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Challenges for Modeling Energy Use in High-rise Office Buildings in Hong Kong

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Abstract

Modeling buildings' energy use is an effective strategy for identifying energy saving potential and seeking for energy efficient building solutions. However, there exist significant challenges for such modeling, particularly of high-rise buildings. The aim of this paper is to examine such challenges drawing on the case of high-density high-rise office buildings in the hot and humid climate of Hong Kong. The challenges are examined in relation to four aspects, namely, modeling approach, modelling tools, data availability and atmospheric conditions. A framework of strategies is developed for addressing the challenges. The strategies are then illustrated through a case study with a hypothesized high-rise office building in Hong Kong. Essential to achieving accuracy of modeling buildings' energy use are found to be the collection and verification of building information and specification of thermal zones and schedules for modeling. The lack of usable data of energy use in high-rise buildings is considered to be a major barrier to verifying modeled results. To establish an integrated model with energy modelling and CFD software should effectively address the challenges.

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Keywords: High-rise; Office building; Energy modeling; Energy use

1. Introduction

Hong Kong has seen a trend of rapid increase in energy use in recent years. The Hong Kong Special Administrative Region (HKSAR) government has proposed a carbon intensity reduction target of 50%-60% by 2020

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compared to 2005 level. Tackling energy consumption in buildings is a critical strategy for achieving the governmental target for carbon reductions and long-term sustainability in Hong Kong. The Environmental Protection Department and the Electrical and Mechanical Services Department [1, 2] proposed a set of 'Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for buildings (Commercial, Residential or Institutional Purpose) in Hong Kong'. Commercial buildings are a major building type responsible for the majority of electricity consumption in Hong Kong. From 2003 to 2013, there was a general gradual increase of electricity consumption of commercial buildings (Fig. 1). Due to the scarce developable land resources in Hong Kong, the majority of buildings in the city are high-rise; approximately one in five are office buildings [3], which offer a considerable energy saving potential. To realize such potential it is vital to examine the building energy performance in comparison with the estimated energy performance of buildings. However, there exist significant challenges for energy simulation for high-rise buildings.

The aim of this paper is thus to examine such challenges drawing on the case of high-density high-rise office buildings in the hot and humid climate of Hong Kong. The paper first reviews the challenges identified and reported in literature. It then explores and elaborates the challenges through a case study with a hypothesized 40-storey office building in Hong Kong. The modelling was conducted using the three-dimensional modeling software SketchUp and energy simulation software EnergyPlus. All results are cross discussed from which conclusions are drawn on the challenges facing the modeling of energy use in high-rise office buildings.

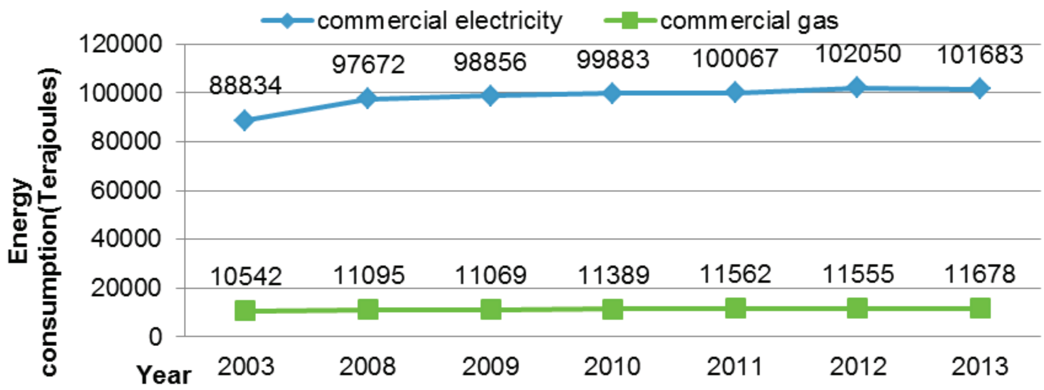

Fig. 1. Electricity and gas consumption of commercial buildings in Hong Kong (2003-2013) [4]

2. High-rise office buildings in Hong Kong

Hong Kong is located on China's south coast and is classified as humid subtropical climate in the Koppen Climate Classification System. Summer months between May and October are hot and humid with warm wind blows from the south and southeast directions. Substantial electricity is required to remove the excessive heat and moisture during summer months. Winter months between November and April are mild with cold and dry wind blowing from the north and northeast directions.

