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Analysis of urban ventilation potential using rule-based modeling

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ABSTRACT

Successful and efficient urban planning requires direct, rapid evaluations of the urban ventilation potential. An urban ventilation environment can be analyzed and evaluated using numerical simulations; however, such simulations require considerable time and effort, especially at the start of planning or when the area is vast. This study presents a method that can rapidly analyze urban ventilation potential of the whole city and each district by combining the rule-based modeling method with urban enclosure index. The first step of the proposed method is to rapidly generate building models using rule-based modeling, and the buildings in different districts are color coded by their use. Then, several vertical sections of the whole city and each district are cut, and the sectional data is extracted for plotting the enclosure charts. Finally, the enclosure index charts are superimposed on the urban wind rose diagram to analyze the ventilation potential of the whole city and each district, and optimization suggestions are proposed based on the analysis results. A case study was then performed on Lipu County, Guangxi, China and the optimization suggestions were proposed from the aspects of road orientations, building layout and the arrangement of greenbelts and open recreational space.

1. Introduction

Urban planners constantly strive to not only maintain but also improve the quality of life of urban residents by providing a comfortable and pleasant environment. Urban ventilation conditions are closely related to residents' health and comfort levels (Chang et al., 2016; Ragheb, El-Darwish, & Ahmed, 2016). Optimal urban ventilation can enhance air flow capacity and reduce building energy consumption in the summer; this plays an important role in improving urban heat island effects (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016; Hong & Lin, 2015). The urban morphology, land use layout, and setting of building functions can all directly affect urban ventilation. Urban planners should take urban ventilation into account to achieve harmony, balance, and quality in urban landscape design and building and function layout (Blocken, Janssen, & van Hooff, 2012; Varapaev & Doroshenko, 2014; Wen, Juan, & Yang, 2017). However, actual urban developments often do not use original ventilation schemes. For example, in a new district in Shenzhen (a southern city in China), the planned design blocked air channels and aggravated the urban heat island effect (Shi, 2012).

It is important to quickly evaluate the urban ventilation potential at the start of urban programming and design. At this stage, the properties of urban land use and building layout have been determined roughly, and designers should quickly evaluate the general urban ventilation potential and revise and adjust the original planning schemes as needed (Hsieh & Huang, 2016; Ren, Yuan, He, & Wu, 2014). Unlike urban landscape design, which relies on qualitative evaluation, the ventilation environment can be reflected by quantitative indexes; accordingly, appropriate evaluation methods should be developed at the start of design for quantitatively predicting and evaluating the ventilation performance after project completion.

By combining rapid rule-based urban modeling and the analysis of the urban enclosure index, we propose a method for quickly evaluating the urban ventilation potential. Three-dimensional (3D) city models were generated based on rules in regular and batch modes; then, the enclosure degrees of the city and each district were calculated to analyze the urban ventilation potential. The analysis results can then serve as a guide for building layout design in urban planning to create a better ventilation environment. This method affords advantages such as rapid modeling and favorable operability. General urban planners and designers can use this method to rapidly predict and analyze a city's overall plan and ventilation potential over a large area.

2. Research status

Currently, computer numerical simulation approaches such as computational fluid dynamics (CFD) are used to analyze urban ventilation environments; specifically, the wind pressure and velocity in both summer and winter according to the plan and design scheme are analyzed

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to provide feedback on the wind environment (Bajsanski, Stojakovic, & Jovanovic, 2016; Guo, Liu, & Yuan, 2015; Hsieh & Huang, 2016). However, this widely used method has several drawbacks. First, these simulations focus strongly on the physical environment of some districts and buildings that cover small ranges; however, they are rarely powerful enough to investigate a city spanning a large area. Even if this method were to work for an entire city, the amount of information and data required would be very large, making both the modeling and the simulation time-consuming and labor-intensive (Tian, Gu, Ji, & Li, 2014). The urban ventilation environment simply cannot be conveniently simulated using existing hardware and software techniques. Second, numerical simulations of even small areas such as districts and buildings require a great deal of time and calculation load; thus, rapid model analysis cannot be performed on multiple schemes simultaneously (Hong, Lin, Hu, & Li, 2012; Wen et al., 2017). Furthermore, numerical simulations require high expertise to perform and therefore must be conducted by highly trained urban planners and designers. All of these problems compound, leading to an inability to revise the scheme according to the feedback during the design process.

Accordingly, solutions to two practical problems need to be addressed: a rapid and convenient urban ventilation evaluation method and a rapid modeling method for providing base objects in urban ventilation environment analysis.

