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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).

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.

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	–	–

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.

Table 2
Internal conditions and HVAC systems for the base-case.

Indoor design condition		Internal load density				HVAC	
Summer	Winter	Occupancy (m^2/person)	Lighting (W/m^2)	Equipment (W/m^2)	AHU	Cooling	Heating
26 °C	20 °C	8	18	13	4-pipe fan coil	Centrifugal chiller (water-cooled)	Gas-fired boiler

Note: HVAC = heating, ventilating and air-conditioning; AHU = air-handling unit.

Table 3
Summary of base-case values, ranges and intervals for the building load input parameters.

Input parameters	Unit	Base-case value	Range	Interval
Building envelope				
Absorptance of roof	–	0.7	0.1–0.9	0.2
Absorptance of wall	–	0.7	0.1–0.9	0.2
Shading coefficient of window	–	Note 1	Note 2	0.1
Window *U*-value	$W/m^2\,K$	Note 1	Note 3	0.5
Roof *U*-value	$W/m^2\,K$	Note 1	Note 4	0.3
Wall *U*-value	$W/m^2\,K$	Note 1	Note 5	0.2
Window-to-wall ratio	–	0.4	0.1–0.95	0.05
Building configuration				
Aspect ratio of plan	–	1	0.5–5	0.5
Floor-to-floor height	m	3.4	2.9–4.9	0.5
Number of storeys	Nos.	40	10–50	10
Perimeter zone depth	m	4.57	1.07–8.07	0.5
Space load and space conditions				
Space air temperature	°C	23	18–28	0.5
Equipment load	W/m^2	13	1–31	2
Infiltration rate	ACH	0.45	0.05–2.05	0.2
Lighting load	W/m^2	18	2–30	2
Occupant density	m^2/psn	8	2–16	2
Building thermal mass				
Floor weight	kg/m^3	342	42–692	50

Note: (1) see Table 1 for different base-case values for the five cities. (2) Harbin 0.04–0.94, Beijing 0.1–0.9, Shanghai 0.1–0.9, Kunming 0.05–0.95, Hong Kong 0.1–0.9. (3) Harbin 1–8.5, Beijing 1.1–8.6, Shanghai 1–8.5, Kunming 1–8.5, Hong Kong 1.1–8.6. (4) Harbin 0.05–1.85, Beijing 0.25–2.05, Shanghai 0.4–2.2, Kunming 0.59–2.39, Hong Kong 0.24–2.04. (5) Harbin 0.04–2.84, Beijing 0.2–3.0, Shanghai 0.2–3.0, Kunming 0.27–3.07, Hong Kong 0.21–3.01.

Table 4
Summary of base-case values, ranges and intervals for the HVAC systems input parameters.

Input parameters	Unit	Base-case value	Range	Interval
System operation				
Outdoor fresh air (OA)	l/s/psn	8.3	0–20	2
Operation hours	h/day	11	5–15	1
System controls				
Throttling range	°C	1.1	0.06–3.33	0.33
Summer set point temperature (TS)	°C	26	20–29	1.0
Pre-cooling set point (summer)	°C	28	22–31	1
Cooling setback temp (summer)	°C	37	30–40	1
Maximum relative humidity	%	65	45–85	10
Minimum relative humidity	%	40	30–55	5
Winter set point temperature (TW)	°C	20	15–24	1
Pre-heating set point (winter)	°C	18	13–22	1
Heating setback temp (winter)	°C	12	5–15	1
Fans				
Fan efficiency (FE)	%	55	10–90	10
Fan static pressure (FS)	In. Aq.	5.5	4–6.5	0.5

Table 5
Summary of base-case values, ranges and intervals for the HVAC Plants input parameters.

