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Sensitivity Analysis of Energy Performance of Office Buildings

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The sensitivity of energy performance of office buildings in Hong Kong is examined. Basic principles of sensitivity methods for the study of building energy performance are explained. The DOE-2 building energy simulation program is used on a generic model of an office building to generate data for the study. Important input design parameters are identified and analysed from points of view of annual building energy consumption, peak design loads and building load profiles. It is believed that sensitivity techniques are useful for assessing thermal responses of buildings and data variability in building energy simulation. However, the results should be interpreted in context with clear understanding of the implications and limitations.

1. INTRODUCTION

ELECTRICITY use in commercial buildings accounts for about one-third of the total energy consumption in Hong Kong [1] and fully air-conditioned high-rise office buildings are important commercial electricity end-users. Study of the factors affecting energy performance of office buildings and the energy characteristics of the building systems is essential for a better understanding of energy-conserving design principles and operational strategies. With the help of computer programs for detailed building energy simulation, it is now possible to examine these factors extensively and systematically through the use of computer modelling techniques [2].

When performing building energy simulations, certain energy changes from the input variables are more significant than others, implying that selected inputs should be given particular attention during modelling [3]. Also, high-sensitivity elements are important from both technical and economic points of view and should be designed with utmost care if optimization of the system performance is to be achieved. Therefore, a great deal of engineering work is devoted to testing the sensitivity of systems [4]. These studies are collectively called sensitivity analysis and may involve a range of different analytical methods.

Sensitivity theory has been used for assessing the thermal response of buildings and their energy and load characteristics [5–9]. The aim of sensitivity analysis is to observe the system response following a modification in a given design parameter [8]. For example, one may want to know to what extent building loads and energy consumption are responsive to changes in the coefficients of material properties, design of building envelope, selection and operation of heating, ventilation and air-conditioning (HVAC) systems, and so on. If we can understand the relationships and relative importance of these parameters, we will be able to achieve optimum building energy performance through proper selection of design variables and conditions.

However, there are no formal rules and well-defined procedures for performing sensitivity analysis for building design because the objective of each study may be different and building descriptions are quite complicated. In most cases, perturbation techniques and sensitivity methods are being used to study the impacts of input parameters on different simulation outputs, as compared to a base case situation. Then, the results are interpreted and generalized so as to predict the likely responses of the system.

The concept is simple and straightforward but a clear understanding of what sensitivity analysis can do for building energy studies and how the results should be interpreted is very important. Study of the background theory can provide us with a better picture of the sensitivity figures and their implications. In this paper the sensitivity of energy performance of office buildings in Hong Kong is examined. A detailed building energy simulation program has been used on a generic model of an office building to generate simulation data for the study. Important input design parameters of the building systems are identified and analysed from the points of view of annual building energy consumption, peak design loads and building load profiles. The purposes of the analysis are as follows.

(a) To assess the significance and impact of input design parameters.
(b) To identify important characteristics of the input and output variables.
(c) To examine data variability and to assist error analysis of simulation outputs.
(d) To study the responses of building systems to perturbations.

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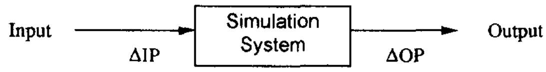


Fig. 1. Input–output analysis of simulation system.

2. METHODOLOGY

Sensitivity is a general concept. If a parameter A causes a change in another parameter B and we can measure the change of both, we can determine the sensitivity of A with respect to B. In the simplest terms, the aim of sensitivity analysis is to compare quantitatively the changes in output with the changes in input. Thus, it can also be considered as an 'input–output analysis' of the simulation system [3], as shown in the simple diagram in Fig. 1.

2.1. *Sensitivity coefficients*

As a measure of the sensitivity, a sensitivity coefficient is often used in the fields of mathematics and controls engineering, as in [4, 10]. In economics, the concept of elasticity is employed to measure the sensitivity and responsiveness of a system [11]. For thermal system and building energy simulation, the term influence coefficient (IC), which is defined by the partial derivatives of output and input, has been used [12, 13], and it is defined as follows:

$$IC = \frac{\text{change in output}}{\text{change in input}} = \frac{\partial OP}{\partial IP} \approx \frac{\Delta OP}{\Delta IP}, \qquad (1)$$

where OP is the output and IP is the input; the last two terms in the above equation are the partial derivative and the ratio of simple difference respectively.

If only one step change is used to calculate the sensitivity, the influence coefficient in equation (1) will be determined as follows by two sets of data:

$$IC = \frac{\Delta OP}{\Delta IP} = \frac{OP_1 - OP_2}{IP_1 - IP_2}, \qquad (2)$$

where OP_1 and OP_2 are the output values and IP_1 and IP_2 are the corresponding input values.

If more perturbations are used in the analysis, the influence coefficient can be determined from the slope of the regression straight line for the data. It should be noted that if the correlation between the output and input variables is not a linear function, the sensitivity (or the slope) will vary from point to point.

Sensitivity coefficients may be determined on the basis of any number of the simulation results [13]. Even using the same output results, the sensitivity coefficient may be expressed in various forms. Five different forms of sensitivity coefficient are shown in Table 1 and they are categorized into three main groups as indicated by the numberings (1, 2 and 3) in the table. The first group, which is the simplest one, is the same as that defined in equation (1). The second group makes use of the base case value to express the sensitivity in percentage change whereas the third group takes the mean values to express the percentage change. Forms (2a) and (3a) in Table 1 are also known as point elasticity and arc midpoint elasticity in economics [11]. When calculating for form (3b), the slope of the linear regression line divided by the ratio of the mean output and mean input values will be taken for determining the sensitivity coefficient.