With the total land area of 1108 km^2, Hong Kong is one of the most densely populated areas in the world with an overall population density of 6,487 persons per km^2 [5]. Nevertheless, only 30% of the areas are usable for various developments, rendering a much higher effective density. The high population and limited land resources together drive the booming construction of super tall buildings in Hong Kong. According to EMSD and EPD [1, 2], office buildings are an important category of commercial buildings that account for about 65% of the total energy consumption in Hong Kong. As Zhang, Pan and Kumaraswamy [6] pointed out, office buildings normally feature more straightforward energy use patterns than the other types of commercial buildings, and owners and developers of office buildings are more likely to adopt low energy measures for improving building energy performance targeting better commercial returns of their assets. The examined challenges for modeling energy use in high-rise office buildings in Hong Kong as an international center for business and finance should yield useful learning for other contexts in similar climates.

3. Challenges in energy modeling of high-rise office buildings

There exist significant challenges for modeling energy use in high-rise office buildings with accuracy. The many challenges are reviewed hereinafter, which can be categorized into four aspects: 1) limited use of whole building energy modelling approach; 2) shortcomings in the energy modeling tools for high-rise buildings; 3) lack of usable energy data; and 4) lack of consideration for different atmospheric conditions. Several representing approaches to model-ling energy use in office buildings are compared in Table 1.

Table 1. Typical approaches to modeling energy use in office buildings

Object	Location	Data source	Approach	Author
A commercial building	Hong Kong	Auditing data	TRACE 600	Yu and Chow (2007) [7]
Four office buildings	Hong Kong	Monitored data	None	Lam, Li and Cheung (2003) [8]
An office building	Turkey	Auditing data	EnergyPlus	Eskin and Turkmen (2008) [9]
Twenty two high-rise office buildings	Chicago	Auditing data	Fractional factorial analysis method	Langner et al. (2012) [10]
A 38-storey office building	Thailand	From the Department of Alternative Energy Development and Efficiency	Life cycle energy analysis method	Kofoworola and Gheewala (2009) [11]

3.1 Limited use of whole building energy modelling approach

Research on energy performance of high-rise buildings is largely focused on the analysis of building components rather than of the whole building's energy consumption. For example, Yu and Chow [7] focused on the energy consumption of mechanical ventilation and air-conditioning. They used Princeton Scorekeeping Method to derive the correlation relation-ships between the building envelope heat gain and the electrical energy use. The energy simulation software TRACE was used to justify the data. Pasquay [12] selected the Siemens building in Dortmund as the architecture archetype to evaluate the whether natural ventilation in high-rise buildings can save energy. Li and Tsang [13] focused on daylighting performance of Hong Kong office buildings, and concluded that proper daylight linked lighting controls could save over 25% of total electric lighting consumption.

Although the whole building simulation approach has been used, such application is limited to evaluating specific building types and analyzing the proportions of the energy use categories. For examples, Lam and Hui [14] used DOE-2 to analyze the existing annual building energy consumption and examine the sensitivity of energy performance of office buildings in Hong Kong. Eskin and Turkmen [9] applied EnergyPlus to assess existing building parameters like the climatic conditions, insulation, glass ratio, color of external surfaces, shading and different outdoor air control strategies on annual building energy requirements. However, different building types possess their own characteristics, e.g. building form and function, envelope and HVAC system. There is limited understanding of buildings' energy use at normalized level and its relationship with various building parameters.