Input parameters	Unit	Base-case value	Range	Interval
Refrigeration and heat rejection				
Chiller COP (COP)	–	4.7	3–6	0.2
Number of identical chillers	Nos.	5	3–7	1
Minimum ratio of nominal rated load	–	0.1	0.1–0.5	0.05
Minimum temperature for leaving tower cooling water	°C	18	14–22	2
Design water temperature (leaving the tower)	°C	30	20–35	5
Throttling range	°C	5	4–7	1
Number of identical cooling towers	Nos.	5	2–6	1
Chilled water (Chw.) circuit				
Chw. supply temperature (CT)	°C	6.67	4–9	0.5
Chw. throttling range	°C	1.39	0.6–2.6	0.4
Chw. design temperature difference	°C	5.56	3–8	0.5
Chilled/hot water pumps				
Pump motor efficiency	%	90	60–95	5
Pump impeller efficiency	%	77	60–80	5
Fraction of pump loss	–	0.01	0.001–0.02	0.005
Pump head pressure	m	20	5–40	5
Boilers				
Boiler efficiency (BE)	%	89	55–100	5
Number of identical boilers	Nos.	3	2–6	1
Minimum ratio of nominal rated load	–	0.5	0.2–0.6	0.05

The simulation output of interest was the total building energy consumption (OP). As sensitivity tends to follow the end-use components that consume the most energy, it is believed that input design variables affecting these components will have significant influence on the total building energy consumption [24–27]. To quantitatively assess how sensitive the total building energy use would be to changes in the input design parameters, influence coefficient (IC) was determined as follows:

$$IC = \frac{OP - OP_{bc}}{OP_{bc}} \div \frac{IP - IP_{bc}}{IP_{bc}} \tag{1}$$

The IC is essentially a ratio of the percentage change (with respect to the base-case value) in computed output (i.e. total annual building energy use) to the percentage change in input design parameter (the subscript refers to base-case value). A total of 12 key design parameters were identified – wall *U*-value (WU), window *U*-value (WINU). window shading coefficient (SC), window-to-wall ratio (WWR), equipment load (EQ), lighting load (LL), outdoor fresh air (OA), summer set point temperature (SST), winter set point temperature (WST), fan efficiency (FE), chiller COP (COP) and boiler efficiency (BE). These are design variables frequently considered in the initial design stage and/or tend to have relatively large ICs. Table 6 shows a summary of the IC determined for the 12 key design variables for the five cities. In general, larger the IC, more important the design parameter would be as it tends to exert greater influence on building energy use. For instance, winter heating is the major energy use in Harbin, whereas summer cooling dominates in Hong Kong. The summer set point temperature IC in Harbin is −0.541, less than half the −1.131 in Hong Kong. Likewise, because of the short and mild winter in Hong Kong the win-

Table 6
Influence coefficients of the 12 key design parameters for the five cities.

Input parameter	Influence coefficient				
	Harbin	Beijing	Shanghai	Kunming	Hong Kong
Building load					
Wall *U*-value (WU)	0.041	0.034	0.044	0.009	0.065
Window *U*-value (WINU)	0.129	0.056	0.038	−0.024	−0.008
Shading coefficient of windows (SC)	0.055	0.139	0.114	0.170	0.124
Window-to-wall ratio (WWR)	0.194	0.203	0.140	0.131	0.070
Equipment load (EQ)	0.143	0.228	0.263	0.317	0.264
Lighting load (LL)	0.191	0.307	0.354	0.432	0.359
HVAC system					
Outdoor fresh air (FA)	0.295	0.151	0.136	0.057	0.129
Summer set point temperature (SST)	−0.541	−0.813	−0.898	−1.144	−1.131
Winter set point temperature (WST)	0.407	0.253	0.230	0.185	0.035
Fan efficiency (FE)	−0.146	−0.228	−0.217	−0.260	−0.253
HVAC plant					
Chiller COP (COP)	−0.135	−0.227	−0.247	−0.210	−0.313
Boiler efficiency (BE)	−0.261	−0.060	−0.035	−0.017	−0.010

Table 7
Summary of the different input values for the 12 key parameters used in the 1001 simulation runs for multiple regression.

