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Sensitivity of façade performance on early-stage design variables

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ABSTRACT

Early-stage façade design is a complex and multi-objective process. There are two principal barriers in the process of identifying an optimal façade solution. Firstly, the number of design variables and their uncertainty are relatively large, making design decisions difficult. Secondly, each design variable is likely to affect several performance indicators simultaneously, which makes it difficult to quantify the impacts of the design variables. In this paper, we perform sensitivity analyses on two generic building scenarios (a cellular office room and an open-plan office floor) in three geographic locations (London, Helsinki, and Rome). A series of façade sensitivity coefficient charts for early-stage façade design are produced for these locations thereby providing quantitative relationships between a comprehensive list of design variables and façade performance indicators. The sensitivity coefficient charts provide a guide for allocating the limited design time and construction budget to the design variables that will generate the largest impact on facade performance.

1. Introduction

Façade design is a cross-disciplinary multi-objective optimisation process. In order to provide a quantitative holistic assessment of alternative façade options, a whole-life value (WLV) approach should be implemented [1]. The façade performance indicators generally fall into three categories: functional (Table 1), financial (Table 2), and environmental sustainability (Table 3), which represent the three principal dimensions of WLV. A façade should achieve the optimal trade-offs between the performance indicators by adopting an appropriate combination of various façade design variables. These façade design variables include façade-intrinsic variables (such as window-to-wall ratio, thermal properties of the façade components, initial capital costs of the façade components) and facade-extrinsic variables (such as building location, layout, orientation, usage, HVAC system and the corresponding control strategies). In the early design stage, the number of design variables and their uncertainty is relatively large, which makes design decisions problematic. In such cases it is desirable to identify those design variables that have a large impact on the performance of the façade and focus a proportionate amount of design effort on them. In order to do so, it is necessary to quantify the relative impacts of the facade design variables.

There are several studies that adopt some form of sensitivity analysis to identify high-impact design variables in building design. For example, Heiselberg et al. [2], Garcia Sanchez et al. [3], and Struck et al. [4] adopted the Morris method [5]; Hopfe and Hensen [6], Yildiz and Arsan [7], and Tian and Wilde [8] implemented regression analysis; Purdy and Beausoleil-Morrison applied differential sensitivity analysis [9]. These studies considered the effects of both façade-intrinsic variables and facade-extrinsic variables on building energy performance, and provide a useful ranking of design variables for a specific building in a specific location. However, they all share three limitations. Firstly, all the studies focused specifically on the energy demand of the building, while other important performance indicators such as comfort were ignored. Secondly, each study is based on a particular building in a particular climate, so the usefulness of extending the results to other projects is limited. Thirdly, only one sensitivity analysis method is adopted in each study, whereas two or more, preferably with dissimilar foundations, should be applied to increase the confidence that the correct key input variables have been identified [10]. This paper identifies the fundamental traits in façade design, i.e., the design variable changes that have the largest influence on the façade performance in terms of energy demand, occupant comfort, and economic cost. Rather than focusing on a particular building, generic building scenarios (a generic cellular office room and a generic open-plan office floor) in locations that represent three generic climates (Helsinki, London, and Rome) are modelled. This ensures a wide applicability of the results. In addition, both a sampling-based and a variance-based method of analysis are

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Table 1
Functional indicators for façade performance assessment.