Form (1) is often used in comparative energy studies because the coefficients so calculated can be used directly for error assessment. Forms (2a), (3a) and (3b) have the advantage that the sensitivity coefficients are dimensionless values expressed in percentage. However, form (3a) only applies to one-step change and cannot be used for multiple sets of data. It is believed that forms (1), (2a) and (3b) are most useful for the assessment of sensitivity using building energy simulation methods. Whichever form is chosen, the sensitivity coefficients should be

Table 1. Different forms of sensitivity coefficient

Form	Formulae	Dimensions	Common name(s)
1	$\frac{\Delta OP}{\Delta IP}$	with dimension	Sensitivity coefficient, influence coefficient
2a	$\frac{\Delta OP \div OP_{BC}}{\Delta IP \div IP_{BC}}$	$\frac{\%\ OP\text{ change}}{\%\ IP\text{ change}}$	Influence coefficient, point elasticity
2b	$\frac{\Delta OP \div OP_{BC}}{\Delta IP}$	with dimension	Influence coefficient
3a	$\frac{\Delta OP \div \left(\frac{OP_1 + OP_2}{2}\right)}{\Delta IP \div \left(\frac{IP_1 + IP_2}{2}\right)}$	$\frac{\%\ OP\text{ change}}{\%\ IP\text{ change}}$	Arc mid-point elasticity
3b	$\left(\frac{\Delta OP}{\Delta IP}\right) \div \left(\frac{\overline{OP}}{\overline{IP}}\right)$	$\frac{\%OP\text{ change}}{\%\ IP\text{ change}}$	(see note 2)

1. ΔOP, ΔIP = changes in output and input respectively.
OP_{BC}, IP_{BC} = base case values of output and input respectively.
IP_1, IP_2 = two values of input.
OP_1, OP_2 = two values of the corresponding output.
$\overline{OP}$, $\overline{IP}$ = mean values of output and input respectively.
2. For the form (3b), the slope of the linear regression line divided by the ratio of the mean output and mean input values will be taken for determining the sensitivity coefficient.

defined clearly to avoid confusion and misunderstanding, especially when they are in a dimensionless form.

2.2. *Background theory*

Real problems often include more than one variable. The output result (OP) which forms the basic criterion of the analysis can be expressed in general by the multi-variable function f with n numbers of depending variables, like this:

$$OP = f(x_1, x_2, \ldots, x_n). \tag{3}$$

By using the chain rule of partial differentiation, its differential is given by

$$\mathrm{d}f = \frac{\partial f}{\partial x_1}\mathrm{d}x_1 + \frac{\partial f}{\partial x_2}\mathrm{d}x_2 + \cdots + \frac{\partial f}{\partial x_n}\mathrm{d}x_n. \tag{4}$$

The gradient of the function for parameter x_1 can be expressed as

$$\frac{\mathrm{d}f}{\mathrm{d}x_1} = \frac{\partial f}{\partial x_1} + \frac{\partial f}{\partial x_2}\cdot\frac{\mathrm{d}x_2}{\mathrm{d}x_1} + \frac{\partial f}{\partial x_3}\cdot\frac{\mathrm{d}x_3}{\mathrm{d}x_1} + \cdots + \frac{\partial f}{\partial x_n}\cdot\frac{\mathrm{d}x_n}{\mathrm{d}x_1}. \tag{5}$$

If x_1 is independent of $x_2, x_3, \ldots, x_n$, then

$$\frac{\mathrm{d}x_2}{\mathrm{d}x_1} = \frac{\mathrm{d}x_3}{\mathrm{d}x_1} = \cdots = \frac{\mathrm{d}x_n}{\mathrm{d}x_1} = 0. \tag{6}$$

By substituting equation (6) into equation (5), therefore, the partial derivatives of x_1 may be approximated by the simple differential

$$\therefore \frac{\mathrm{d}f}{\mathrm{d}x_1} = \frac{\partial f}{\partial x_1}. \tag{7}$$

This simple but essential axiom forms the basis of sensitivity methods and permits the use of numerical approximations for estimating complicated partial derivatives. Equality of the above equation holds as long as the difference from the base case value is not very large. If the difference is large, then the approximation may not be accurate enough.

Basically, sensitivity analysis is a kind of technique developed in optimization methods and mathematical programming [14]. The basic optimization problem in mathematics is to minimize a scalar quantity which is the value of a function (the objective function) of a certain number of system parameters, whereas the usual aim of sensitivity study on building energy performance is to minimize building energy consumption and to achieve the best load and energy characteristics with respect to input design variables. The case of building thermal design and energy analysis is a constrained optimization because there are often limitations (physical, practical and economical) on the input design variables. For example, Bouchlaghem and Letherman [15] described the thermal design of buildings as a multi-variable optimization problem with a non-linear objective function and linear constraints on the variables.

In theory, the problem statement can be translated into a practical problem definition if the variables involved can be determined explicitly or implicitly. However, for building systems, descriptions and relationships are so abstract and complicated that simple mathematical relationships are not adequate for their representation. For instance, it is difficult to find a simple relationship linking the building energy performance to the window area and to the type of air-conditioning system. There are also some other factors in the simulation system which are only vaguely defined [12], such as the control mechanism. Therefore, the problem definition for a building energy study, except in some very simple cases, cannot be stated out clearly. Unlike mathematical problems, energy modelling is usually carried out abstractly [16]. Nevertheless, it is not to say that analysis in building simulation cannot be quantified unambiguously. The essence of doing sensitivity analysis for building simulation is not only quantitative in nature but should also involve understandings of the simulation process and the practical implications.

2.3. *Techniques for sensitivity analysis in building simulation*

To model a building by computer simulation methods, specific building data have to be formulated and supplied to the simulation program. The sensitivity study is so designed that specific building data are the same in the whole of the simulation input except for the input parameter under concern. As a result, the difference in simulation results can be interpreted as having only been caused by the change in that input parameter. The general approach suggested by Spitler *et al.* [13] has been used and expanded here for the present study. The procedure is summarized as follows.

(a) Formulate a base case reference and its descriptions.
(b) Study and break down the factors into basic parameters (parameterization).
(c) Identify parameters of interest and find out their base case values.
(d) Determine what simulation outputs are to be investigated and their practical implications.
(e) Introduce perturbations to the selected parameters about their base case values one at a time.
(f) Study the corresponding effects of the perturbation on simulation outputs.
(g) Determine the sensitivity coefficients for each parameter if appropriate.

The above procedure is pretty standard and can be automated on a simulation tool to facilitate the analysis [9]. However, many people making sensitivity analyses are not fully aware of the fact that the usefulness of the results hinges on the selection of output and the adequacy of the simulation model. Usually not all useful simulation outputs have been examined and compared during the analysis.

Energy performance itself is a general and abstract concept which has different meanings for different people. The choice of objective function will be governed by the nature of the problem and it is one of the most important steps in the optimization of building design. There are different forms of results from different stages of the simulation. The simulation output chosen for an energy study often depends on the application and the simulation methods adopted. In many cases, the criteria are the annual building energy consumption and the peak cooling and heating loads. The target is to minimize consumption of energy by adopting a proper set of design variables for the system. It is of course possible to optimize the system for a different criterion such as life-cycle costs of the building if sufficient information and relationships can be established accordingly.

The present study focuses on the factors which are essential to the design of office buildings in Hong Kong. The analysis was designed and done in the context of the subtropical climate in Hong Kong. The results and interpretations will be specific under these limitations. Nevertheless, it is believed that the approach can be extended to other building types at different locations, and with other simulation tools. General characteristics can then be established through comparisons and evaluations among different models. The most important thing is to understand the basic principles and to quantify, with reasons, the relative importance and impact of input parameters to the output results selected.

