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Multiple regression models for energy use in air-conditioned office buildings in different climates

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ABSTRACT

An attempt was made to develop multiple regression models for office buildings in the five major climates in China – severe cold, cold, hot summer and cold winter, mild, and hot summer and warm winter. A total of 12 key building design variables were identified through parametric and sensitivity analysis, and considered as inputs in the regression models. The coefficient of determination R^2 varies from 0.89 in Harbin to 0.97 in Kunming, indicating that 89–97% of the variations in annual building energy use can be explained by the changes in the 12 parameters. A pseudo-random number generator based on three simple multiplicative congruential generators was employed to generate random designs for evaluation of the regression models. The difference between regression-predicted and DOE-simulated annual building energy use are largely within 10%. It is envisaged that the regression models developed can be used to estimate the likely energy savings/penalty during the initial design stage when different building schemes and design concepts are being considered.

1. Introduction

In China, there has been steady increase in the use of energy since the adoption of the Policy of Reforming and Opening in the 1980s, and energy conservation is of vital importance both economically and environmentally [1–4]. It was estimated that buildings stocks accounted for 24.1% of total national energy use in mainland China in 1996, rising to 27.5% in 2001, and is projected to increase to about 35% in 2020 [5,6]. Under constant energy efficiency, total annual energy consumption would be around 5000 Mtce (1 Mtce = 29.3×10^6 GJ) in 2020 [7]. With rapid economic growth, there is a growing desire for better indoor built environment, particularly in winter space heating and summer comfort cooling, and it was estimated heating, ventilation and air-conditioning (HVAC) accounted for some 65% of the energy use in the building sector [8]. It is envisaged that the building sector will continue to be a key energy end-user in the years ahead. Office building development is one of the fastest growing areas in the building sector especially in major cities such as Beijing and Shanghai. On a per unit floor area basis, energy use in large office building development with full air-conditioning can be 70–300 kWh/m^2, 10–20 times that in residential buildings [9,10]. Because of the climatic diversity in China, the designs of these buildings and their thermal and energy performances could vary a great deal in different climate zones across China [11]. Computer building energy simulation is an acceptable technique for assessing the dynamic interactions between the external climates, the building envelopes and the HVAC systems, and has been playing an important role in the designs and analysis of energy-efficient buildings and the development of performance-based building energy codes [12–15]. In most architectural and engineering design practices, however, full hourly building energy simulations could be costly and time-consuming. Simple estimation models are often preferred, especially during the initial design stage when different design concepts and building schemes are being considered. There is, however, very little work on comparing hour-by-hour simulated building energy consumption with those from simple estimation models for different climates. The primary aim of the present work was, therefore, to develop simple energy estimation models for fully air-conditioned office buildings in major climate zones across China. The work involved four main aspects:

(i) Generation of an energy use database through a series of building energy simulation runs for office buildings in major climate zones in China.
(ii) Identifying key building design variables using sensitivity analysis technique.
(iii) Develop simple energy estimation models as functions of the key design variables using regression technique.
(iv) Regression models evaluation.

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2. Major climates

China is a large country with an area of about 9.6 million km^2. Approximately 98% of the land area stretches between a latitude of 20°N–50°N, from the subtropical zones in the south to the temperate zones (including warm-temperate and cool-temperate) in the north. China also has a complex topography ranging from mountainous regions to flat plains. These diversity and complexity have led to many different regions with distinct climatic features [16,17]. In terms of the thermal design of buildings, there are five major climates, namely severe cold, cold, hot summer and cold winter (HSCW), mild, and hot summer and warm winter (HSWW) [18]. This simple climate classification is concerned mainly with conduction heat gain/loss and the corresponding thermal insulation issues. The zoning criteria are mainly based on the average temperatures in the coldest and hottest months of the year. The numbers of days that the daily average temperature is below 5 °C or above 25 °C are counted as the complementary indices for determining the zones. A major city within each of the five climatic zones was selected for this study. These were Harbin (severe cold, 45°45′N and 126°46′E), Beijing (cold, 39°48′N and 116°28′E), Shanghai (HSCW, 31°10′N and 121°26′E), Kunming (Mild, 25°01′N and 102°41′E) and Hong Kong (HSWW, 22°18′N and 114°10′E).

Table 1
Summary of base-case building envelope design parameters.

