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Sensitivity analysis of design parameters and optimal design for zero/low energy buildings in subtropical regions

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Abstract: To reduce building energy use and mitigate CO_2 emissions, zero/low energy buildings have attracted increasing attention. However, the impacts of the main design parameters and optimal design for zero/low energy buildings only provided with cooling in subtropical regions are seldom studied, and the objectives for building performance assessment and design optimization in such particular situations are not addressed sufficiently. In this study, the impacts of the main design parameters and optimal design for zero/low energy buildings in subtropical regions are studied. A holistic approach integrating sensitivity analysis and design optimization is developed for zero/low energy buildings. A new optimization objective is proposed, which considers annual energy consumption and winter thermal discomfort, for buildings without heating provision. A multi-stage sensitivity analysis approach is proposed to identify the key design parameters for design optimization. The key building design parameters are optimized to minimize the optimization objective using the genetic algorithm. A case study is conducted, using the zero carbon building (ZCB) in Hong Kong as a reference building, to illustrate the implementation steps and effectiveness of the proposed approach. This paper presents the identification of the key influential design parameters in the subtropical climate and the design optimization method of zero/low energy buildings as well as the procedures and the results of the case study.

Keywords: zero/low energy building, design optimization, sensitivity analysis, energy efficiency, subtropical region

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Nomenclature

F	Performance objective (J)
E_{tot}	Annual total electricity consumption (J)
E_{ele}	Annual electricity consumption of lighting and other equipment (J)
Q_{cool}	Annual cooling demand of building (J)
D_{dis}	Hourly discomfort index
a	Penalty ratio of discomfort (J)
COP	Overall coefficient of performance of air-conditioning system
PMV	Predicted Mean Vote
U_T	Overall wall U value including thermal bridge (W/(m^2·K))
U_0	Wall U value (W/(m^2·K))
A_{tot}	Total opaque wall area (m^2)
L	Total length of linear thermal transmittance (m)
ψ	Linear thermal transmittance (W/(m·K))
χ	Point thermal transmittance (W/K)

1. Introduction

Energy conservation and environmental protection are among the most critical issues faced by the sustainable development of human societies. Buildings play very significant roles in mitigating these issues as they account for over 40% of end-use energy in the world [1] and this percentage is even much higher (i.e. 80% of end-use energy and 90% of electricity) [2] in Hong Kong. In order to reduce building energy consumption, zero/low energy buildings are becoming increasingly attractive [3-5]. Many efforts have been made on the design for zero/low energy buildings. The design involves two major tasks: building envelope design and energy system design. This study only focuses on the building envelope design of zero/low energy buildings. Three main aspects of the building design are addressed in the previous studies: (1) energy-efficient technologies [6]; (2) impacts of the main building design parameters [7-23]; (3) building design optimization [24-37]. The main energy-efficient technologies have already been explored thoroughly by researchers, which mainly include thermal insulation, thermal mass, window area, glazing, building orientation, reflective/green roof and shading [6]. In recent years, many researchers are concerned about the impacts of the main design parameters in different climates and their design optimization.

The impacts of main design parameters and climate/site: The impacts of the main building design parameters in different climates/sites have been studied by many researchers and the results show that the highly-sensitive parameters of building thermal performance are different in different climate regions as listed in Table 1 [7-23]. The internal loads, infiltration and temperature set-point of heating, ventilation and air-conditioning (HVAC) systems were proven to be the highly-sensitive parameters concerning the building thermal performance in all climate regions [7-10]. Thermal insulation of external walls is important for buildings in the climate regions with cold winter [8, 10, 11], while window area, glazing and solar protection are very influential to building energy consumption in the climate regions with hot summer [7- 9, 11]. For buildings in the climate regions with mild seasons, natural ventilation can make a great contribution to reducing the building cooling demands [12]. However, there are two limitations in the existing studies. First, only one sensitivity analysis method is usually adopted to assess the design parameters which may lead to the missing of important design parameters. Yang et al. [13] recommended that at least two fundamentally different sensitivity analysis methods should be performed to provide more robust results. The second is that sensitivity analysis often does not comprehensively address design parameters and the identification of key design parameters since many other non-design parameters are involved.

Table 1. Summary of sensitivity analysis in previous studies

Reference	Analysis method	Site/climate region	Performance objectives	Highly-sensitive (envelope) parameters
Yildiz and Arsan [7]	Regression (SRRC)	Hot-humid	Cooling load & heating load	Total window area, window U value and window solar heat gain coefficient
Yu et al. [8]	Local sensitivity analysis	Hot summer and cold winter	Cooling load & heating load	Wall U value and WWR
Lam and Hui [9]	Local sensitivity analysis	Hong Kong (Hot humid summer and mild winter)	Annual energy consumption, peak design loads and load profiles	Shading coefficient, WWR, space air temperature, equipment load, lighting load and occupancy density
Zhao et al. [11]	Local sensitivity analysis	Severe cold, cold, hot summer and cold winter, hot summer and warm winter, mild	Annual energy consumption	Infiltration rate and wall insulation thickness (climate regions with cold seasons); shading coefficient, window solar heat gain coefficient and wall insulation thickness (climates with hot/warm seasons);
Heiselberg et al. [12]	Morris	Denmark (cool summer and mild winter)	Annual energy consumption	Lighting control and ventilation rate in winter
Corrado and Mechri [18]	Morris	Turin (humid subtropical climate)	Cooling load, heating load, heating degree days etc. (14 objectives)	Indoor temperature, air change rate, number of occupants, metabolism rate, and equipment heat gains
Mechri et al. [19]	FAST	Italy (three climate zones)	Cooling load & heating load	Envelope transparent surface ratio and compactness ratio
Spitz et al. [20]	Sobol	France (hot summer and cold winter)	Indoor air temperature	Infiltration rate, internal gains, window U value, capacity of electric heating and heat exchanger efficiency

Building design optimization parameters and methods: The commonly optimized parameters are insulation thickness of the external walls, building orientation, window to wall ratio (WWR), glazing type, and external shading [24-37]. The parameters/design are generally optimized using two approaches. The typical approach adopted in the old days can be regarded as "local design optimization" which optimizes individual design parameter one-by-one [24]. The typical approach adopted in recent years can be regarded as "global design optimization" which optimizes all the concerned design parameters at the same time to identify the optimal set of the design parameters. The first approach has its limitation that the obtained design options may not be the optimum since it ignores the correlation and interaction between the design parameters. The second approach can overcome this drawback. The genetic algorithm (GA) is the most favorable global optimization method [25]. So far, most building design optimization studies focus on the regions with cold winters probably because of the government policy (e.g. European initiatives) and the urgency for the cold regions to reduce building energy consumption. The envelope design optimization of zero/low energy buildings without heating in subtropical regions is seldom studied. Most studies on the design optimization for zero/low energy buildings in subtropical regions focused on building energy systems [38-43]. In addition, the design parameters are determined mainly based on experiences and previous impact studies in similar climate regions. Very few researchers addressed sensitivity analysis on design parameters and design optimization comprehensively.

Building performance and design optimization objectives: The commonly-used building design optimization/performance objectives are building energy consumption (including cooling/heating load), thermal comfort and life cycle cost. Concerning the performance objectives, optimization can be classified into single objective optimization and multi-objective optimization. Wang et al. [26] applied multi-objective genetic algorithms to a green building design optimization. Yu et al. [27] studied the low-energy envelope design of residential buildings in the hot summer and cold winter zone of China. Pikas and Thalfeldt et al. [28-29] studied the cost optimal fenestration (window size and glazing type) design solutions for a nearly ZEB. No comprehensive objectives have been found to assess both energy performance and thermal comfort for buildings without heating.

In this study, the impacts of main design parameters and optimal design for zero/low energy buildings without heating provision in subtropical regions are studied. A holistic approach integrating sensitivity analysis and design optimization is developed for zero/low energy buildings. A new optimization objective is proposed, which comprehensively considers annual energy consumption and winter thermal discomfort in buildings only provided with cooling in subtropical regions. A multi-stage sensitivity analysis approach is adopted to identify the key design parameters for design optimization. The key design parameters of buildings are optimized to minimize the performance objective, using the genetic algorithm. A case study, using the zero carbon building (ZCB) in Hong Kong as the reference building, is conducted to study the impacts of main design parameters and optimal design for zero/low energy buildings in subtropical regions, which are provided with cooling only. The methods and steps of the sensitivity analysis and design optimization, the identification of key design parameters in subtropical regions and the design case study are presented in this paper.

2. Methods and procedures of building design optimization

2.1 Outline of the holistic design optimization approach

The proposed holistic approach integrates a comprehensive sensitivity analysis and design optimization for the optimal design of zero/low energy buildings. At first, a multi-stage sensitivity analysis is conducted and the impacts of the main design parameters on performance or design objective are studied to identify the key envelope design parameters for building design optimization in the specific condition concerned, such as the climate condition. Then design optimization is used to optimize the identified key design parameters and achieve the optimal design with the minimum performance objective. Where, the performance objective value of each scenario in the sensitivity analysis or each design option in the design optimization is quantified by building performance simulation.