2.4. *Computer-based building energy simulation*

Computer-based building energy simulations are becoming more and more popular. Energy performance of dynamic building systems can be assessed using detailed computer simulation programs so that designers can adopt a prototype and test approach for selection of appropriate design options [16]. Detailed building energy simulation programs incorporate sets of mathematical models that seek to explain quantitatively how each component of a building behaves under given circumstances. Modelling and calculations of load and energy characteristics of the building are performed hour-by-hour for all the 8760 hours in a year. Then, the year-round energy consumption and loads are determined from the simulation results.

The simulation tool employed in the present study is the DOE-2.1D building energy simulation program from Lawrence Berkeley Laboratory [17]. It has been used in many parts of the world for analysing energy consumption and conservation measures in buildings. The DOE-2 program is chosen because it can offer great capability for simulating a wide range of design features and energy conservation measures and it has been validated for accuracy and consistency [18]. Although the simulation program can perform energy modelling with good accuracy and detail, it is a rather complicated and error-prone process to carry out such a large number of simulation runs because there are huge numbers of data to be handled and analysed. To ensure robustness and consistency, the simulation and analysis process has been automated and standardized [2]. Great care has been taken to first develop the model building in a simplified form and then to refine the building descriptions to more detail.

2.5. *Base case model and weather data*

The base case model forms a very important part in the analysis because all subsequent calculations and analyses are based on the comparison with it. A base case office building has been established from a pilot survey and study of local construction and engineering practices in Hong Kong [19]. The descriptions of this base case model were determined by careful selection of typical design and construction. References have also been made to energy simulation studies carried out in other countries with a climate similar to Hong Kong, such as those in Singapore [20, 21]. Brief descriptions of the base case building are given in Table 2 and the plan and section of it are shown in Fig. 2. It is expected that the base case model can represent a typical high-rise office building in the urban district of Hong Kong.

Apart from the building descriptions, another important factor in building simulation is the external weather data. In order to provide weather data for the analysis, a weather database has been established by compiling weather files from the raw weather data collected from the local weather station in Hong Kong. The year 1989 was found to be representative of the prevailing weather conditions in Hong Kong and it has been selected as the Test Reference Year (TRY) of Hong Kong [22]. Weather data for the year 1989 are therefore taken in this comparative study for all the building energy simulations.

3. RESULTS

Careful selection of input parameters and correct interpretations of simulation output are important for obtaining meaningful results. Like many other building energy simulation programs, the DOE-2 program adopts a sequential modelling strategy which executes the loads subprogram, the systems subprogram and the plant subprogram consecutively for every hour of the simulation [17]. Different kinds of cooling, heating and electrical demands are reported from the subprograms. The output results selected for the present study are the loads and energy requirements of the primary HVAC system after plant simulation because they can represent the final energy end-use of the building. Three kinds of simulation output are chosen here for the sensitivity analysis, as follows.

- Annual building energy consumption.
- Peak design loads.
- Load profiles of electrical demand and cooling loads.

3.1. *Parameterization*

Before performing the analysis, it is essential to understand what input parameters are to be studied. A list of the input parameters was prepared and they represented a variety of different factors encountered in building design. There are all together about 60 input parameters and they are categorized into three main groups as follows.

- Building load.
- HVAC systems.
- HVAC refrigeration plant.

Each of the three main groups can also be sub-divided into different sub-groups as shown in Fig. 3. By categorizing the input design parameters, a clear picture of the energy-related factors can be established.

Selecting and defining the input parameters is often a difficult task that requires good engineering judgement and good knowledge of the simulation system. Breakdown of the parameters is worked out according to the

Table 2. Brief descriptions of base case office building

Location:	Hong Kong (latitude 22.3°N, longitude 114.2°E)
Building type and storeys:	Office building, 40 storeys above ground
Floor areas:	Total gross floor area = 49,000 m^2 Air-conditioned area = 41,160 m^2
Dimensions and heights:	35 m × 35 m (square); floor-to-floor = 3.4 m; window height = 1.5 m; window-to-wall ratio = 0.44

Constructions of building envelope:
(a) External walls (spandrel portion of curtain wall)—6 mm glass + 25 mm airspace + 19 mm plywood + wall paper
(b) Roof—13 mm slag + 10 mm roof build-up + 50 mm roof insulation + 200 mm h.w. concrete + ceiling void + 19 mm ceiling panel
(c) Windows—6 mm reflective single glazing (SC = 0.4, U-value = 5.6 W/m^2 K)

Constructions of internal structure:
(a) Floor (typical middle floor)—carpet + 50 mm screeding + 150 mm l.w. concrete + ceiling void + 19 mm ceiling panel
(b) Internal core wall—5 mm mosaic tile + 19 mm plaster + 200 mm h.w. concrete + 19 mm plaster + wall paper
(c) Internal partitions—16 mm gypsum board + 25 mm airspace + 16 mm gypsum board

Operating hours: Mon. to Fri.—0900 to 1700 hr; Sat.—0900 to 1300 hr;
Sun. and holidays—closed

HVAC design parameters:
(a) Building load
—Occupancy density = 5 m^2/person
—Lighting load = 20 W/m^2; equipment load = 15 W/m^2
—Infiltration = 0.6 air change per hour
—Space design temperature = 25.5°C
(b) HVAC system
—Outdoor air flow = 7 l/s per person
—Throttling range = 1.1°C
—Night setback: cooling = 37°C; heating = 10°C
—HVAC system type = VAV reheat
(c) HVAC plant and equipment
—Type: packaged air-cooled reciprocating chillers
—Chiller COP (kWr output/kWe input) = 2.93

input building description language of the DOE-2 program so that maximum effectiveness and compatibility can be achieved. It is expected that a similar procedure of parameterization can also be carried out on other simulation tools as well so that comparisons can be made.

After determining the design variables to be studied, perturbations were introduced by assigning a range of different values to each of the input parameters, one at a time. The change in the parameter may represent a certain energy-efficient measure proposed for the building for achieving energy conservation and control purposes. For example, changing the design of the window system which involves parameters like shading coefficient, window-to-wall ratio and window U-value can reduce cooling energy use from the envelope load.