Input parameter	Unit	Different input values			
		1	2	3	4
Building load					
Wall *U*-value (WU)	W/m^{2}K	0.04	1.49	3.01	–
Window *U*-value (WINU)	W/m^{2}K	1.00	4.8	8.60	–
Window shading coefficient (SC)	–	0.04	0.5	0.95	–
Window-to-wall ratio (WWR)	–	0.10	0.53	0.95	–
Equipment load (EQ)	W/m^2	1	16	31	–
Lighting load (LL)	W/m^2	2	16	30	–
HVAC system					
Outdoor fresh air (FA)	l/s/psn	0.3	6.9	13.8	20.3
Summer set point temperature (SST)	°C	20	23	27	29
Winter set point temperature (WST)	°C	15	18	21	24
Fan efficiency (FE)	%	15	40	65	90
HVAC plant					
Chiller COP (COP)	–	2.9	3.9	4.9	5.9
Boiler efficiency (BE)	%	54	69	84	99

ter set point temperature IC is 0.035 very much smaller than the 0.407 in Harbin. Direct comparison in strict quantitative terms of the ICs, however, is not always feasible or appropriate because the parameters might have different dimensions, units of change and base-case values. Only if the input parameters are measured in the same units and of the same nature are their ICs directly comparable. When the parameters differ substantially in units, the sheer magnitude of the ICs cannot reveal the relative importance of the design parameters. Evaluation of the ICs should, therefore, be conducted in context, with a clear understanding of the physical and energy performance implications [28]. It is interesting to note that window *U*-value IC is negative in Kunming and Hong Kong. There are occasions (especially during mid-season) when the outdoor air temperature is lower than the indoor design temperature (usually a few degrees) and yet the building is in cooling mode because of the large internal loads (e.g. people, lighting and equipment) and solar heat gain in the perimeter zones. In these situations, conduction heat loss through the windows tends to lower the cooling load, thus making a high *U*-value desirable. This of course has to be balanced against excessive winter heat loss and hence increases in the heating requirement. The negative ICs, therefore, suggests that higher window *U*-value might not necessarily lead to higher overall building energy consumption in warmer climates in the south (i.e. Kunming and Hong Kong). Similar findings had been reported for hot and dry climates, where the "point of thermal inflexion" indicated the changing of beneficial thermal insulation [29].

5. Multiple regression analysis

There had been a number of studies on energy signatures of buildings for energy savings analysis of pre- and post-building retrofits using mean outdoor temperatures or degree-days data [30–35]. Earlier works on cooling-dominated office buildings in subtropical Hong Kong also concentrated largely on the mean monthly outdoor dry-bulb temperature and degree-days data using simple two-parameter regression analysis techniques [36–38]. These empirical or regression-based models showed good correlations between energy use and the prevailing weather conditions, and had proved useful in the monitoring and estimation of energy use for existing buildings. Multiple regression technique was adopted in the present study to develop simple energy estimation models for office buildings in the five cities. The database used for the multiple regression analysis should ideally consist of simulated annual building energy use covering all possible combinations of the 12 parameters. This, even for only three different values per input, however, would involve more than half a million (i.e. 3^{12}) simulations. To keep the analysis manageable, possible combinations were only considered within each of the three main groups (i.e. building load, HVAC system and HVAC plant). A total of 1001 simulation runs were conducted: three different values for the six input parameters in building load (3^6, i.e. 729 runs), four values for the four parameters in HVAC system (4^4, i.e. 256 runs) and four values for the two parameters in HVAC plant (4^2, i.e. 16 runs). Table 7 shows a summary of the input values. The 1001 simulated annual building energy consumption data (E) were regressed against the 12 input parameters as follows:

$$
\begin{aligned}
E(\text{in MWh}) = {} & A + B_1x\text{WU} + B_2x\text{WINU} + B_3x\text{SC} + B_4x\text{WWR} \\
& + B_5x\text{EQ} + B_6x\text{LL} + B_7x\text{FA} + B_8x\text{SST} + B_9x\text{WST} \\
& + B_10x\text{FE} + B_11x\text{COP} + B_12x\text{BE} \qquad (2)
\end{aligned}
$$

