. Also based on the vector field we find that most parts of the building are located in wind shadow areas but the tilt angle and tilt direction provide the building a windward area, which creates a high pressure difference between this windward area and leeward side of the building.

Discussion

This study mainly focused on a design methodology by integrating CFD simulation and a optimization algorithm, which provides designers more information regarding natural ventilation potential in the early design stage. With scripts developed in Grasshopper, currently available commercial CFD simulation software was employed to provide detail and precise wind environment data and a genetic algorithm provided a stable optimization result of the building form for highest natural ventilation potential.

However, there are three main limitations of the study. First are the building form design options. In this case, only seven design variables about the target building itself were investigated, while in the design process there would be more parameters involved, including different urban context, different wind conditions and even multiple target buildings. Second is, the optimization function. Average highest pressure difference was used as the optimization function in this study, which is proposed according to the limited information available in the early design stage. Other optimization functions could be used with different design conditions and may lead to very different final optimization results. Last but not least is the optimization time. With current simulation settings, each CFD case took around one hour and the whole optimization process took around one week, which is very expensive in terms of time, especially in the early design stage. This problem could be solved through parallel computing or cloud computing in the future.

CONCLUSION

Many studies have been conducted on integrating design with simulation tools in recent years, which would provide more performance related information to designers for a better decision making process. One question that may be solved by this concept is how to design buildings with high performance ventilation potential, especially in the early design stage. This paper describes a methodology that integrated CFD simulation with design in these early stages. Currently available commercial CFD software was used to provide precise wind environment data and then conclude one single index with which to evaluate natural ventilation potential. Investigated building form within an urban context was optimized for best performance of natural ventilation and a genetic algorithm was employed to conduct the optimization process. As expected, an optimized building form was given by the genetic algorithm.

However, there are still some limitations of this study. First, the building form design options were limited and could be expanded to more design parameters. Second, the optimization target was proposed specifically for the early design stage with limited available design information, and could be replaced by other optimization functions according to different design conditions. Lastly, the optimization time is a practical problem now, but could be solved in the near future through advanced computing technologies.

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