3.2 Shortcomings in the energy modelling tools for high-rise buildings

There exist a variety of energy simulation tools for predicting buildings' annual energy use, e.g. Carrier HAP, Trane TRACE 700, DOE-2, eQUEST, EnergyPlus, ESP-r, IDA ICE, TRN-SYS, HVACSIM+, VA114, SIMBAD. Based on the given boundary conditions and operation schedules and different systems, energy simulation tools perform hourly or sub-hourly report. However, the conversion of data from three-dimensional modeling to building energy simulation is not straightforward. Interoperability issues occur during the transitions. For in-stance, EnergyPlus is the widely adopted tools with comprehensive simulation engine. Conversely, this tool lacks a user friendly interface, making user input more difficult. It will take tremendous time to obtain the outcome for high-rise buildings attributable to the massive number of thermal zones. This tool is therefore more suitable at later design stages where a good level of detail is available. DesignBuilder is based on the EnergyPlus and redeveloped with an easy-to-use interface. This enables the whole design team to use the same software, developing comprehensive and energy-efficient design solutions from conceptual phase to completion. However, DesignBuilder has limited options for manually defining heating and cooling sizes. These limitations are due to EnergyPlus requiring all HVAC data to be either autosized or manually defined.

3.3 Lack of useable data of energy use in high-rise buildings

In Hong Kong, under current conditions, basic sources of office buildings can be found in the Monthly Digest published by the Buildings Department [15]. This publication contains in-formation about building construction in Hong Kong, such as location, number of storeys, gross floor area, etc. Other unmentioned but necessary information can be consulted through the proper standards, such as the Code of Practice for Energy Efficiency of Air Conditioning Installations (AC Code) published by the Housing Department [16]. However, there is a lack of useable data of buildings' energy use in Hong Kong due to, e.g. inadequate use of energy sub-meters. It is thus difficult to estimate buildings' energy use in an accurate way [8]. After the typical buildings are selected to model the energy use, it is necessary to calibrate the simulation models because the calibration is crucial for the accuracy and usability of energy simulation [17]. The calibration process is that the simulation model is tuned with measured data until the simulated results closely match the practical data.

3.4 Different atmospheric conditions for high-rise buildings

Because the atmospheric conditions change with altitude, high-rise buildings can experience significant differences in environmental factors between the lower floors and the higher floors. These include differences in air temperature, barometric pressure, and wind speed [18]. The urban environment imposes additional environmental factors because of shading and refection from surrounding buildings. These environmental factors create a microclimate that can vary from floor to floor of a high-rise building. Therefore, the environment of high-rise office building is significant to the final energy simulation result. Modeling a high-rise building must consider the characteristic of the tall building, such as the elevator installation, strategy of HVAC system and the interaction between outside microclimate and the energy use. The shading from other buildings is another index to impact the final result. However, a simulation tool considering both the building itself and its outside conditions is still cumbersome. In current energy modeling, the microclimate is considered as a constant input.

4. A framework of strategies for addressing the challenges

In addressing the challenges to energy modeling of high-rise buildings a framework of strategies is developed (Fig 2). The basic solutions aim at quickly modeling high-rise office buildings considering the challenges. Such basic solutions are illustrated through a case study later in this paper. For high-rise office buildings the thermal zones can get very complicated, which would take an incredible amount of time to be modelled. To address this issue, the input data can be simplified (e.g. thermal zones). The microclimate can be addressed by utilizing CFD tools. Then the outside conditions result (e.g. wind, temperature) can be connected to the energy consumption results with qualitative analysis. For instance, with the CFD simulation, double glazed facade building with natural ventilation was able to minimize energy consumption as well as to enhance thermal comfort compared to single glazed facade building [19].

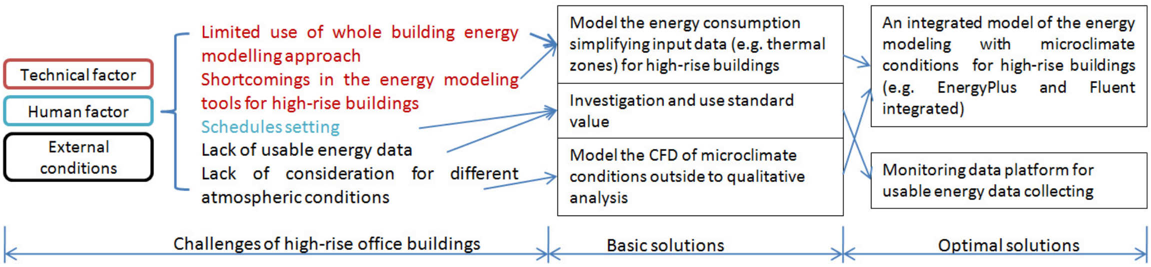

Fig. 2. Challenges to energy modelling of high-rise office buildings and solutions