Aspects		Impact Factors	Performance Indicators (↑/↓: larger/smaller values are preferable)
Visual Comfort	Daylight	▪ Incident illuminance ▪ Reflectance of the reference surface ▪ Position of reference point	Light level ↑ [25] Daylight factor ↑ [25] Acceptance of light level ↑ [15]
Visual Comfort	Glare	▪ Incident illuminance ▪ Reflectance of the reference surface ▪ Position of reference point	Glare index (GI) ↓ [26] Bubble glare index (BGI) ↑ [27]
Visual Comfort	View	▪ Window area ▪ VT of glass ▪ Exterior and interior shading devices ▪ Interior reflections	View index ↑ [27]
Visual Comfort	Aesthetics	▪ Look and feel	N/A
Thermal Comfort		▪ Mean radiant temperature ▪ Room air temperature ▪ Relative humidity ▪ Air speed ▪ Activity level ▪ Amount of clothing	Predicted percentage of dissatisfied (*PPD*)↓ [16] Predicted mean vote (*PMV*) [16] Acceptance of thermal comfort ↑ (1-*PPD*)
Air quality		▪ Air tightness ▪ Ventilation devices and strategies	Ventilation rate ↑ CO_2 concentration ↓ [13] Acceptance of CO_2 level ↑ [15]
Aural comfort		▪ Frequency and amplitude of the incident sounds ▪ Air tightness ▪ Mass and natural resonances	Noise level (dBA)↓ Noise rating ↓ [25] Sound Reduction Index (SRI) [28] Acceptance of noise level ↑ [15]
Indoor environmental quality (IEQ)		▪ Visual comfort ▪ Thermal comfort ▪ Air quality ▪ Aural comfort	Acceptance of IEQ [15] Satisfaction with IEQ [19]
Safety	Structural performance	▪ Wind load ▪ Thermal load ▪ Snow load on sloped (>15°) facades ▪ Geometry of each component ▪ Strength and stiffness of the materials	Failure stress ↑ Maximum deflection ↓
Safety	Fire protection	▪ Ability to resist heat, flames, and smoke	Fire resistance (30 minutes to 3 hours) ↑ [29]
Safety	Blast resistance	▪ Peak increase in pressure ▪ Duration of the overpressure ▪ Peak pressure	GSA/ISC projection levels (1-5) ↑ [30]
Durability	Service life	▪ Sensitivity to weathering (heat, ultraviolet radiation, moisture, air, corrosive materials, etc)	Number of years that the system can maintain the thermal performance, structural performance, and aesthetics features. ↑
Durability	Condensation resistance	▪ Surface temperature, or outdoor and indoor air temperature ▪ Relative humidity ▪ Air movement	Vapour resistance ↓ [31]
Durability	Water penetration resistance	▪ Rain angle, speeds and volumes ▪ Quality of installation	Rate of leakage [32]

adopted to validate the results. The façade design variables that have largest impacts on the performance indicators are identified, and their relative influences are quantified. A series of façade sensitivity coefficient charts are produced to aid early-stage façade design. In Section 2, the models of the generic building scenarios are described, the facade design variables and performance indicators are identified, and two sensitivity analysis methods are introduced. Section 3 compares the results from the two sensitivity analysis methods. Section 4 summarises the main outcomes of this paper.

2. Methodology

2.1. Generic cellular office room

A building energy simulation model of a generic cellular office room (Fig. 1) is constructed using EnergyPlus 7.0 [11]. This model was adapted from an experimentally validated model of a climatic chamber [12]. All the internal surfaces are assumed to be adiabatic. The façade is a partially glazed unitised curtain wall with a typical unit width of 1.5 m south, north, east, and west orientations are investigated. The occupancy density is assumed to be 9 m^2/person [13]. The internal heat gain from lighting and equipment are 12 W/m^2 and 20 W/m^2, respectively. All illuminance reference points are located at a height of 0.8 m above the finished floor level. For a room depth of 3 m, the illuminance reference point is positioned at the centre of the room (Fig. 2a); for a room depth of 6 m or 9 m, the illuminance reference points are positioned at third points along the room depth (Fig. 2b). The illuminance set point is 500 lux. Automated continuous dimming control of lighting is implemented. It is assumed that vertical internal blinds are installed. The slats are 'on' if the internal air temperature is equal to