The tables in the Appendix show the input parameters, their base case values and the number of perturbations performed. Some input parameters are numerical in nature while some are not. For example, the shading coefficient of windows is a numerical figure from 0 to 1 whereas the type of air-conditioning system is non-numerical and abstract in nature. For numerical parameters, their possible ranges of perturbations are selected from common engineering and design practice. A total of about 400 simulations have been performed. The sensitivity and correlation between the simulation

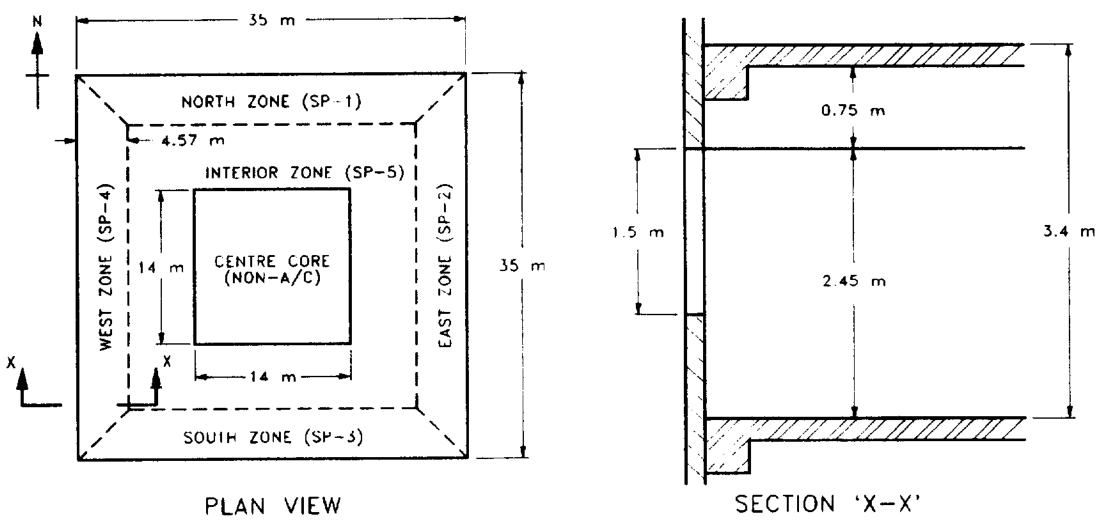


Fig. 2. Plan and section of base case building (typical floor).

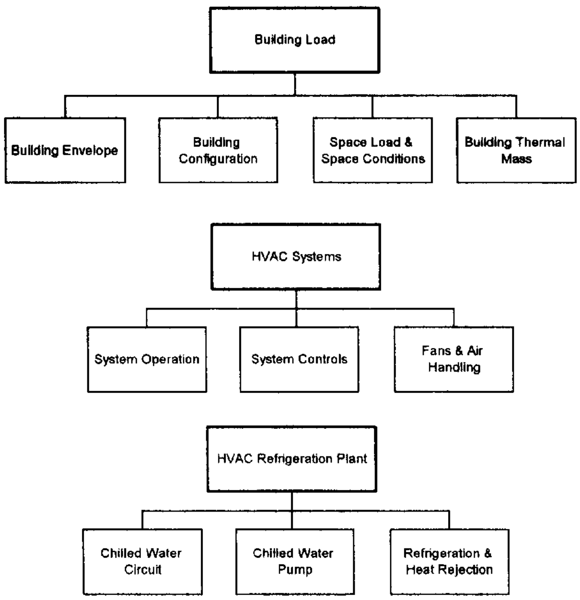
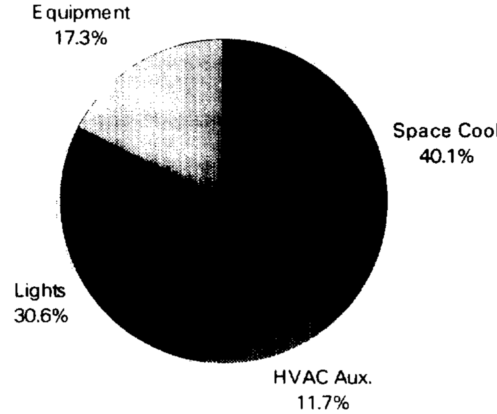


Fig. 3. Parameterization of input parameters.



Note: Space heat not shown in the chart, is at 0.3% only.

Fig. 4. Components in annual building energy consumption for base case model.

outputs and each of the input parameters have been examined.

3.2. *Sensitivity on annual building energy consumption*

The simulation output of interest is the total building electricity consumption in MWh (megawatt-hours), which is given at the very end of the simulation results. Annual building energy consumption in kWh/m^2 per annum can be calculated by dividing the building MWh figure by the total gross floor area of the building. It is an indicator of the whole building energy performance and is often the most significant factor of interest to building energy analysts. This annual figure serves to set out a 'consumption target' for the building as a whole, which allows trade-offs among different building subsystems. The total MWh can be broken down into five components according to the simulation results of the DOE-2 program, as follows.

- Space cooling (chiller).
- Space heating.
- HVAC auxiliary (pumps, fans).
- Lighting.
- Equipment.

Figure 4 shows a breakdown of the above components for the base case model. It can be seen that energy demands related to the air-conditioning system are the most important elements. Cooling energy requirements dominate the building energy consumption at 52% (space cooling + HVAC auxiliary) and heating energy use is relatively insignificant, only 0.3%. It can also be observed that the internal electric loads such as lighting and equipment are very important and have accounted for about 48% of the total electricity consumption in the building. These components are affected by the load schedules, design load intensities and year calendar taken in the simulation. Because the HVAC system has to remove all these heat gains from the conditioned space, the real influence of the internal loads is even greater than this. 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 annual building energy consumption.

The input–output characteristics of the building MWh can be studied by looking at the sensitivity coefficients and the correlations. Sensitivity coefficients calculated for the annual MWh for some important parameters are summarized in Table 3. Three forms of sensitivity coefficient as discussed before in Table 1 are calculated and the coefficients of determination (R^2) for linear regression for the correlation of the input parameters are also provided. It can be seen that the important parameters in Table 3 have a strong linear relationship with the building energy consumption.

Correlations for some of the input parameters for building envelope design are shown in Figs 5–7. Some interesting results are explained in the following. Firstly, it can be seen from Fig. 5 that the annual MWh decreases exponentially with the increase in projection ratio of the external shading devices (overhangs, side-fins and egg-crates). External shading up to a projection ratio of about 1.5 is an effective measure for energy-conserving design. Secondly, the regression straight lines in Fig. 6 indicate that variables for the design of window system have significant influence on annual building energy consumption. Thirdly, the correlations with the U-values of building structure as shown in Fig. 7 vary a lot for different building components. For instance, the annual MWh increases with increase in U-value of opaque wall but decreases with increase in U-value of windows. This suggests that care should be taken to select a combination of envelope design which will optimize the energy performance of the building envelope.