2.2 Building performance quantification method

EnergyPlus [44], a commonly-used building simulation software, is applied for building performance quantification in this study. In general, free energy sources, such as natural ventilation and daylight, are taken into full consideration in the design of zero/low energy buildings in order to satisfy the low energy requirement. Therefore, the control logic, adopted by EnergyPlus for the building performance simulation and quantification in this study, is set to maximize natural ventilation and daylight in order to minimize building energy consumption while maintaining an acceptable thermal comfort as far as possible. This simulation control logics concerning the uses of natural ventilation and daylight are described here below.

The “hybrid ventilation availability manager” in EnergyPlus is used and set to maximize the use of natural ventilation in order to reduce the cooling loads of buildings, as illustrated in Fig.1. “Operative temperature control using adaptive comfort 90% acceptability limits” is selected as the ventilation control mode (i.e. criteria) of the hybrid ventilation availability manager in order to maximize the use of natural ventilation while maintaining an acceptable thermal environment as far as possible. First, the natural ventilation test is conducted at the beginning of each simulation time step based on the inputs of weather data, maximum window/door opening settings, internal loads, etc. The zone operative temperature is calculated and examined to assess whether it is favorable for the use of natural ventilation, i.e. whether it is within the comfortable zone based on ASHRAE standard [45]. This standard sets the range of comfortable zone air operative temperature within the lower and upper adaptive comfort 80%/90% acceptability limits while 90% acceptability is adopted in this study. If the indoor environment can be controlled within the comfortable zone, natural ventilation is allowed and no cooling/heating is needed and the mechanical ventilation is off. Otherwise, natural ventilation is not applicable and will be shut off. Under this condition, if it is in the system operation hour, the mechanical ventilation will be switched on for the intake of the minimum outdoor air needed for acceptable indoor air quality. Otherwise, both mechanical ventilation and air-conditioning systems are shut off. In operation hour, if the zone air temperature is higher than its (cooling) set-point, the air-conditioning system operates and the indoor air temperature will be controlled at its set-point whilst the calculated cooling demand will be used for further performance assessment. If zone air temperature is equal to or lower than the indoor set-point, the air-conditioning system is off and the indoor air temperature will be lower than its set-point as no heating is available whilst the calculated Predicted Mean Vote (PMV) [37] of the zone is used for further performance assessment.

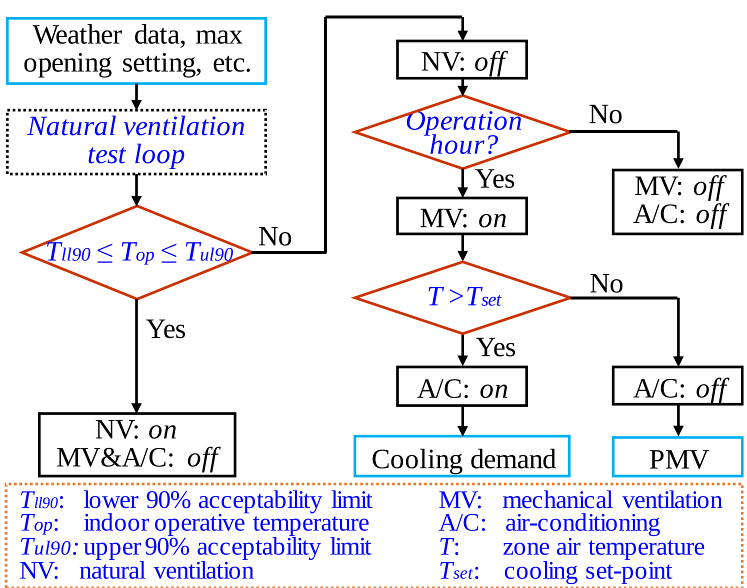


Fig. 1. Hybrid control logic of natural ventilation and air-conditioning operation in simulation

The artificial lighting output in a zone is adjusted based on the daylight illuminance at the reference point in the simulation according to the lighting control set-point. In this study, the reference points are chosen at the center of each room at the height of 0.8m. The lower and upper limit for daylight illuminance are set as 100lux and 500lux, respectively. A simplified daylight dimming control logic is illustrated in Fig.2. When the daylight illuminance is lower than the lower limit, the lighting power input equals to the design (full) lighting load. When the daylight illuminance increases between the lower and upper limits, the lighting power input decreases linearly with the increased daylight illuminance until 10% of the design lighting load. And if the daylight illuminance reaches or exceeds the upper limit, the lighting system will be switched off and the lighting power input becomes zero. The annual electricity demand of lighting and other equipment (except air-conditioning system) is used for further performance assessment.

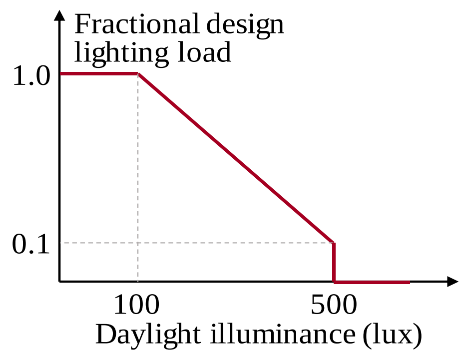


Fig. 2. Daylight dimming control logic

2.3 Performance objective for buildings in subtropical regions

An important issue concerning envelope design of buildings without heating provision in subtropical regions is that discomfort may occur in cold seasons since no heating is available. Since the thermal comfort issue in cold seasons has not been taken into consideration in previous studies when selecting optimal design option for these buildings, the obtained optimal design may cause severe cold indoor environment in the winter season. In order to reduce building energy demands while maintaining an acceptable indoor thermal comfort as far as possible, a comprehensive objective, which integrates building energy consumption and winter thermal discomfort, is defined for building performance assessment and design optimization in the specific condition concerned in this study. The objective function is defined as Eq. (1) - (3). A discomfort index is introduced to quantify the building thermal discomfort in cold winter days. It is obtained by normalizing the hourly PMV value to a value between 0 and 1. The value 1 of the discomfort index represents the case when PMV is -3, which means cold. The value 0 of the discomfort index represents the case when PMV is -0.5 or more, which means not cool. In order to consider building thermal discomfort and energy consumption comprehensively, a penalty ratio (a) is assigned to the discomfort index accumulated over the period concerned. a indicates the energy that consumers would like to pay to mitigate the discomfort. It can be determined based on the weighting of comfort in the mind of consumers and is also significantly affected by the size of buildings. In the case study presented in this paper, a is set at 4.0×10^8J, which is a typical hourly electricity consumption for cooling the reference building in a typical summer day. It is based on the assumption that the owner likes to pay the same amount of electricity used in summer to heat the building in winter when its indoor PMV reaches -3.

$$F=E_{tot}+a*\sum D_{dis} \tag{1}$$

$$E_{tot}=E_{ele}+Q_{cool}/\mathrm{COP} \tag{2}$$

$$D_{dis}=\begin{cases}\frac{-\mathrm{PMV}-0.5}{2.5} & \mathrm{PMV}<-0.5\\ 0 & \mathrm{PMV}\geq-0.5\end{cases} \tag{3}$$

where, F is the performance objective (J). E_{tot} is the annual total electricity consumption (J), including the electricity consumption of equipment, lighting and air-conditioning (cooling) system. D_{dis} is the hourly discomfort index. a is the penalty ratio (J) of discomfort. E_{ele} is the annual electricity consumption (J) of lighting and other equipment. Q_{cool} is annual cooling demand of building (J). COP is the overall coefficient of performance of air-conditioning system, which is set at 4 in this study. PMV is the hourly PMV value.

2.4 Sensitivity analysis approach and methods

A multi-stage sensitivity analysis approach is proposed in this study to identify the key design parameters for building design optimization. The multi-stage approach involves two stages of sensitivity analysis. The magnitudes of the effects of the main design parameters on the performance objective are assessed at the first stage while, at the second stage, the directions of the effects of highly-sensitive design parameters, which are selected at the first stage, on the thermal discomfort and the energy consumption are assessed respectively.

At the first stage, three global sensitivity analysis methods, namely the regression method, Morris method [46] and FAST method [47], are adopted to assess the impacts of the main design parameters. The highly-sensitive design parameters are identified based on the results of the sensitivity analysis using the three methods. At first, highly-sensitive parameters (usually the top parameters with obviously higher sensitivity measures) of individual methods are identified and ranked respectively. Then top 5 highly-sensitive parameters of individual methods and the other highly-sensitive parameters (but not top 5) of 2 or 3 sensitivity analysis methods are finally identified as the highly-sensitive parameters to be considered at later stage. Note, the proper numbers of highly-sensitive design parameters to be selected could be different for different building applications.

At the second stage, the highly-sensitive envelope design parameters identified at the first stage are further assessed with the local sensitivity analysis method [14] to select the key design parameters. The impacts (in percentage) on annual discomfort index and annual total electricity consumption of each highly-sensitive design parameter are assessed (compared to a base case) when other parameters remain unchanged. The parameters with opposite effects on annual discomfort index and annual total electricity consumption (i.e. the change of the parameter in one direction results in the changes of discomfort index and consumption in opposite directions, one increases and the other decreases) are identified as the key design parameters which need to be optimized eventually.