Table 8 shows a summary of the regression coefficients (i.e. A and B_i) and relevant statistics (see Tables 3–5 for details of the abbreviations and corresponding units used for the design variables). It can be seen that 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 changes in the 12 parameters. It seems that warmer climates in the south tend to have strong correlation between the annual building energy use and the design parameters with smaller standard errors. The negative coefficients indicate an inversely proportional relationship between the annual building energy use and the design variables. It was found that window *U*-value and boiler efficiency for Hong Kong were statistically insignificant. This is consistent with the fact that the net annual heat gain/loss through the windows tends to be small and is not included in the local building energy code (i.e. overall thermal transfer value (OTTV) control) [22]. Moreover, winter is short and mild in subtropical Hong Kong, and heating requirement is small. These two parameters were, therefore, excluded from the regression model for Hong Kong.

6. Random inputs and model evaluation

To get an idea about performance of the regression models, an independent set of simulation results was used. Twenty simulation

Table 8
Summary of the multiple regression coefficients and relevant statistics for the 5 cities.

City	Regression coefficient													R^2	Standard error (MWh)
	A	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}		
Harbin	5677	284.6	359.8	200.9	3691.3	84.9	83.5	285.7	−173.6	164.4	−27.6	−226.7	−19.8	0.89	304
Beijing	8836	401.0	151.5	615.4	3490.0	121.0	114.1	136.2	−245.6	88.1	−40.7	−378.9	−3.4	0.96	159
Shanghai	8349	310.5	82.4	1211.4	2236.5	130.2	125.9	109.1	−247.3	70.7	−31.1	−384.9	−0.3	0.96	155
Kunming	9247	133.2	−34.4	1790.9	1840.9	141.7	140.2	38.9	−278.3	52.0	−36.2	−296.4	−0.5	0.97	145
Hong Kong	13,378	261.4	–	2198.3	1194.8	144.2	143.3	105.9	−334.6	16.3	−43.4	−551.1	–	0.96	169