3.3. *Sensitivity on peak design loads*

The simulation outputs of interest are the peak building electrical load (in kW) and the peak cooling and heating loads (in kW). Peak design loads determine the maximum demands and hence the equipment sizes and capacities required for the systems. Initial costs and operating strategies of the building system will be affected directly by the maximum demands, even though the

Table 3. Sensitivity coefficients for annual electricity MWh for important parameters

Abbreviation	Input parameter	Sensitivity coefficients for annual elec. MWh* Form (1) (MWh per input unit)	Form (2a) (% *OP* per % *IP*)	Form (3b) (% *OP* per % *IP*)	Coefficient of determ. R^2 for linear regression
1. *Building load*					
SC	shading coefficient of windows	1670	0.083	0.099	0.997
WR	window-to-wall ratio	1101	0.060	0.069	0.996
AT	space air temperature (°C)	−44.2	−0.140	−0.138	0.996
EQ	equipment load (W/m^2)	135	0.252	0.251	1.000
LL	lighting load (W/m^2)	168	0.418	0.349	1.000
OC	occupancy density (psn/m^2)	8453	0.210	0.308	1.000
2. *HVAC system*					
OA	outdoor air flow rate (l/s per psn)	131	0.114	0.151	0.996
TS	summer therm. setpoint (°C)	−283	−0.900	−0.851	0.981
FE	fan efficiency†	640	0.145	0.234	1.000
FS	fan static pressure (Pa)	0.869	0.148	0.177	1.000
3. *HVAC refrig. plant*					
CH	chw. supply temperature (°C)	−164	−0.136	−0.131	0.931
CP	chiller coeff. of performance (kWr output/kWe input)†	8560	0.363	0.350	1.000

* Please refer to Table 1 for definition of the different forms of sensitivity coefficient.
† The inverses of FE and CP were used for determining the sensitivity coefficients and performing linear regression.

annual building energy consumption remains unchanged. The peak design loads serve to set out a 'demand target' for the building and the information is especially important for load and demand management (e.g. for determining the configuration of HVAC plant and for assessing the potential of using thermal energy storage).

The sensitivity coefficients calculated for peak design loads are given in Table 4. They can be used for predicting the impacts of each parameter on the respective maximum demand and equipment capacities. However, designers should use them cautiously because the determination of equipment and plant sizes often has to take into account factors other than maximum demands. For instance, standby capacities, safety margins and nominal ratings of equipment have to be considered.

Figure 8 shows the sensitivity of peak building electrical kW and annual MWh against the change in floor weight. It can be seen that the two correlations are similar to each other. Both peak kW and annual MWh decrease with increase in the weight of the floor slab because of the effect of thermal mass of the building structure. In fact, by comparing Table 4 with Table 3, it can be seen that the sensitivity of the peak kW has similar patterns as that of the annual MWh.

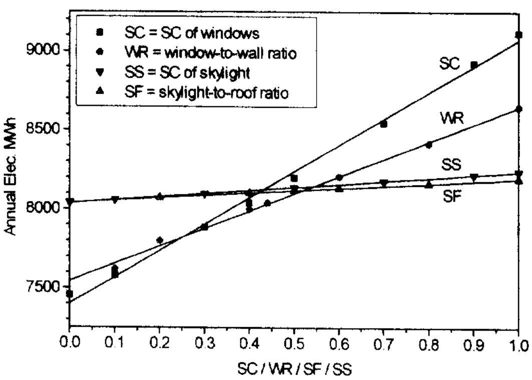


Fig. 6. Effects of window design on annual electricity MWh.

Unlike the annual MWh energy, peak design loads are affected by the coincidence of block loads. By looking at

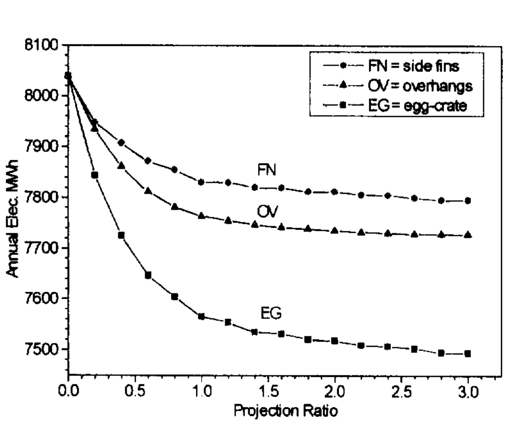


Fig. 5. Effects of external shading on annual electricity MWh.

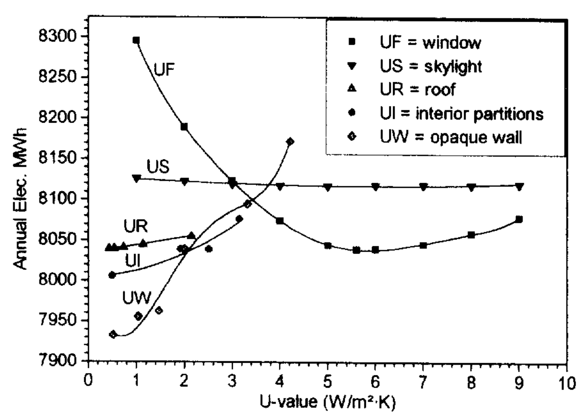


Fig. 7. Effects of U-values on annual electricity MWh.

Table 4. Sensitivity coefficients for peak electricity kW for important parameters

Abbreviation	Input parameter	Sensitivity coefficients for peak elec. kW* Form (1) (kW per input unit)	Form (2a) (% *OP* per % *IP*)	Form (3b) (% *OP* per % *IP*)	Coefficient of determ. R^2 for linear regression
1. *Building load*					
SC	shading coefficient of windows	1210	0.112	0.132	0.993
WR	window-to-wall ratio	812	0.082	0.094	0.995
AT	space air temperature (°C)	−32.4	−0.190	−0.187	0.982
EQ	equipment load (W/m^2)	63.6	0.220	0.218	0.998
LL	lighting load (W/m^2)	62.7	0.289	0.232	0.999
OC	occupancy density (psn/m^2)	7114	0.328	0.445	1.000
2. *HVAC system*					
OA	outdoor air flow rate (l/s per psn)	146	0.236	0.297	0.994
TS	summer therm. setpoint (°C)	−98.3	−0.580	−0.551	0.932
FE	fan efficiency†	367	0.154	0.247	1.000
FS	fan static pressure (Pa)	0.491	0.155	0.185	1.000
3. *HVAC refrig. plant*					
CH	chw. supply temperature (°C)	−19.1	−0.029	−0.029	0.830
CP	chiller coeff. of performance (kWr output/kWe input)†	6602	0.519	0.503	0.997

*Please refer to Table 1 for definition of the different forms of sensitivity coefficient.
†The inverses of FE and CP were used for determining the sensitivity coefficients and performing linear regression.

the hourly values of individual load components, it is found that not all the load components peak and coincide at the same time and by the same hour. Most of them tend to peak in the summer months and the peak time of the building is often dictated by the external weather conditions. The effect of external weather on peak design loads is obvious in this case. If there are some extremities in the weather data file, they are very unlikely to be reflected in the peak design loads. This can be a good indicator for the selection and assessment of typical weather conditions for the purpose of building energy simulation.