For the implementation of simulation-based sensitivity analysis and design optimization at the later step, one of the main challenges is that a large number of building performance simulations are required and the simulation run for each building design requires a new building model description (e.g. input data files (IDF) in EnergyPlus) since the envelope parameters are changed. In this study, jEplus (jE+) [48] and EnergyPlus (E+) are adopted to achieve the automatic process of numerous new building design establishment and building performance simulation. jEplus is a parametric study software, which can automatically change the parameter values in building simulation model and call EnergyPlus to do the building performance simulation. Apart from jEplus and EnergyPlus, SimLab [49] is also adopted for sensitivity analysis at a higher level. The process of each sensitivity analysis is illustrated in Fig.3. Firstly, SimLab generates the input scenarios based on the defined main design parameters and selected sensitivity analysis method, and a job list is also created based on the input scenarios for jEplus. Secondly, jEplus changes the corresponding parameter values in the building model based on the job list and generates a set of the corresponding building simulation model descriptions (IDF files) for EnergyPlus. EnergyPlus will automatically run the simulations of all the scenarios using the weather data input. Finally, jEplus collects all the simulation results and a simple calculation is conducted to obtain the corresponding objective values using the outputs of the performance simulations. With the input scenarios and the corresponding objective values, SimLab can calculate the sensitivity measures based on the selected sensitivity analysis method.

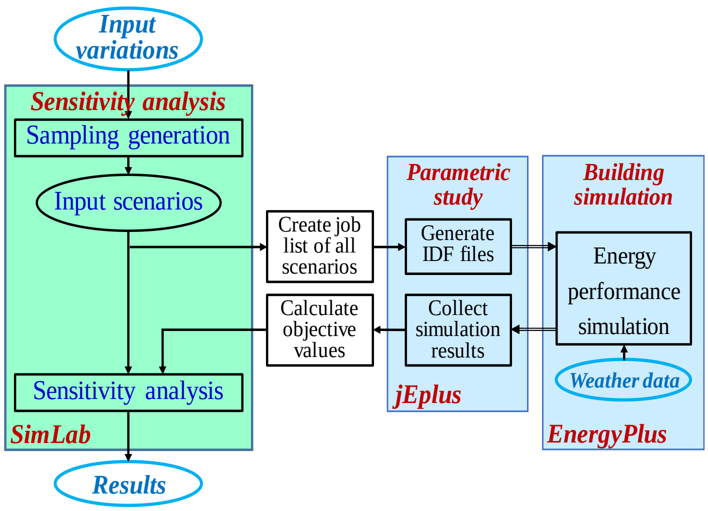


Fig. 3. Procedures of sensitivity analysis

2.5 Design optimization method and procedures

With the identified key envelope design parameters, design optimization is performed to obtain their optimal values by minimizing the performance objective. GA [50], as the most popular global optimization method applied in building design optimization, is selected for the design optimization in this study. Matlab with various optimization tools including GA optimizer is used to perform the optimization. Similar to the process of sensitivity analysis, jEplus is used to automate the simulation process and Energyplus is used to perform the building performance simulation, as shown in Fig.4. Firstly, the GA optimizer generates the populations (sets of design parameter values) within the predefined searching ranges of the design parameters for their initial generation. Then, a job list is created based on the generated parameter values for jEplus. jEplus creates the corresponding IDF file for EnergyPlus based on the created job list and automatically call EnergyPlus to conduct the simulation using the weather data input. After the simulation, jEplus collects all the simulation results and sends them back to Matlab for further processing. Then, the optimization objective values corresponding to these simulation results are calculated by a simple function routine developed on Matlab. The GA optimizer further evaluates the objective values and judge whether the objective value has reached the minimum within the preset convergence tolerance. If not, the sets of design parameter values with the relatively smaller objective values are selected as parents and used to generate the next populations within the searching ranges of the design parameters. The process is repeated until the objective value reaches the minimum within the preset convergence tolerance. The set of design parameter values with the minimum objective value is eventually the optimal design option.

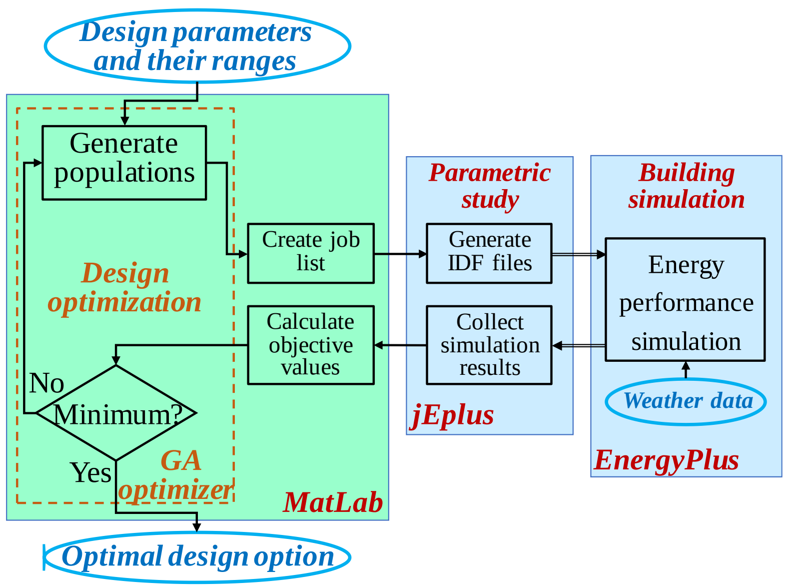


Fig. 4. Procedures of design optimization

3. Overview of reference building and climate condition

3.1 The reference building

In this study, Hong Kong ZCB is selected as the reference building for the case study. ZCB is the first and the only zero energy building in Hong Kong, which covers a total land area of 14,700 m^2. It consists of two indoor exhibition areas, an eco-home, an eco-office, a multi-purpose hall, two executive rooms, a meeting room and a guest room. A variety of passive design technologies are used in the building, such as cross-ventilated layout, high performance glazing, ultra-low thermal transfer, north glazing, light shelf, light pipes, heat reflecting shade, cool paint, optimized window to wall ratio, external shading, wind catcher, earth cooling tube and clerestory for daylighting. Fig.5 shows an aerial view of the ZCB.

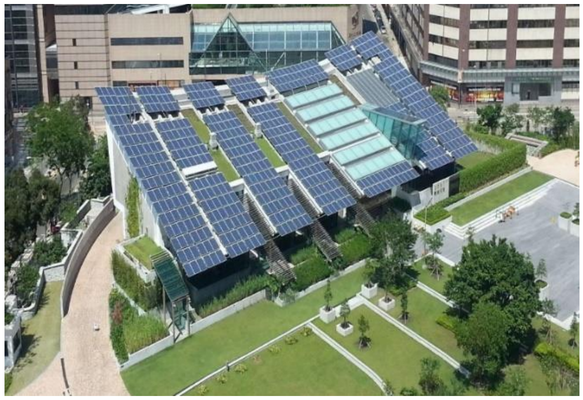


Fig. 5. Aerial view of ZCB in Hong Kong

A base building model (as shown in Fig.6) for building performance simulation is built referring to the ZCB using the OpenStudio Sketchup Plug-in [51]. The building shape, room distribution, room functions, and design assumptions of internal loads for building performance simulation (as shown in Table 2) are assumed to be fixed as that of ZCB. An ideal air-conditioning system with infinite cooling capacity is adopted, providing cooling at working hours (8:00-19:00, except Wednesday. Note: Saturdays and Sundays are working days due to the public education/demonstration purpose of the building).