The optimal solutions to handling the challenges to modelling high-rise office buildings are to establish an integrated model with energy modelling and CFD software. The atmospheric conditions, such as temperature and wind speed, will influence input data for energy model-ling. The process embedded in the integrated model is showed in Fig 3. The value of the out-side conditions from CFD simulation can replace the energy simulation's original input, the Typical Meteorological Year (TMY) data. On the other hand, the CFD result and energy simulation result can be integrated to adjust the energy simulation (see Fig. 3). To solve the problem of the lack of data, the best way will be to build an energy data collection and monitoring platform. The collected data can be used to verify and fine-tune the simulation model for improved accuracy.

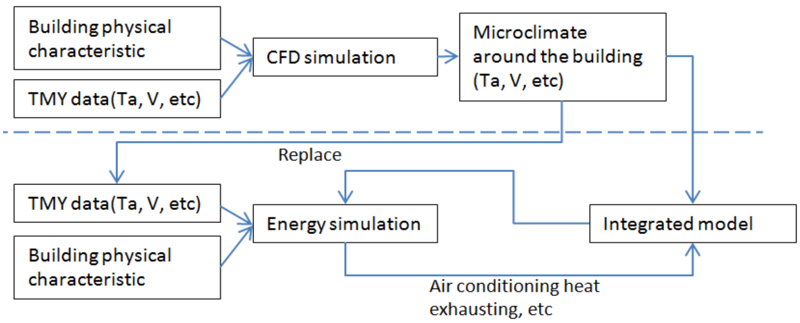

Fig. 3. An integrated model for energy use simulation in high-rise office buildings

5. Project case study

In order to explore and elaborate the basic solutions to the challenges identified through the literature review, a case study was conducted with a hypothesized 40-storey office building through a whole building energy simulation process. In this study, SketchUp and EnergyPlus were utilized as the modeling environment and energy simulation engine respectively. EnergyPlus is building energy simulation software developed by the US Department of Energy. It uses heat balance method to calculate thermal loads. SketchUp is a friendly 3D modeling software, which can be transmitted to EnergyPlus through Legacy OpenStudio plug-in.

5.1 Case building's information

Due to the specific conditions of Hong Kong, a typical meteorological year developed for Hong Kong was used in the calculations. The weather data of typical meteorological year included dry bulb, wet bulb, wind speed, wind direction, global solar radiation. The TMY data used in this study were downloaded from the EnergyPlus official website. The typical location is assumed at Hong Kong Island. The weather file used in the energy simulation is provided by EnergyPlus weather database (CHN_Hong.Kong.SAR.bin). Table 2 summarizes the fundamental information of this typical Hong Kong office building for the case study.

Table 2. Summary of the case building's information

Building parameter	Value
GFA (m^2)	80000
Number of storeys	40
Envelope type	Curtain walls with reflective single glass
Shading coefficient	0.4
Window-to-wall ratio (WWR)	0.8
U-Values ($W/m^2.K$)	Wall:1.9 Window:5.6 Roof:0.5
Indoor setting of relative humidity	55%
Indoor setting of dry bulb temperature	23 degree
Air-side HVAC	VAV system
Water-side HVAC	Air-cooled chiller plant (COP:3)

5.2 Thermal zones

Due to the load analysis foundation and the distinction of load, it is vital to partition building with internal and external zones to improve the indoor thermal environment and reduce the energy consumption. Cooling season varies from late March to early November for office buildings. The large scale of high-rise buildings means that many thermal zones may be required to fully simulate the whole building. Common practice is to select and simulate only a few floors, such as the top floor, one typical floor in the middle, first floor and ground floor. The results are multiplied by a factor to arrive at estimation for the entire building. Therefore, the case building is set with a 48x48m layout with a 24x24m non-air-conditioned central core (Fig. 4). The toilet has the mechanical ventilation.