If the objective and decision criteria of the building energy study are more on initial costs of the systems, then the peak design loads should be a priority area for analysis. In addition to peak design loads, decisions on load and energy demand management for a comprehensive approach to total building energy management will also require further information about the load profiles and their characteristics.

3.4. *Sensitivity on load profiles*

The simulation outputs of interest are the monthly and hourly profiles of electrical MWh and cooling loads. These load profiles provide information on the seasonal behaviour and part-load performance of the building systems. By examining the profiles of energy use, thermal response of a building at a detailed level can be studied. It is believed that these investigations can offer us information that is not available from the studies of annual building MWh and peak kW. However, greater efforts are required to extract and analyse the load profiles obtained from the simulation results. Results from the study of monthly MWh profiles are illustrated in Figs 9–14. For building loads, Figs 9 and 10 show the profiles for SC (shading coefficient) and WR (window-to-wall ratio) respectively. For the HVAC system, Figs 11 and 12 show the profiles for outdoor air flow rate (OA) and cooling thermostat setpoint (TS) respectively. For HVAC refrigeration plant, Figs 13 and 14 show the profiles for chilled water supply temperature (CH) and chiller COP (CP) respectively.

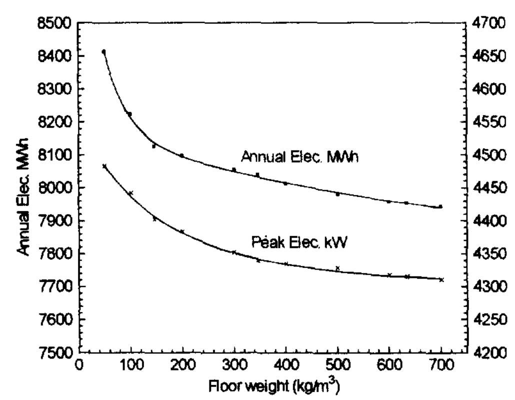


Fig. 8. Sensitivity of annual MWh and peak kW for floor weight.

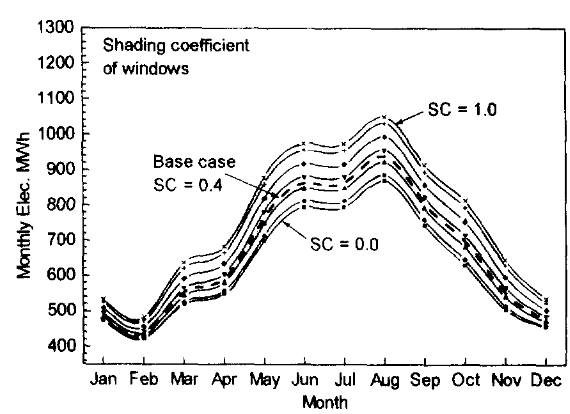


Fig. 9. Monthly MWh profiles for shading coefficient (SC).

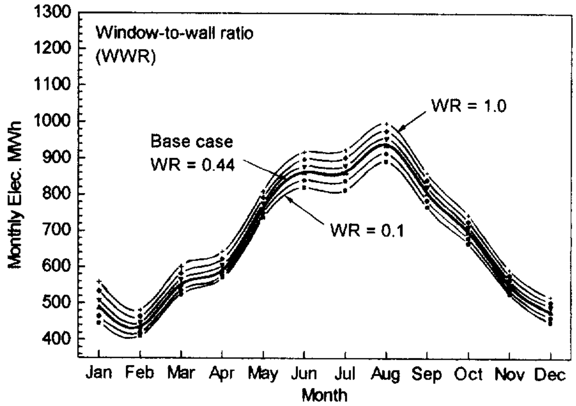


Fig. 10. Monthly MWh profiles for window-to-wall ratio (WR).

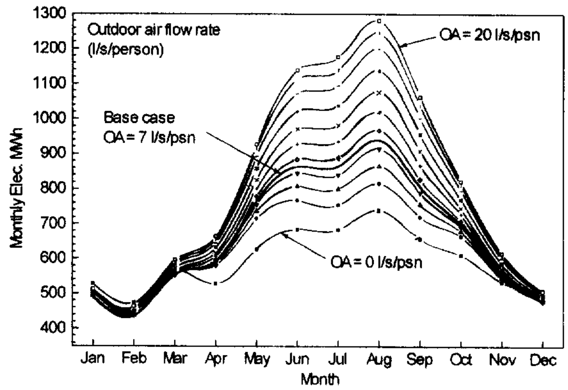


Fig. 11. Monthly MWh profiles for outdoor air flow rate (OA).

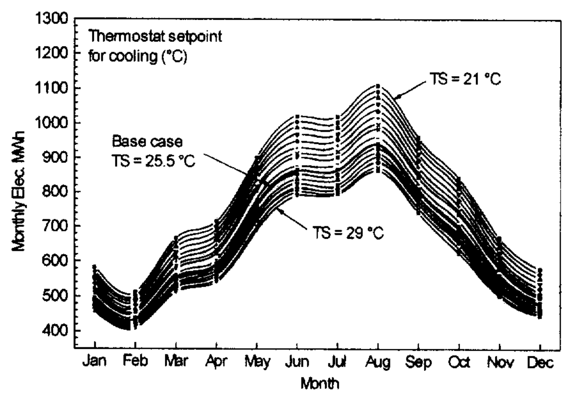


Fig. 12. Monthly MWh profiles for cooling thermostat setpoint (TS).