Table 2. Design assumptions of internal loads for building performance simulation

Feature		Design
Lighting load	Office	6 W/m^2
	Exhibition area	6 W/m^2
	Multi-purpose room	6 W/m^2
Equipment load	Office	20 W/m^2
	Exhibition area	10kW
	Multi-purpose room	5 W/m^2
People load	Office	130 W/person
	Exhibition area	130 W/person
	Multi-purpose room	95 W/person
Occupancy	Office	8 m^2/person
	Exhibition area	4.7 m^2/person
	Multi-purpose room	300 person
Fresh air		4.3 L/s/person

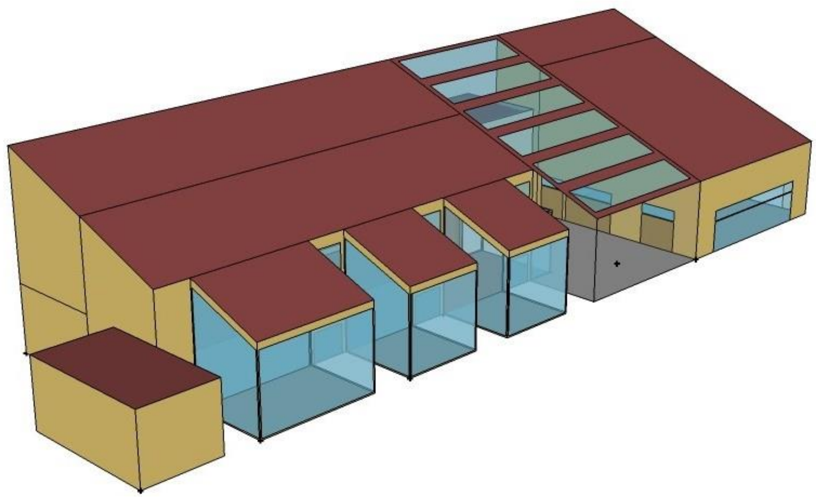


Fig. 6. Base architecture model for sensitivity analysis and design optimization

3.2 The climate conditions

The Hong Kong climate is subtropical, tending towards temperate for nearly half the year. Between 1981 and 2010, the mean monthly temperature in Hong Kong ranged from 18.6°C to 31.4°C, and the mean monthly relative humidity ranged from 71% to 83% [52]. It is not uncommon for the ambient temperature to drop below 10°C in urban areas for a short period in winter. In this study, the typical meteorological year (TMY) weather data [53] in Hong Kong are used. Fig.7 shows the daily maximum/minimum dry-bulb temperatures, daily mean dew point and daily maximum global horizontal radiation.

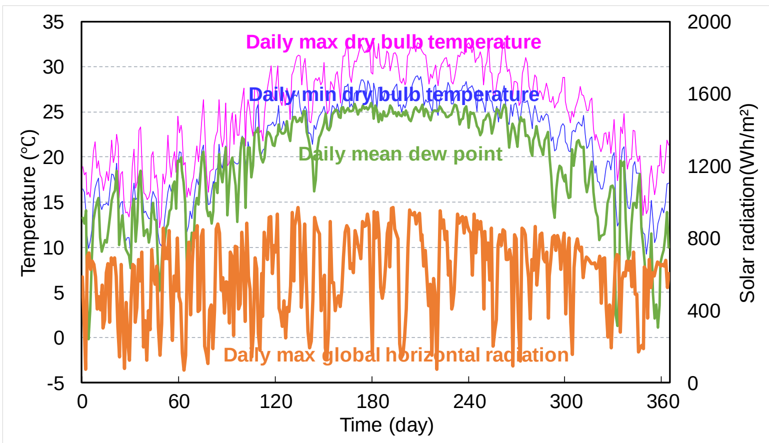


Fig. 7. Daily max/min dry bulb temperatures, mean dew point and maximum global horizontal radiation of TMY weather data [53] in Hong Kong

4. Sensitivity analysis results and discussions

4.1 Selection of main design parameters

The main building design parameters can be classified into 5 categories: building layout, envelope thermal characteristics, energy efficiency measures, energy system design parameters and construction quality. In total, 29 main design parameters of these 5 categories are considered for sensitivity analysis of the reference building. Among the 29 parameters, a few parameters which are not envelope parameters are also included in the sensitivity analysis in order to identify, comparatively, the key building envelope design parameters which have significant influence on building performance. For the sensitivity analysis, all 29 design parameters are treated as continuous variables having a uniform distribution over their preset ranges. Their typical ranges are determined based on a few previous publications [9, 15-16, 54-57] and summarized in Table 3. All the doors (including the windows on the top of the doors) and interior windows remain unchanged. Thermal bridge and thermal characteristics of skylight and ground slab, which were seldom considered in previous studies, are assessed in this study. In addition, the parameters influencing thermal bridge and natural ventilation are used directly instead of using global parameters to avoid the double-counting of their impacts. For instance, the impact of thermal bridge is determined by thermal transmittance and length of building connection. The common use of a thermal loss percentage will double-count the impacts of building shape if the impacts of building shape are also assessed. In this study, an overall wall U value is used to integrate the thermal bridge in the building simulation, as shown in Eq.(4) [58].

$$U_T = \frac{\sum(\psi \cdot L) + \sum(\chi)}{A_{tot}} + U_0 \tag{4}$$

where, U_T is the overall wall U value including the effects of thermal bridge (W/(m^2·K)). U_0 is the wall U value (W/(m^2·K)). A_{tot} is the total opaque wall area (m^2). ψ is the linear thermal transmittance (W/(m·K)) representing the additional heat transfer of a linear thermal bridge, which is not included in the wall U value. L is the total length of linear thermal transmittance (m). χ is the point thermal transmittance (W/K) representing the additional heat transfer of a point thermal bridge, which is not included in the wall U value.

4.2 Sensitivity analysis results

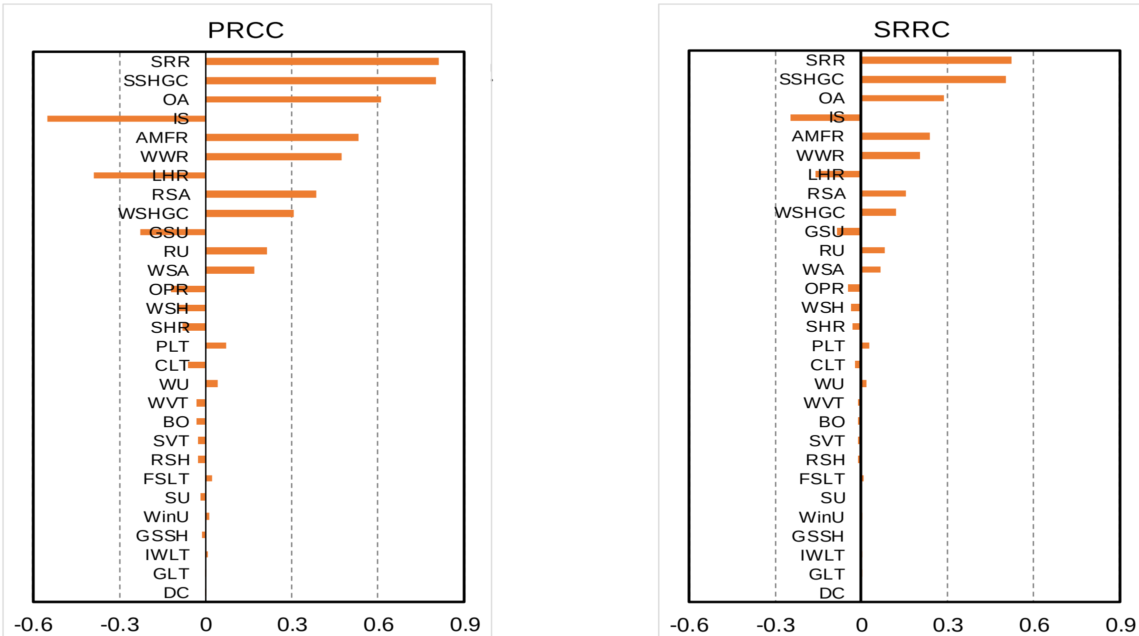
<u>*4.2.1 Results of first-stage sensitivity analysis*</u>

Sensitivity analysis results using regression method: Latin Hypercube Sampling method [59] is used for sampling the 29 selected design parameters within their ranges and a total number of 1000 samples are generated by SimLab for the sensitivity analysis using regression method. Two indicators, i.e. standardized rank regression coefficient (SRRC) and partial rank correlation coefficient (PRCC), are used as the sensitivity measures. SRRC measures the linear impacts of design parameters, while PRCC provides a sensitivity analysis excluding the correlation impacts between the design parameters [7]. A positive value of the indicators means that an increase of a design parameter results in an increase of performance objective. A negative value means that the changes in a design parameter and the consequential performance objective go in opposite directions.

The results are shown in Fig.8. It can be seen that the sensitivity ranking of the two indicators are the same although the values of the sensitivity measures are different. The values of PRCC are obviously larger than that of SRRC, which indicates that non-linear impacts exist. The skylight to roof ratio (SRR) and skylight solar heat gain coefficient (SSHGC) have the most significant influence on the building performance. The parameters of system design and construction quality (i.e. air flow rate (OA), indoor set-point (IS) and infiltration air mass flow rate (AMFR)) have higher impacts on building performance compared with the envelope design parameters except two parameters (i.e. SRR and SSHGC). This means a higher indoor set-point within the acceptable comfort zone and a good construction quality with high air tightness can contribute significantly to the performance objective reduction (improvement). The thermal bridge has little impact in subtropical regions. The sensitivity measure of latent heat recovery effectiveness (LHR) is larger than that of sensible heat recovery effectiveness (SHR), which was not addressed in previous studies. So latent heat recovery is more important than sensible heat recovery in subtropical regions with high relative humidity. Among the envelope thermal parameters, roof solar absorptance (RSA), window solar heat gain coefficient (WSHGC), ground slab U value (GSU), roof U value (RU) and wall solar absorptance (WSA) have more significant impacts on the building performance compared with the U value of wall (WU), skylight (SU) and window (WinU). Natural ventilation is mainly determined by WWR and building orientation (BO) and the impacts of discharge coefficient (DC) are very low. Eventually, 12 highly-sensitive parameters are identified based on the sensitivity analysis results using regression method, including SRR, SSHGC, OA, IS, AMFR, WWR, LHR, RSA, WSHGC, GSU, RU and WSA.