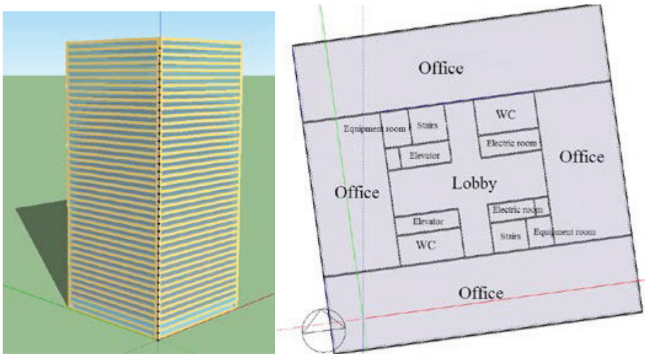

Fig. 4. The layout of the hypothesized office building for case study

5.3 Schedules for modeling

Some additional input parameters should also be considered in the study, such as the setting of schedule. Most of the air-conditioning equipment in the commercial sector, especially purpose-built office buildings, operated at definite time between 08:00 and 18:00, the usual office (business) hours. Shifting cooling demand to the late evening and early hours in the morning attracted the growing attention. Precisely simulating occupants' interaction with building control systems is difficult, most previous studies regarding occupant behavior use a static value. The assumption value of human behavior can be applied to describe user presence and action in a building or a room. The building is operated for the whole year. Occupancy and operation schedules are assumed according to the Chinese local code - Design Standard of Energy Efficiency of Public Buildings (GB 50189-2005).

5.4 Modeling results

According to the results, the case building from May to September occupies the largest amount of energy consumption, showing the energy saving potential in these months. Due to the Hong Kong climate, office buildings need to operate the air-conditioning system for cooling demand during the whole year. The total energy use in the case building was estimated to be 135.48kWh/m2/yr, of which nearly half (44%) was contributed by space cooling, followed by miscellaneous equipment (27%), area lighting (20%), ventilation and fans (9%) (Fig 5). The estimated total energy use in the case building is lower than the results of some previous research, e.g. by Yu and Chow [7] (259.2 kWh/m2/yr). The divisions among energy use mainly attribute to different HVAC systems and schedules. Nevertheless, the splits of the energy use in the categories in the case building suggest a general alignment with the published data of commercial buildings in Hong Kong Annual Digest of Statistics [4].

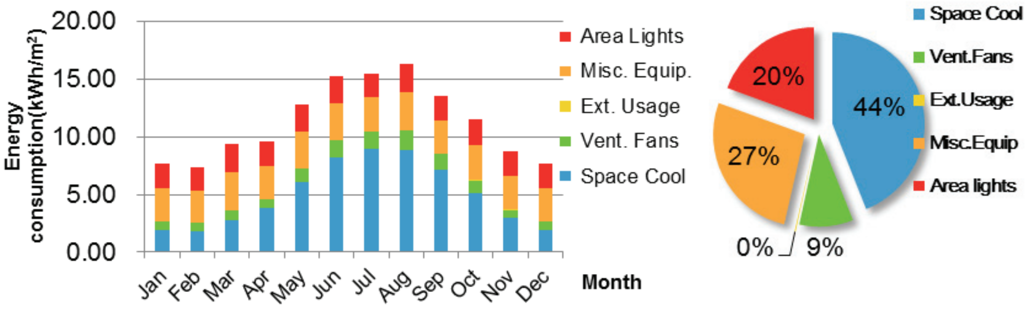

Fig. 5. Estimated energy use in the case building

6. Discussion and conclusions

This paper has examined the challenges to modeling energy use in high-rise office buildings within the context of Hong Kong. The challenges are found to be centered on modeling approaches, modelling tools, data availability and atmospheric conditions. Essential to achieving accuracy of modeling buildings' energy use are found to be the collection and verification of building information and specification of thermal zones and schedules for modeling. The lack of usable data of energy use in high-rise buildings is considered to be a major barrier to verifying modeled results. The paper has also developed a framework of strategies for addressing the identified challenges, which are illustrated through a case study with a hypothesized 40-storey office building in Hong Kong. In light of different data sources and human behaviors, the estimated total energy use of office buildings may vary. Different air conditioning systems may also skew the energy use. While the building physics models and algorithms used by building energy simulation programs are now fairly mature, there are distinct shortcomings in quantifying the energy use attributable to the environmental and occupancy impacts. To establish an integrated model with energy modelling and CFD software should effectively ad-dress the challenges. The findings and strategies developed should also inform energy use modeling for high-rise buildings in other urban settings.

Acknowledgements

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