It can be seen that some input parameters have significant influence on the load profiles but the general shape (rises and falls) remains relatively constant in all the parameters. Some parameters affect the load profiles evenly throughout the whole year (e.g. window-to-wall ratio), whereas the effects of some other parameters may vary at different months of the year. For example, changes in OA and CP are more influential in summer months than in winter months because they mainly affect the cooling energy use in the hot summer. This suggests that the sensitivity may vary through the year and there are potentials for improving partload performance

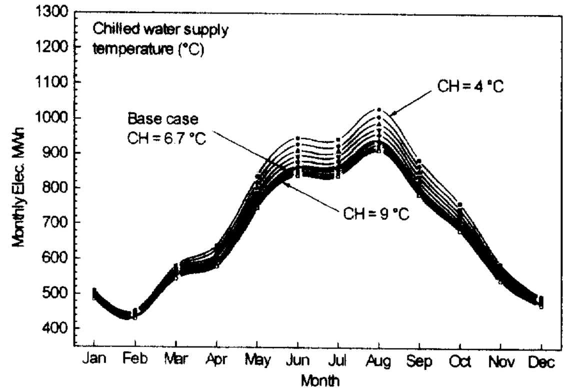


Fig. 13. Monthly MWh profiles for chilled water supply temperature (CH).

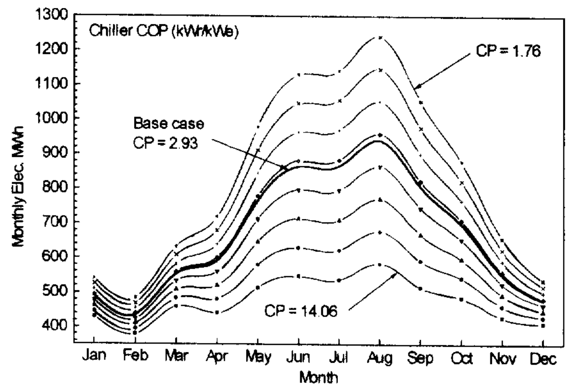


Fig. 14. Monthly MWh profiles for coefficient of performance of chiller (CP).

by controlling individual parameters at different times of the year.

Knowledge about the response of load profiles is also useful for visualizing the effects of the change during different times of the year. However, it is difficult to quantify and compare these effects because they are not single figures like the annual MWh and the peak kW. The computation of sensitivity coefficients is not valid in this case unless the profile can be prescribed by one of its statistical properties such as mean and variance. It is believed that quantitative analysis of load profiles will require different forms of techniques in the input–output analysis, such as time series and frequency response methods. More research work has to be done to integrate the mathematical and statistical techniques for the analysis of load profiles and time-varying variables in building simulation.

4. DISCUSSION

Sensitivity analysis is a tool for optimization and it can also offer useful information for gauging the accuracy of simulation. When integrated with building energy simulation methods, sensitivity techniques can be a powerful tool for the study of thermal response of buildings and error analysis.

4.1. *Significant parameters*

Input parameters with significant influence on the annual MWh and peak kW are identified and they include the following.

(a) For building load—occupant density, lighting load and equipment load are the most important. Other significant parameters include design variables of the window system and building envelope.
(b) For HVAC system—summertime thermostat setpoint, supply fan efficiency and fan static pressure are essential.
(c) For HVAC refrigeration plant—coefficient of performance (COP) of chillers, chilled water supply temperature, chilled water design temperature difference and chilled water pump impeller efficiency are influential.

It is important that direct comparison in strict quantitative terms of the sensitivity coefficients is not always feasible and fair because the parameters might have different dimensions, units of change and base case values (see Tables 3 and 4). The actual magnitude of the coefficients depends on the units in which the parameters are measured. Only if the input parameters are measured in the same units and are of the same nature are their coefficients directly comparable. When the parameters differ substantially in units, the sheer magnitude of their coefficients does not reveal anything about relative importance. Therefore, evaluation of the sensitivity coefficients should be carried out in context, with clear understandings of the physical and engineering implications.

It was found by Corson [3, 23] in his simulation studies that the building energy models were comparatively less sensitive to measures affecting the building envelope and lighting, and more sensitive to measures involving occupancy, weather, air supply, systems and plant. Part of his findings agree with those in the present study and this suggests that similar sensitivity properties of energy performance of office buildings can be found in different geographical locations.

4.2. *Error analysis and assessment of uncertainties*

Data used to model and interpret building energy performance are susceptible to variations and errors. The ability to perceive the accuracy of the results when the input data are subject to uncertainty or systematic errors is essential to the present-day building energy simulations. If we can see how input errors impact the results, the probable range of variability can be defined. Therefore, identification of data variability and possible errors is often a first step in improving the modelling input and hence the quality of the output estimates [23].

In many practical situations of building energy simulation, errors may arise from:

- modelling assumptions in simulation tool
- difference in calculation algorithms and modelling features
- form and accuracy of input descriptions.

Details of the building design often are not known at the early design stage when building energy estimations are performed. Selection of input data is therefore often based on assumptions made by the designer or modeller. The simulation results will be subject to a high degree of uncertainty as the total sensitivity and errors accumulate across the input variables. In theory specific errors may be compensating and offsetting one another, but for risk assessment purpose the errors are assumed all cumulative in nature. The more complex the model is, the greater the chance of multiple errors. Therefore, it is essential to assess and minimize the possible errors at every stage of the simulation if a more reliable result is to be achieved.

The sensitivity coefficients (output change over input change) can be used for this purpose and the errors in output can be estimated by this simple equation:

$$\text{errors in output} = (\text{estimated error in input}) \times (\text{sensitivity coefficient}). \quad (8)$$

4.3. *Thermal response of buildings*

People are interested in studying the thermal response of buildings because it can provide information about how the building reacts and how the various parameters interact when a given design parameter is altered. However, the precise relationships between the simulation outputs and the input design parameters usually cannot be explained analytically and explicitly because of the complex effects of couplings by building load, HVAC system and HVAC plant. Therefore, sensitivity methods and regression techniques are often employed for the thermal and energy analysis of buildings [2].

The input and output variables involved in the analysis are often isolated variables but, generally speaking, they might also be a time series which is a chronological sequence of observations on a particular variable. For example, study of the effects on load profiles (time series of load and energy use) in the simulation output and study of the sensitivity to climatological factors (time series of weather data) in the simulation input will involve time-varying variables. If a time series is involved, the sensitivity assessment will be more complicated and will require the use of mathematical and statistical techniques in time series analysis.

An attempt has been made in this study to examine the behaviours of the building load profiles under changes of the input parameters. It is believed that the investigations are of practical importance and have interesting implications because they can offer additional information for the thermal response of buildings and the seasonal characteristics of building energy flows. If it is possible to predict the change in load profiles by studying the simulation results in greater detail, we will be able to establish effective strategies for load and demand management.