Table 3. Building design parameters concerned for sensitivity analysis

Category	Parameter	Abbreviation	Distribution	Range	Units
Layout	Building orientation	BO	Uniform	0-360	^{o}
	Window to wall ratio	WWR	Uniform	0.045-0.9	-
	Skylight to roof ratio	SRR	Uniform	0-0.9	-
Envelope thermal characteristics	Wall U value	WU	Uniform	0.09-11.1	W/(m^2·K)
	Wall specific heat	WSH	Uniform	800-2000	J/(kg·K)
	Wall solar absorptance	WSA	Uniform	0.1-0.9	-
	Ground slab U value	GSU	Uniform	0.15-2.27	W/(m^2·K)
	Ground slab specific heat	GSSH	Uniform	800-2000	J/(kg·K)
	Roof U value	RU	Uniform	0.09-4.8	W/(m^2·K)
	Roof specific heat	RSH	Uniform	450-1400	J/(kg·K)
	Roof solar absorptance	RSA	Uniform	0.1-0.9	-
	Window U value	WinU	Uniform	0.2-9	W/(m^2·K)
	Window solar heat gain coefficient	WSHGC	Uniform	0.1-0.9	-
	Window visible transmittance	WVT	Uniform	0.06-0.81	-
	Skylight U value	SU	Uniform	0.2-9	W/(m^2·K)
	Skylight solar heat gain coefficient	SSHGC	Uniform	0.1-0.9	-
	Skylight visible transmittance	SVT	Uniform	0.06-0.81	-
Construction quality	Infiltration air mass flow rate	AMFR	Uniform	0.01-0.03	kg/(s·m)
	Floor slab linear transmittance	FSLT	Uniform	0.007-1.842	W/(m·K)
	Glazing transition linear transmittance	GLT	Uniform	0.03-1.058	W/(m·K)
	Parapet linear transmittance	PLT	Uniform	0.056-1.06	W/(m·K)
	Corner linear transmittance	CLT	Uniform	0.036-0.684	W/(m·K)
	Interior wall intersection linear transmittance	IWLT	Uniform	0.039-1.15	W/(m·K)
System design	Indoor set-point	IS	Uniform	22-26	^{o}C
	Outdoor air flow rate	OA	Uniform	0-0.02	m^3/s/psn
Energy efficient measures	Overhang projection ratio	OPR	Uniform	0.2-3	-
	Discharge coefficient (natural ventilation)	DC	Uniform	0.6-1	-
	Sensible heat recovery effectiveness	SHR	Uniform	0-0.9	-
	Latent heat recovery effectiveness	LHR	Uniform	0-0.9	-



(A) Partial rank correlation coefficient (B) Standardized rank regression coefficient

Fig. 8. Regression/correlation coefficients of all parameters concerned using regression method

Sensitivity analysis results using Morris method: 240 simulations (the number of elementary effects per parameter is set as 8), obtained by sampling all the 29 design parameters within their ranges, are conducted for sensitivity analysis using the Morris method and the sensitivity analysis results are shown in Fig.9. A μ value on the x–axis represents the absolute value of elementary effects of a parameter, which reflects the importance of this parameter. A σ value in y–axis is an indicator that measures the non-linear effects of a parameter and its interactions with other parameters. If a point is within the wedge (i.e. the shadowed area between the two dotted lines), the represented parameter mainly has a non-linear or/and a correlated impact on the performance objective. If a point is outside and far from the wedge, the represented parameter mainly has a linear impact on the performance objective. If a point is near to the lines of the wedge, the represented parameter has both linear and non-linear/correlated impacts. It can be seen that most of the parameters have both linear and non-linear/correlated impacts on the performance objective, while SRR, SSHGC, OA, IS, AMFR and WWR mainly have linear effects. If parameters are ranked based on their μ values, the top 11 highly-sensitive parameters identified using Morris method are the same as that using regression method but with different orders. The biggest difference between results of the two sensitivity analysis methods is that building orientation is found to be very important when using Morris method and overhang projection ratio (OPR) and

SHR are also rather influential to the performance objective. Eventually, 15 highly-sensitive parameters are identified using Morris method, including SRR, IS, OA, SSHGC, AMFR, WWR, RSA, LHR, WSHGC, RU, GSU, OPR, BO, WSA and SHR.

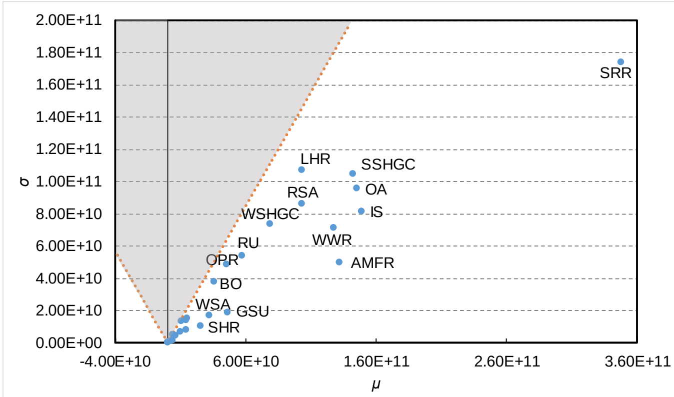


Fig. 9. Mean and standard deviation of all parameters concerned using Morris method (*Remark: only highly-sensitive parameters identified are named*)

Sensitivity analysis results using FAST method: 1885 simulations (minimum sufficient samples for 29 parameters), obtained by sampling all the 29 parameters within their ranges, are performed for sensitivity analysis using the FAST method and the sensitivity analysis results are shown in Fig.10. Two sensitivity measures, i.e. the first order and the total order, are used to assess the parameters. The first order of a parameter reflects its main effects, while its total order reflects its main effects and correlated effects. Fig.10 shows that most of the parameters have correlations with other parameters, while the main effects of IS, WWR, SSHGC and AMFR dominant indicating they have little correlation with other parameters. This result is consistent with that of Morris method. The sensitivity order given by FAST method is very different from that given by regression method and Morris method. SRR, SSHGC, OA, IS, AMFR, WWR, LHR, RSA and RU are the common recognized highly-sensitive parameters by the three sensitivity analysis methods. Parapet linear transmittance (PLT) and wall specific heat (WSH) are identified as highly-sensitive parameters by FAST method, which is very different from the results of the former two methods. The performance objective is proven to be very sensitive to BO and OPR, which is in consistent with the results of Morris method. The highly-sensitive parameters identified based on first order and total order are a bit different. 11 highly-sensitive parameters can be identified based on the first order. They are SRR, AMFR, SSHGC, WWR, IS, RU, OPR, BO, OA, RSA and LHR. Two more highly-sensitive parameters are identified based on the total order, i.e. PLT and WSH.

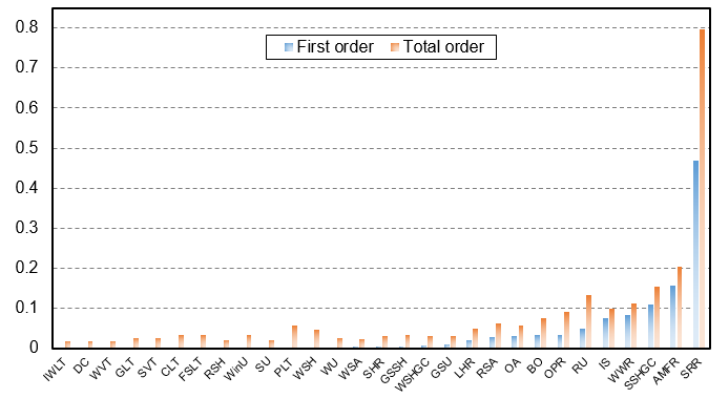


Fig. 10. First and total order of all parameters concerned using FAST method

Table 4. Ranking orders of highly-sensitive parameters based on three different sensitivity analysis methods (objective considering energy consumption and winter thermal discomfort)

Parameter	**Regression**		**Morris**	**FAST**	
	SRRC	PRCC	μ	first order	Total order
SRR	1	1	1	1	1
SSHGC	2	2	4	3	3
OA	3	3	3	9	10
IS	4	4	2	5	6
AMFR	5	5	5	2	2
WWR	6	6	6	4	5
LHR	7	7	8	11	12
RSA	8	8	7	10	9
WSHGC	9	9	9		
GSU	10	10	11		
RU	11	11	10	6	4
WSA	12	12	14		
OPR			12	7	7
WSH					13
SHR			15		
PLT					11
BO			13	8	8

Remark: The parameters in bold and italic are identified as the highly-sensitive parameters

The ranking orders of the highly-sensitive parameters using the three different sensitivity analysis methods are presented in Table 4. The results of Morris method are highly consistent with the results of regression method and rather consistent with the results of FAST method. The ranking order using FAST method are very different from that using regression method. Therefore, identifying key design parameters using a single sensitivity analysis method likely results in missing important parameters. For instance, the use of regression method can lead to missing OPR and BO, which are commonly recognized as highly-sensitive parameters in hot climate regions. Eventually, a total number of 14 highly-sensitive parameters are identified using the three methods collectively including: SRR, SSHGC, OA, IS, AMFR, WWR, LHR, RSA, RU, WSHGC, GSU, WSA, OPR and BO. Among these parameters, OA, IS, AMFR, WWR, WSHGC, OPR and BO are highly-sensitive parameters commonly considered in previous studies (as shown in Table 1). WSA and GSU are considered as important parameters of buildings without heating in subtropical regions in terms of energy consumption and winter thermal discomfort, which are seldom considered in previous studies. This inconsistency may result from the consideration of winter thermal discomfort in performance objective, which can be deduced from the comparison with the identified highly-sensitive parameters when annual energy consumption is the only concern as shown in Table 5.