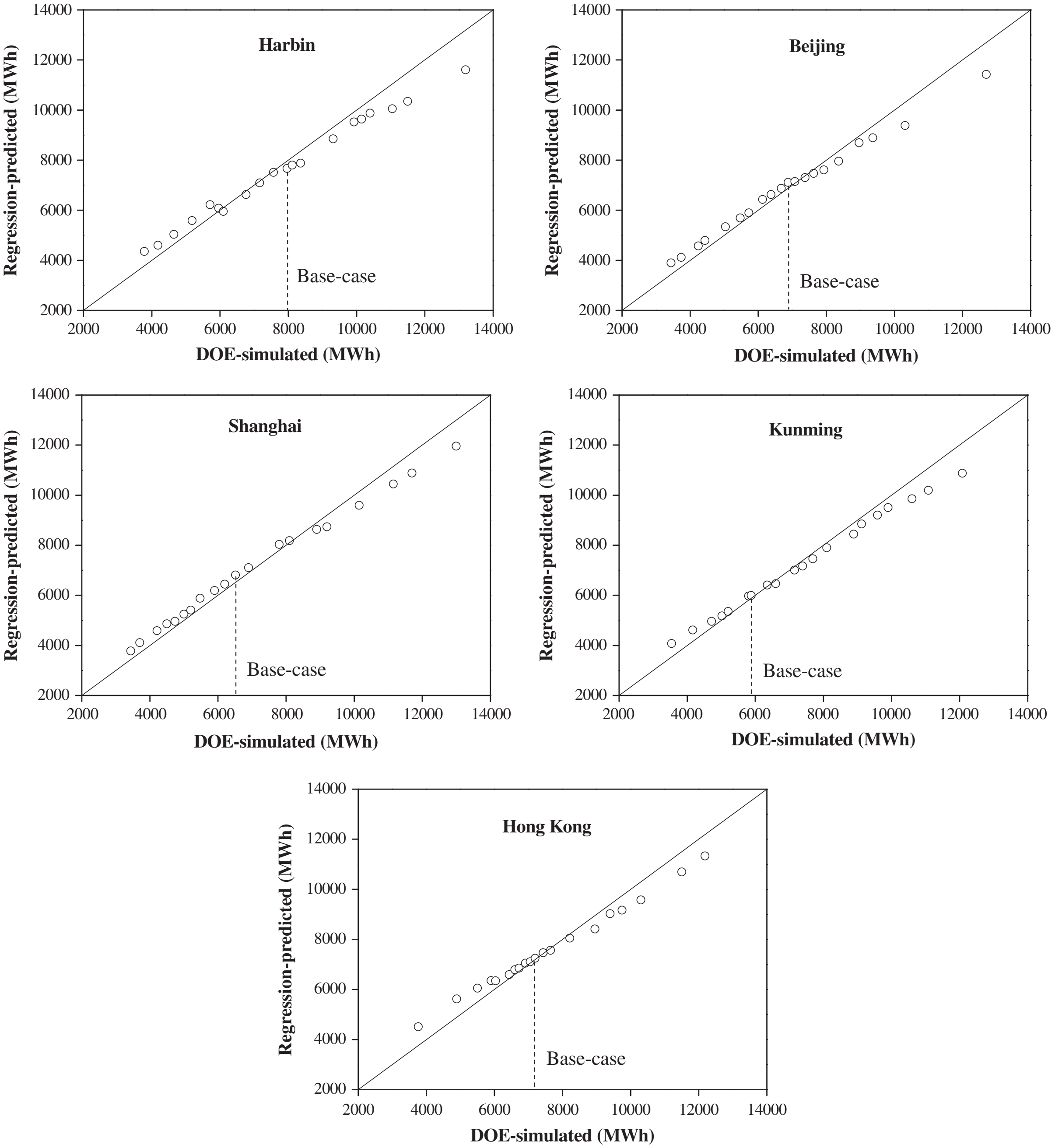

Fig. 1. Comparison between regression-predicted and DOE-simulated annual building energy use based on the 20 sets of random inputs.

runs were conducted for each city. A random numerical experiment was carried out to generate 20 sets of input design parameters for the simulation exercise. A set of random numbers is a set of numbers for which knowledge of any subset of the numbers will not tell people with certainty the value of the next one sampled from the set. The random experiment methods are also called

Monte Carlo methods, and the procedures which produce the random quantities are called random number generators (RNGs) [39]. The pseudo-random number generator based on the three simple multiplicative congruential generators developed by Wichmann and Hill [40] was adopted for this study, and executed through Microsoft's Excel Spreadsheet [41]. These 20 sets of randomly generated input variables represented 20 different designs independent of those used in the development of the regression models. These 20 sets of input were checked for: (i) inconsistency (e.g. the randomly generated combinations of window *U*-value and shading coefficient were feasible), (ii) within the same ranges as those used in the parametric and sensitivity analysis shown in Tables 3–5, and (iii) not the same as any of those involved in the regression models. Fig. 1 compares the DOE-simulated annual total building energy consumption with those from the regression models. All five cities show both underestimation and overestimation. In general, regression model data tend to follow quite closely those from the simulation, especially near the base-case design. The deviations are largely within 10%. Harbin appears to have slightly larger data scattering. It is envisaged that the regression models developed can be used to estimate the likely energy savings/penalty associated with certain design changes during the initial design stage when different building schemes and design concepts are being considered.

7. Conclusions

There is a growing concern about energy use in China. With rapid building development programmes and improvements of the living conditions, building sector is and will continue to be a major energy end-user. An attempt was made to develop simple 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 changes in the 12 parameters. It seems that warmer climates in the south tend to have strong correlation between the annual building energy use and the design parameters with smaller standard errors. 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%. We believe these simple regression models developed can be used for comparative energy studies to estimate the likely energy savings/penalty during the initial design stage when different building schemes and design concepts are being considered.

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