2.1. Prediction of urban ventilation using urban enclosure index

In consideration of the complexity of and large time investment required for numerical simulations, various methods have been proposed for predicting urban ventilation environments. For example, Mikhailuta et al. compared weather data over the past several years with urban development to analyze the relationship between urban development and ventilation conditions (Mikhailuta, Lezhenin, Pitt, & Taseiko, 2016). Yuan, Ren, and Ng proposed a method to analyze urban ventilation conditions using the city surface roughness based on geographic information system (GIS) data (Yuan, Ren, & Ng, 2014). Koen noted that urban ventilation conditions can be reflected by analyzing the enclosure index of the city in different directions (Koen, 2004). The enclosure distribution characteristics of urban morphology refer to the blocking degrees of the city's different entities in different directions, therefore reflecting these entities' ability to hinder wind. The sparse and dense distributions of buildings and wide, open spaces make a city almost porous and result in variations in enclosure characteristics in different directions. A city's overall porosity or blocking degree can be described by analyzing the heights and areas of the vertical sections of the city along different directions; this information can then be used to evaluate the city's ventilation efficiency along these directions.

A specific point in the city can be established as the origin of polar coordinates. Then, several urban sections along different directions from the origin can be acquired; the areas or heights of these sections reflect the city's approximate enclosure degrees. The indexes can then be extracted to plot the city's enclosure index chart in a plane-coordinate system, and the urban ventilation condition can be adequately predicted and evaluated by comparing the enclosure index chart and the wind rose diagram. By using this method, London's ventilation condition in January and July was analyzed to determine blocks that had favorable and poor ventilation conditions (Koen, 2004). Furthermore, by using simplified indexes of urban construction, this method can roughly predict urban ventilation conditions and is thus applicable to cities and districts over a wide range.

Nevertheless, the theoretical prediction of urban ventilation based on the urban enclosure index has some shortcomings. First, Koen's theory, once proposed, was seldom used to evaluate urban ventilation. The extraction of enclosure indexes is quite complicated; furthermore, the acquired data is generally two-dimensional, and it does not have an intuitive relationship to practical 3D city models. Further, the complexity of index extraction has led to studies focusing on the overall urban enclosure degree and ventilation but ignoring the specific ventilation conditions in each unique district. Second, in this method, the objects are all built regions, as this method has not been applied to planning schemes during the design stage. Therefore, the analysis results and optimization suggestions generated cannot be applied to urban planning and design.

In summary, although this theory was proposed long ago, the progress toward successfully implementing it has yet to realize its full potential. The simplification of the index extraction method and the combination of urban enclosure and 3D visualization will make the analysis easier to understand, promoting the application of the theory based on the urban enclosure index and enabling the optimal design of the ventilation environment in urban planning.

2.2. Rapid urban modeling

2.2.1. Conventional and rule-based modeling methods

Simplified representation of 3D models, for example, LOD 1 and LOD 2, and their rapid reconstruction can be obtained from many other methods, such as 2D maps and building floor information, 2D maps and LIDAR, and 2D maps and ArcGis (Alam, Coors, Zlatanova, & Oosterom, 2016; Biljecki, Stoter, Ledoux, Zlatanova, & Çöltekin, 2015). There are limitations to how these methods can be applied to new planning preparations. Some existing city modeling methods are described below.

Existing 3D city modeling methods usually generate 3D models (Guan, Zhou, & Zhang, 2007) (a) based on 2D urban data (e.g., planning maps) using interactive software such as AutoCAD and Sketch Up (SU); (b) from spatial geographical data, that is, GIS data; (c) from laser scanning data; or (d) from digital photogrammetry. Method (a) is most popular in the field of urban planning. Although its 3D models have high accuracy, model generation is time-consuming, and the models are static and limited in single use. In other words, this approach is good for stereoscopic visualization but is unsuitable for attribute query or 3D spatial analysis (Xie, Zhu, Du, Xu, & Zhang, 2012). Among other existing modeling methods, GIS-based modeling is restricted to regular buildings; laser scanning is expensive, and its model generation is time-consuming and has high calculation load; and digital photogrammetry models cannot be modified easily (Guan et al., 2007). Generally, conventional modeling methods are more suitable for reconstructing and flexibly modifying existing cities and their models and are used to assist urban planners in new planning programs.

Rule-based modeling methods have also been proposed to rapidly construct 3D city models to realize more efficient urban modeling (Bellotti, Berta, Cardona, & De Gloria, 2011; Smelik, Tutenel, de Kraker, & Bidarra, 2011; Trubka, Glackin, Lade, & Pettit, 2016). Rule-based modeling is a type of semantic modeling method in which real-world information is transformed into logical information and the generated model is determined by rules. The rule-based modeling ideology provides constraint conditions and uniform standards while simultaneously reducing the modeling complexity (Luo, He, & He, 2017; Zhang et al., 2016). Unlike conventional modeling methods, the rule-based modeling method is good at flexible and efficient modeling and is suitable for both built-up areas and new planning areas. It allows alternatives to be created and analyzed and therefore shows some potential for supporting urban planning.

2.2.2. CityEngine rule-based modeling

Currently, CityEngine (CE) software is widely used for rule-based modeling in the urban programming community. The CE modeling principle is based on the use of statements to describe modeling elements in a computer-generated architecture (CGA) language. These languages are referred to as rules in CE. The biggest difference between CE and conventional, pure interactive modeling is that the rule determines the variation of the modeling objects; then, the variation results are