Table 5. Ranking orders of highly-sensitive parameters based on three different sensitivity analysis methods (objective considering energy consumption only)

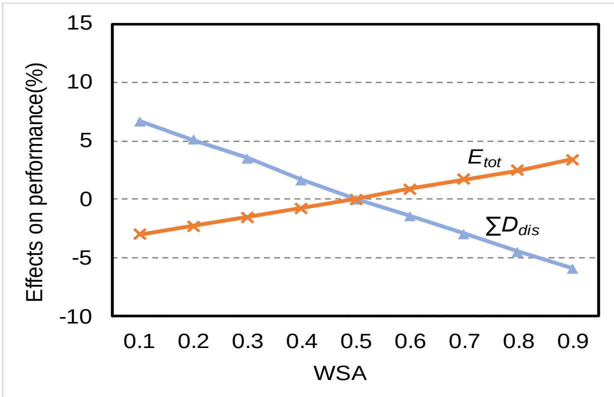
Parameter	**Regression**		**Morris**	**FAST**	
	SRRC	PRCC	μ	first order	Total order
SSHGC	1	1	2	3	3
SRR	2	2	1	1	1
OA	3	3	4	10	11
IS	4	4	3	4	7
AMFR	5	5	5	2	2
RSA	6	6	6	6	8
WWR	7	7	7	5	6
WSHGC	8	8	8	12	
LHR	9	9	9	11	12
WSA		10			
GSU		11			
RU		12		9	5
OPR		13		7	4
WSH					10
PLT					13
BO				8	9

Remark: The parameters in bold and italic are identified as the highly-sensitive parameters

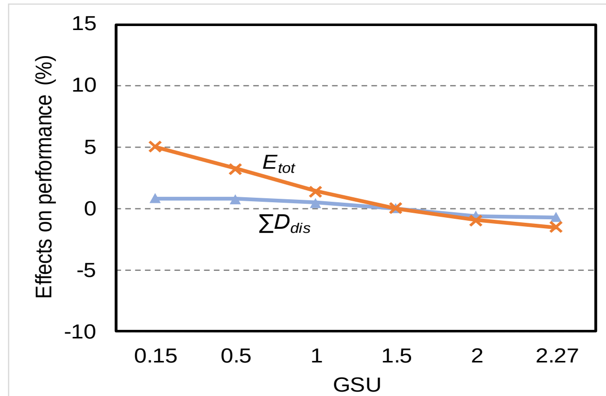
4.2.2 Results of second-stage sensitivity analysis

Since there is no need to optimize all the highly-sensitive parameters (e.g., some parameters are obviously the higher the better or the lower the better), a second-stage sensitivity analysis is conducted on the identified 14 highly-sensitive parameters to further select the key design parameters which need to be optimized. At this stage, the local sensitivity analysis method is used to assess the directions of the effects of the parameters on annual electricity consumption and annual discomfort index respectively. The reason not to assess the directions of the effects on the combined optimization objective is that its change direction is affected by the preset penalty ratio for the discomfort, leading to potentially missing key design parameters. Only the highly-sensitive envelope design parameters are assessed at this stage. The parameters related to building operation, i.e., OA, IS, AMFR, are not considered although they are included in the first-stage sensitivity analysis due to the reason explained earlier. In addition, the skylight (windows) is not considered for design optimization since the skylight is not used for the indoor spaces in this study. A few selected main results of the local sensitivity analysis are presented in Fig.11. It can be seen that WSA and RSA have the opposite impacts on the annual electricity consumption and annual discomfort index. It means that they need to be optimized in order to minimize the performance objective. The impacts of GSU and RU on both annual discomfort index and annual electricity consumption are in the same directions. It means that their values are either the higher the better or the lower the better. Therefore, there is no need to optimize them when optimizing the building design according to the defined objective in the climate condition of concern.

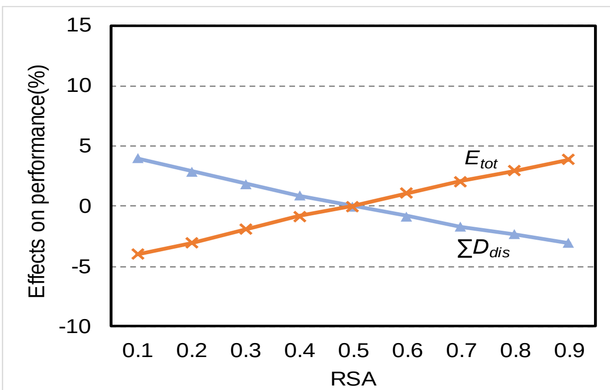
Eventually, six key design parameters are identified and selected for design optimization, including BO, RSA, WWR, WSA, WSHGC and OPR. It is worth noticing that four of them (i.e., BO, WWR, WSHGC and OPR) are commonly-selected design parameters for design optimization in existing studies. RSA and WSA are rarely selected as the key design parameters for design optimization except one case [27]. In this study, the sensitivity analysis results show that these two parameters should be considered when thermal comfort issue is concerned in the situation without heating provision in subtropical regions.



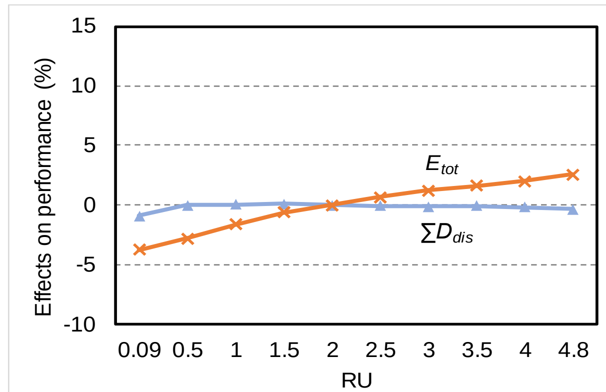
(A) Wall solar absorptance (WSA)



(B) Ground slab U value (GSU)



(C) Roof solar absorptance (RSA)



(D) Roof U value (RU)

Fig. 11. Effects of selected design parameters on annual discomfort index ($\sum D_{dis}$) and annual electricity consumption (E_{tot})

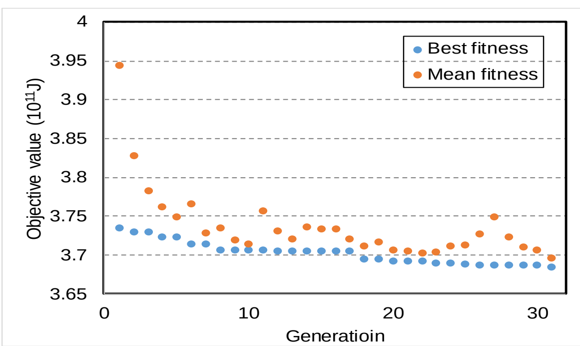
5. Results of design optimization

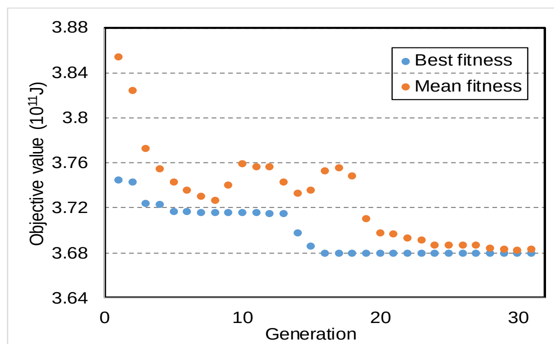
The identified key design parameters are optimized further using GA. The searching ranges of the parameters in the optimization are set as shown in Table 6. The building orientation (the long side with lower walls is considered as the front of the building) is optimized within 0^o and 360^o. A minimum value of 0.25 is set for WWR to guarantee that there is at least a reasonable ratio of window area. Different settings for GA are tried to make sure the obtained optimal design is the global optimum. First, an optimization without a setting of minimum generation number is tried and the result shows that a minimum generation number of 30 is needed to avoid a local optimum output. Optimization tests are then conducted by using different population sizes while the minimum generation number is set as 30. The optimization process at different population sizes are shown in Fig.12. It can be found that the minimum objective value can be achieved when the population size is 30. No more improvement is achieved with further increased population size.