City	Climates	Building element	U-value (W/m^2 K)	Shading coefficient	
				North	Other orientations
Harbin	Severe cold	Wall	0.44	–	–
		Window	2.50	0.64	0.64
		Roof	0.35	–	–
Beijing	Cold	Wall	0.60	–	–
		Window	2.60	0.70	0.70
		Roof	0.55	–	–
Shanghai	Hot summer and cold winter	Wall	1.00	–	–
		Window	3.00	0.60	0.50
		Roof	0.70	–	–
Kunming	Mild	Wall	1.47	–	–
		Window	3.50	0.55	0.45
		Roof	0.89	–	–
Hong Kong	Hot summer and warm winter	Wall	2.01	–	–
		Window	5.60	0.40	0.40
		Roof	0.54	–	–

3. Hourly weather databases and generic base-case building designs

Building energy simulation was conducted using the simulation tool DOE-2.1E [19]. Two major inputs were developed for each of the five cities – hourly weather databases and generic base-case office building designs, details of which can be found in our earlier work on building energy simulation in different climates [11]. Briefly, typical meteorological year (TMY) consisting 8760 hourly records of dry-bulb temperature, dew-point temperature, solar radiation, wind speed and wind direction for each city was developed for the simulation exercise [20]. A base-case office building was developed to serve as a baseline reference for comparative energy studies. The base-case was a 35 m × 35 m, 40-storey building with curtain walling design, 3.4 m floor-to-floor height and 40% window-to-wall ratio. The total gross floor area (GFA) is 49,000 m^2 (41,160 m^2 air-conditioned and 7840 m^2 non-air-conditioned). The air-conditioned space had five zones – four at the perimeter and one interior. Obviously, each city would have rather different building envelope designs to suit the local climates. Generic building envelope designs were developed based on the prevailing architectural practices and local design/energy codes [21,22]. Table 1 shows a summary of the key building envelope design parameters. For instance, heat loss is a key design consideration in Harbin, and as such walls and roofs tend to have substantial thermal insulation (*U*-value = 0.44 W/m^2 K). In subtropical Hong Kong, however, office buildings are cooling-dominated, where solar heat gain is by far the largest component of the building envelope cooling load. Thermal insulation to the external walls is less important (*U*-value = 2.01 W/m^2 K) and windows tend to have small shading coefficients. The building and its lighting system operated on an 11-h day (07:00–18:00) and 5-day week basis. Infiltration rate was set at 0.45 air change per hour (when the HVAC system was off) throughout the year. For comparative energy studies, the same internal loads, indoor design conditions and basic HVAC systems were assumed for the five cities with the corresponding design data taken from local energy/design codes on the mainland [23] as well as the prevailing engineering practices. Ref. [21] stipulates 25 °C as the summer indoor design temperature, but in the interest of energy conservation many buildings are designed to 26 °C. A summary of the key data is shown in Table 2.

4. Parametric building energy simulation and sensitivity analysis

Before conducting the simulation and subsequent analysis, it is important to understand what input parameters are to be studied. Selecting and defining the input parameters is often a difficult task that requires sound engineering judgement and a good understanding of the simulation system. Breakdown of the parameters was worked out according to the input building description language of the DOE-2 program so that maximum effectiveness and compatibility could be achieved. A list of the input parameters was prepared and they represented a variety of different factors encountered in building design. These were the design parameters that architects and engineers would consider during various stages of the design process. There were all together about 36 input parameters categorized into three main groups – building load (17), HVAC system (7) and HVAC plant (12). By categorizing the input design parameters, a clear picture of the energy-related factors was established. Each of the three main groups was further divided into different sub-groups as follows:

(i) Building load – building envelope, building configuration, space load and conditions and building thermal mass.
(ii) HVAC system – system operation, system controls and fans.
(iii) HVAC plant – refrigeration and heat rejection, chilled water circuit, chilled/hot water pumps and boilers.

After determining the design variables to be considered, perturbations were introduced by assigning a range of different values to each of the input parameters (IP), one at a time. Changes in the parameters might represent a certain energy-efficient measure proposed to the building for achieving energy conservation and control purposes. For instance, windows with smaller SC and WWR could lower the amount of heat gain through the building envelope and hence reduce cooling energy use. Tables 3–5 show the summaries of the base-case values, ranges of the perturbations and intervals used in the parametric simulation. There were altogether 321 perturbations among the 36 parameters and a total of 357 simulation runs were conducted for each city. The simulated results formed an energy use databases for subsequent sensitivity analysis.