Similarly, the variability of weather data on the input side can be examined by studying the sensitivity of the climatic variables in the weather file. However, the difficulty, also experienced by Buchberg [7], is that quantitative generalizations regarding the influence of external climate on the thermal behaviour of a building structure are very difficult, if not impossible, to make. Sensitivity analysis of building energy performance for time-varying variables will require an integration of time series techniques into building energy analysis. It is expected that this approach will be developed further as computing technology accelerates and building energy analysts strive for better accuracy and confidence for their simulations.

5. CONCLUSIONS

The beauty of sensitivity analysis lies in the fact that it helps designers spend their time where it matters most and it helps decision-makers determine how much they can rely on simulation predictions. Sensitivity analysis for building thermal design can provide insights about the building system as a part of the simulation process and can present opportunities for improved handling and analysis of data so that energy estimates can be improved and uncertainties can be quantified.

It has been found that the annual building energy consumption and peak design loads are sensitive to measures affecting internal loads, window system, temperature set-points and HVAC plant efficiencies. Sensitivity of both energy consumption and peak demand shows similar patterns and the sensitivity coefficients for each of them have been determined. Direct comparison of the sensitivity values in strict quantitative terms is not always practical and fair. Interpretations should be taken in context with clear understandings of the implications and limitations. Further research work is needed to examine the sensitivity of load profiles and weather data. To make the best use of sensitivity methods, designers should focus more on problem definitions, understanding of the sensitivity theory and better interpretation of the simulation results. It is believed that a 'sensitive' mind is important for understanding the building simulation system and the thermal response of buildings.

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APPENDIX

The following tables show the input parameters studied, their base case values and the number of perturbations performed. Tables A1, A2 and A3 give the data for the input parameters of building load, HVAC systems and HVAC refrigeration plant respectively.

Table A1. Base case values and perturbations for building load

Abbreviation	Input parameter	Unit	Base case	Perturbations Nos.	Min.	Max.
1.1. *Building envelope*						
AR	absorptance of roof	—	0.7	6	0	1
AW	absorptance of wall	—	0.7	6	0	1
EG	egg-crate shading	—	0	15	0.2	3
FN	side-fins projection ratio	—	0	15	0.2	3
OV	overhang projection ratio	—	0	15	0.2	3
SC	shading coefficient of windows	—	0.4	7	0	1
SF	skylight to roof ratio SRR	—	0	6	0.2	1
SS	shading coefficient of skylight	—	N/A	7	0	1
UF	U-value of fenestration	$W/m^2 K$	5.6	9	1	9
UI	U-value of interior partitions	$W/m^2 K$	2.513	3	0.49	3.149
UR	U-value of roof	$W/m^2 K$	0.539	4	0.426	2.147
US	U-value of skylight	$W/m^2 K$	N/A	9	1	9
UW	U-value of opaque wall	$W/m^2 K$	2.005	5	0.513	4.208
WR	window-to-wall ratio WWR	—	0.44	6	0.1	1
1.2. *Building configuration*						
AS	aspect ratio of plan	—	1.0	9	0.5	5
FH	floor-to-floor height	m	3.4	6	2.5	5
NS	number of storeys	nos.	40	4	10	50
OR	orientation	degree	N,E,S,W	9	5	45
PZ	perimeter zone depth	m	4.57	15	1	8
1.3. *Space load and space conditions*						
AT	space air temperature	°C	25.5	9	21	29
EQ	equipment load	W/m^2	15	6	0	30
IF	infiltration rate	ACH	0.6	10	0	2
LL	lighting load	W/m^2	20	6	0	30
LT	lighting type	—	Rec-F-Nv	3	—	—
OC	occupant density	psn/m^2	0.2	6	0.1	1
1.4. *Building thermal mass*						
FT	furniture type (weight)	—	Heavy	1	—	—
FW	floor weight	kg/m^3	342	10	50	700
RW	roof weight	kg/m^3	496.1	4	483.1	502.6
WW	wall weight	kg/m^3	25.2	5	195.3	794.9

Table A2. Base case values and perturbations for HVAC systems

Abbreviation	Input parameter	Unit	Base case	Perturbations Nos.	Min.	Max.
2.1. *System operation*						
AC	type of air side system	—	VAV Reheat	4	—	—
EC	economizer control	—	Yes	4	—	—
OA	outdoor air flow rate	l/s/psn	7	11	0	20
OH	operation hours	—	10 h/day	3	—	—
2.2. *System controls*						
OL	outdoor air control	—	By temp.	2	—	—
QR	minimum cfm ratio	—	0.3	4	0.1	0.5
RD	reheat delta temperature	°C	5	13	2	15
SR	supply air temperature reset	—	Yes	3	—	—
TR	throttling range	°C	1.1	14	0.06	3.33
TS	thermostat setpoint (summer)	°C	25.5	17	21	29
TT	thermostat type	—	Rev. action	2	—	—
TW	thermostat setpoint (winter)	°C	21	17	19	27
2.3. *Fans*						
FC	fan control method	—	Inlet vane	2	—	—
FE	fan efficiency	—	0.55	5	0.1	0.9
FM	fan motor placement	—	In air flow	1	—	—
FP	fan placement	—	Draw-thru	1	—	—
FS	system fan static pressure	Pa	1369	6	500	3000

Table A3. Base case values and perturbations for HVAC refrigeration plant

Abbreviation	Input parameter	Unit	Base case	Nos.	Perturbations Min.	Max.
3.1. *Chilled water circuit*						
CH	chw. supply temperature	°C	6.7	11	4	9
CR	chw. throttling range	°C	1.39	6	0.6	2.6
DT	chw. design delta temperature	°C	5.56	11	3	8
3.2. *Chilled water pump*						
PE	pump motor efficiency	—	0.9	6	0.8	1
PH	pump head	m H_2O	20	7	5	40
PI	pump impeller efficiency	—	0.77	11	0.5	1
PL	fraction of pump loss	—	0.01	6	0.001	0.02
PS	pump sizing option	—	System peak	2	—	—
PT	pump speed control type	—	Fixed	1	—	—
3.3. *Refrigeration and heat rejection*						
CP	chiller COP (kWr output/kWe input)	—	2.93	8	1.76	14.06
HG	max. PLR for hot gas bypass	—	0.25	10	0.2	0.7
HR	heat rejection method	—	Air-cooled	1	—	—
MA	min. entering air temperature	°C	18.33	11	10	30
NC	number of identical chillers	Nos.	6	9	1	10
PC	ratio of condenser fan electric power to chiller capacity	—	0.03	5	0.02	0.1
RF	type of chiller compressor	—	Herm. recip.	3	—	—