The minimum objective value is 3.6804×10^{11}J. The corresponding optimal values of building orientation, roof solar absorptance, window to wall ratio, wall solar absorptance, window solar heat gain coefficient and overhang projection ratio are 6°, 0.1, 0.25, 0.86, 0.11 and 0.24, respectively, as shown in Table 6.

Table 6. Optimization parameters, their variations and optimal values

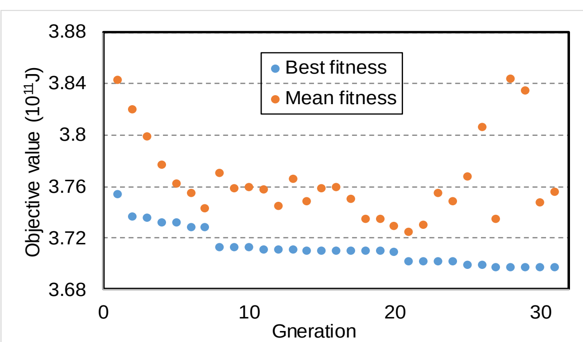
Optimization parameters	Variations		Optimal value
	Minimum value	Maximum value	
Window solar heat gain coefficient	0.1	0.9	0.11
Window to wall ratio	0.25	0.8	0.25
Wall solar absorptance	0.1	0.9	0.86
Overhang projection ratio	0.2	0.5	0.24
Building orientation	0°	360°	6°
Roof solar absorptance	0.1	0.9	0.1

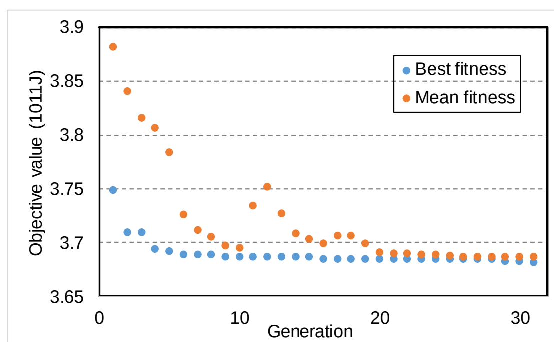




(A) Population size = 24

(B) Population size = 30





(C) Population size = 36

(D) Population size = 60

Fig. 12. Design optimization process at different population sizes

It can be observed that for the window solar heat gain coefficient, the smaller the better, while a rather small value of overhang projection ratio can contribute to approaching the minimum performance objective value. This result is consistent with the observation in the design optimization study for a high-rise residential building in Hong Kong [60].

It is also observed, in the sensitivity analysis, that an increase of wall and roof solar absorptance can lead to an increase of total electricity consumption, which is confirmed in a previous study on low-energy envelope design of a residential building in hot summer and cold winter zone in China [27]. However, it is also observed, in the design optimization, that the optimal wall solar absorptance is better larger, while for roof solar absorptance the smaller the better. Such difference between the best choices of wall and roof solar absorptance results from the different magnitudes and directions of their effects on winter thermal discomfort and annual electricity consumption, which are mainly caused by changes in solar radiation and solar altitude. In summer, the solar radiation is strong and the solar altitude is high. Thus the solar absorptance of the (nearly) horizontal roof with larger exposed area has very significant effects on cooling load and therefore much larger effects on the annual electricity consumption than the solar absorptance of the vertical walls. However, in winter, solar radiance reduces and the solar altitude is much lower. Walls have much larger exposed area compared to summer. The increase of wall solar absorptance does not increase electricity consumption and can contribute much more to reducing the winter thermal discomfort and therefore to reducing the annual discomfort index compared with the roof solar absorptance. Therefore, a rather higher value of wall solar absorptance is preferred for reducing the annual discomfort index due to its dominating effect on this index while the lowest value of the roof solar absorptance is the best choice to reduce its dominating effect on the annual electricity consumption. Such combination of solar absorptance choices can achieve a trade-off between electricity consumption and thermal discomfort and therefore achieve the minimum performance objective.

The window to wall ratio is better smaller within the given searching range in this study, which is consistent with the results in Ref. [31]. But, if the lower limit of the searching range is set lower, the optimal value of the window to wall ratio may not be lowest in order to make use of daylight and natural ventilation as well as its effect on winter thermal discomfort.

The optimal building orientation obtained in this study is 6 degrees from north to east, which is different from the original design (southeast oriented/45 degrees from south) of ZCB. There are two major differences resulting in this very different design result. First, the consideration on the impacts of solar radiation is very different. The PV solar-power generation is not considered on the roof in the building envelope design optimization in this study but it is considered in the original design. In the original design, a south-facing shed roof is beneficial to PV solar-power generation. In the optimal design obtained in this study, the south-facing and north-facing envelope have similar solar radiation heat gain per unit area (around 2.5×10^8J/m^2) in summer (i.e. June-August), but the south-facing envelope have much higher solar radiation heat gain per unit area (around 4.9×10^8J/m^2) compared with the north-facing envelope (around 1.5×10^8J/m^2) in winter (i.e. December-February). Therefore, setting the long side with higher walls (of larger area) to face south (namely, north-facing shed roof in this study) is beneficial to reducing the winter thermal discomfort. Second, the consideration of prevailing wind directions in the design is very different. In this study, the global Hong Kong prevailing wind directions, based on the TMY weather data in Hong Kong, are used, which are northeast and southwest. In the original building design, the prevailing wind direction of the local microclimate at the location of ZCB is used, which is southeast. Therefore, north orientation is beneficial to the natural ventilation and the reduction of the winter thermal discomfort in this study, while southeast orientation is beneficial to natural ventilation and solar-power generation in the original design. In fact, if the building natural ventilation is the only concern and the orientation of the shed roof (solar-power generation) is ignored, the difference of building orientations is 51° (i.e. 45° from south to east and 6° from south to west).

6. Conclusions and recommendations

A design approach combining sensitivity analysis and design optimization is proposed for the design of zero/low energy buildings without heating provision in subtropical regions. A comprehensive optimization objective, which integrating energy consumption and winter thermal discomfort, is defined for the sensitivity analysis and design optimization. A multi-stage sensitivity analysis is conducted to identify the key design parameters for design optimization prior to optimizing the identified key design parameters using genetic algorithm. Based on the results of the case study, conclusions can be made as follows.

The test results and experience show that the outputs of the sensitivity analysis using different sensitivity analysis methods can be different and using a single sensitivity analysis method to identify the key design parameters may result in missing some important design parameters. It is therefore recommended to combine more than one sensitivity analysis method to identify and determine the parameters to be optimized. For instance, the sensitivity analysis using regression method only would lead to missing two key design parameters, namely overhang projection ratio and building orientation, which are commonly considered as highly-sensitive parameters in previous studies for buildings in hot climate regions.

The consideration of winter thermal discomfort significantly affects outputs of sensitivity analysis for buildings without heating provision in subtropical regions and therefore the identification and selection of their key design parameters. In this study, the results of sensitivity analysis show that roof and wall solar absorptance are highly-influential parameters when winter thermal discomfort is concerned in the buildings without heating provision in subtropical regions. However, these two parameters are seldom selected as the key design parameters in previous studies, which are mainly concerned about energy consumption.

The consideration of winter thermal discomfort also has significant impacts on the optimal choices of the key design parameters for buildings without heating provision in subtropical regions. In this study, for instance, the results of design optimization show that a rather higher value of wall solar absorptance and nearly north orientation are preferred to achieve the minimum objective when winter thermal discomfort is considered, while low value of wall solar absorptance was suggested in existing studies concerning energy performance only.

It is worth noticing that interaction exists between building envelope design and energy system design for buildings integrated with PV panels. Building orientation affects the power generation of building-integrated PV (or other types of solar power generation), while the PV panels affect the building cooling load and therefore affect the optimal choice of building orientation and even other envelope design parameters. Therefore, building envelope design and energy system design should consider their interaction when building integrated solar-power generation is adopted.

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Reference

1. International Energy Agency. Key world energy statistics, 2017.
2. EMSD. Hong Kong Energy End-use Data, 2016. Available at: http://www.emsd.gov.hk/emsd/eng/pee/edata_1.shtml.
3. Kolokotsa D, Rovas D, Kosmatopoulos E, Kalaitzakis K. A roadmap towards intelligent net zero-and positive-energy buildings. Solar Energy 2011; 85(12): 3067-3084.
4. Torcellini P, Pless S, Deru M. Zero energy buildings: a critical look at the definition. National Renewable Energy Laboratory and Department of Energy, 2006.
5. Rodriguez-Ubinas E, Montero C, Porteros M, Vega S, Navarro I, Castillo-Cagigal M, Matallanas E, Gutiérrez A. Passive design strategies and performance of Net Energy Plus Houses. Energy and Buildings 2014; 83: 10-22.
6. Li DHW, Yang L, Lam JC. Zero energy buildings and sustainable development implications-A review. Energy 2013; 54: 1-10.
7. Yildiz Y, Arsan ZD. Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates. Energy 2011; 36: 4287-4296.
8. Yu JH, Tian LW, Yang CZ, Xu XH, Wang JB. Sensitivity analysis of energy performance for high-rise residential envelope in hot summer and cold winter zone of China. Energy and Buildings 2013; 64: 264-274.
9. Lam JC, Hui SCM. Sensitivity analysis of energy performance of office buildings. Building and Environment 1996; 31(1): 27-39.
10. Sanchez DG, Lacarrière B, Musy M, Bourges B. Application of sensitivity analysis in building energy simulations: Combining first- and second-order elementary effects methods. Energy and Buildings 2014; 68: 741-750.
11. Zhao M, Künzel HM, Antretter F. Parameters influencing the energy performance of residential buildings in different Chinese climate zones. Energy and Buildings 2015; 96: 64-75.
12. Heiselberg P, Brohus H, Hesselholt A, Rasmussen H, Seinre E, Thomas S. Application of sensitivity analysis in design of sustainable buildings. Renewable Energy 2009; 34: 2030-2036.
13. Yang S, Tian W, Cubi E, Meng QX, Liu YL, Wei L. Comparison of sensitivity analysis methods in building energy assessment. Procedia Engineering 2016; 146: 174-181.
14. Tian W. A review of sensitivity analysis methods in building energy analysis. Renewable and Sustainable Energy Reviews 2013; 20: 411-419.

15. Bernal-Agustín JL, Dufo-Lopez R. Simulation and optimization of stand-alone hybrid renewable energy systems. Renewable and Sustainable Energy Reviews 2009; 13(8): 2111-2118.
16. Li DH, Yang L, Lam JC. Zero energy buildings and sustainable development implications–a review. Energy 2013; 54: 1-10.
17. Chen X, Yang HX, Sun K. Developing a meta-model for sensitivity analyses and prediction of building performance for passively designed high-rise residential buildings. Applied Energy 2017; 194: 422-439.
18. Corrado V, Mechri HE. Uncertainty and sensitivity analysis for building energy rating. Journal of Building Physics 2009; 33(2): 125-156.
19. Mechri HE, Capozzoli A, Corrado V. Use of the ANOVA approach for sensitive building energy design. Applied Energy 2010; 87: 3073-3083.
20. Spitz C, Mora L, Wurtz E, Jay A. Practical application of uncertainty analysis and sensitivity analysis on an experimental house. Energy and Buildings 2012; 55: 459-470.
21. Singh R, Lazarus IJ, Kishore VVN. Uncertainty and sensitivity analyses of energy and visual performances of office building with external venetian blind shading in hot-dry climate. Applied Energy 2016; 184: 155-170.
22. Dall’O’ G, Belli V, Brolis M, Mozzi I, Fasano M. Nearly zero-energy buildings of the Lombardy region (Italy), a case study of high-energy performance buildings. Energies 2013; 6: 3506-3527.
23. Kurnitski J, Saari A, Kalamees T, Vuolle M, Niemelä J, Tark T. Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation. Energy and Buildings 2011; 43: 3279-3288.
24. Baker NV. Passive and low energy building design for tropical island climate. The Commonwealth Secretariat; 1987.
25. Huang Y, Niu JL. Optimal building envelope design based on simulated performance: History, current status and new potentials. Energy and Buildings 2016; 117: 387-398.
26. Wang WM, Zmeureanu R, Rivard H. Applying multi-objective genetic algorithms in green building design optimization. Building and Environment 2005; 40(11): 1512-1525.
27. Yu JH, Yang CZ, Tian LW. Low-energy envelope design of residential building in hot summer and cold winter zone in China. Energy and Buildings 2008; 40(8): 1536-1546.
28. Pikas E, Thalfeldt M, Kurnitski J. Cost optimal and nearly zero energy building solutions for office buildings. Energy and Buildings 2014; 74: 30-42.
29. Thalfeldt M, Pikas E, Kurnitski J, Voll H. Facade design principles for nearly zero energy buildings in a cold climate. Energy and Buildings 2013; 67: 309-321.
30. Ascione F, Masi RFD, Rossi FD, Ruggiero S, Vanoli GP. Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study. Applied Energy 2016; 183: 938-957.
31. Yu W, Li B, Jia HY, Zhang M, Wang D. Application of multi-objective genetic algorithm to optimize energy efficiency and thermal comfort in building design. Energy and Buildings 2015; 88: 135-143.

32. Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy and Buildings 2013; 56: 189-203.
33. Lin YH, Tsai KT, Lin MD, Yang MD. Design optimization of office building envelope configurations for energy conservation. Applied Energy 2016; 171: 336-346.
34. Lu YH, Wang SW, Shan K. Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings. Applied Energy 2015; 155: 463-477.
35. Chen X, Yang HX. Integrated energy performance optimization of a passively designed high-rise residential building in different climatic zones of China. Applied Energy 2018; 215: 145-158.
36. Mangkuto R, Rohmah M, Asri AD. Design optimization for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics. Applied Energy 2016; 164: 211-219.
37. Fanger PO. Thermal comfort: Analysis and applications in environmental engineering. McGraw-Hill; 1972.
38. Lu YH, Wang SW, Yan CC, Shan K. Impacts of renewable energy system design inputs on the performance robustness of net zero energy buildings. Energy 2015; 93: 1595-1606.
39. Sun YJ. Sensitivity analysis of macro-parameters in the system design of net zero energy building. Energy and Buildings 2015; 86: 464-477.
40. Fong KF, Lee CK. Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong. Applied Eenergy 2012; 93: 686-694.
41. Kumar KS, Tiwari KN, Jha MK. Design and technology for greenhouse cooling in tropical and subtropical regions: A review. Energy and Buildings 2009; 41: 1269-1275.
42. Lu YH, Wang SW, Zhao Y, Yan CC. Renewable energy system optimization of low/zero energy buildings using single-objective and multi-objective optimization methods. Energy and Buildings 2015; 89: 61-75.
43. Liu ZB, Zhang L, Gong GC, Li HX, Tang GF. Review of solar thermoelectric cooling technologies for use in zero energy buildings. Energy and Buildings 2015; 102: 207-216.
44. Crawley DB, Lawrie LK, Winkelmann FC, Buhl WF, Huang YJ, Pedersen CO, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy and Buildings 2001; 33(4): 319-331.
45. ASHARE, Standard 55-2010. Thermal environmental conditions for human occupancy. ASHRAE, 2010.
46. Morris MD. Factorial sampling plans for preliminary computational experiments. Technometrics 1991; 33: 161-174.
47. McRae GJ, Tilden JW, Seinfeld JH. Global sensitivity analysis - a computational implementation of the Fourier Amplitude Sensitivity Test (FAST). Computers & Chemical Engineering 1982; 6: 15-25.
48. Zhang Y. “Parallel” EnergyPlus and the development of a parametric analysis tool. In: Proceedings of the 11th International IBPSA Conference, Glasgow, Scotland, July 27-30 2009.
49. SIMLAB. V2.2. Simulation environment for uncertainty and sensitivity Analysis. Developed by the Joint Research Center of the European Commission. 2011.
50. Whitley D. A genetic algorithm tutorial. Statistics and Computing 1997; 4(2): 65-85.

51. Guglielmetti R, Macumber D, Long N. OpenStudio: an open source integrated analysis platform. In: Proceedings of Building Simulation 2011, Sydney, Australia, November 14-16 2011.
52. Hong Kong Observatory. Monthly Meteorological Normals for Hong Kong, 2015. Available at: http://www.hko.gov.hk/cis/normal/1981_2010/normals_e.htm#table4.
53. Wilcox S, Marion W. Users Manual for TMY3 Data Sets, 2008. National Renewable Energy Laboratory (NREL), Golden, Colorado, NREL/TP-581-43156.
54. Ge H, Baba F. Dynamic effect of thermal bridges on the energy performance of a low-rise residential building. Energy and Buildings 2015; 105: 106-118.
55. Tavares P, Martins A. Energy efficient building design using sensitivity analysis – a case study. Energy and Buildings 2007; 39(1): 23-31.
56. Schnieders J, Schulz T, Feist W, Kaufmann B, Sheng S, Jiang HJ, Winkel S, Buteikyte E and Sifferlen C. Passive houses in Chinese climates. Germany: Wolfgang Feist, Passive House Institute and University of Innsbruck, Unit for Energy Efficient Buildings; 2016.
57. Johnson MH, Zhai ZQ, Krarti M. Performance evaluation of network airflow models for natural ventilation. HVAC&R Research 2012; 18(3): 349-365.
58. Morrison Hershfield Limited. Building envelope thermal bridging guide. BC Hydro Power Smart, 2016.
59. Helton JC, Davis FJ. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. Reliability Engineering & System Safety 2003; 81(1): 23-69.
60. Chen X, Yang HX, Zhang WL. Simulation-based approach to optimize passively designed buildings: A case study on a typical architectural form in hot and humid climates. Renewable and Sustainable Energy Reviews 2018; 82(2): 1712-1725.