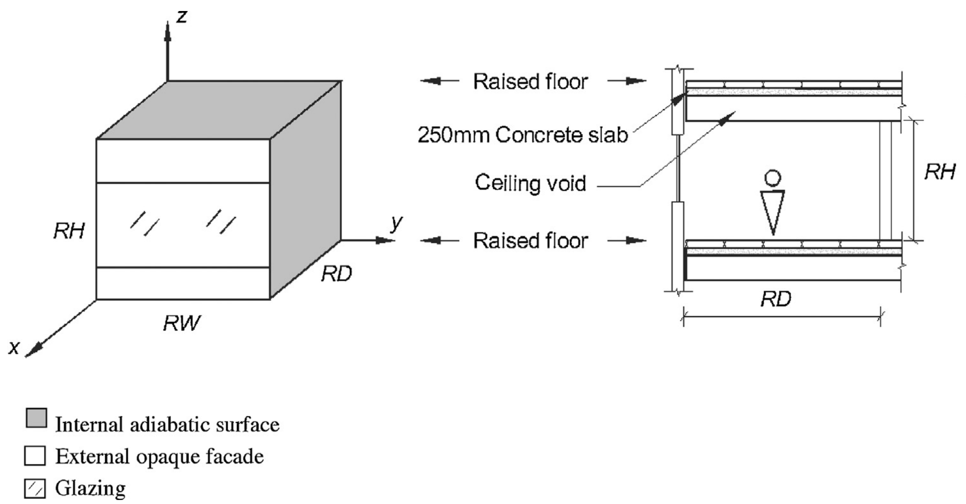


Fig. 1. 3-D view and section of the generic cellular office room.

Table 2
Financial indicators for façade performance assessment.

Aspect	Impact factors	Performance indicators (↑/↓: larger/smaller values are preferable)
Economic cost	■ Production ■ Transportation ■ Installation	Initial capital cost ↓
	■ Cleaning strategies	Maintenance cost ↓
	■ Lighting energy demand ■ Heating energy demand ■ Cooling energy demand ■ Equipment energy demand ■ Cost of unit of energy	Operational energy cost ↓
	■ Satisfaction with IEQ ■ Occupants' salary	IEQ cost due to occupant productivity loss ↓[33]
	■ Frequency of replacement	Replacement cost ↓
	■ Demolition ■ Transportation ■ Disposal	Disposal cost ↓

Table 3
Environmental sustainability indicators for façade performance assessment [34] (The list has been limited to the commonly used indicators, for a comprehensive list of LCA indicators *c.f.* [35]).

Aspects	Impact factors	Performance indicators (↑/↓: larger/smaller values are preferable)
Input	■ The energy required to create 1 kg of material/product	Embodied energy ↓
	■ Total non-renewable energy: embodied energy and energy used for production, transportation, maintenance, and elimination (MJ)	Non-renewable energy (NRE) ↓
Emissions	■ Gas emissions responsible of the global warming process (g or kg eq. CO_2)	Global warming potential (GWP) ↓
	■ Gas emissions responsible of the acidification (g or kg eq. SO_x)	Acidification potential (AP) ↓
	■ Photochemical ozone production process (g or kg eq. C_2H_4)	Photosmog ↓

or higher than the cooling set point temperature, or if discomfort glare is detected at the day lighting reference points (glare index > 22). The slat angle is adjusted at each time step (10 min) to just block beam solar radiation. It is assumed that occupants will open the operable windows when the internal air temperature is higher than the cooling set point temperature and the external air temperature is lower than the cooling set point temperature. The HVAC system is assumed to be a variable air volume (VAV) system. The heating supply air temperature is 50 °C, and the cooling supply air temperature is 13 °C. The capacity of VAV terminal boxes varies from 80 L/s to 1370 L/s and the cost varies from €662 to €1142 [14].

A selection of facade-intrinsic and facade-extrinsic variables considered in this model is listed in Table 4. The facade performance indicators are listed in Table 5, which are a selection of performance indicators in Tables 1 and 2.

2.2. Generic open-plan office floor

A building energy simulation model of a generic open-plan office floor (Fig. 3) is constructed using EnergyPlus 7.0 [11]. The floor and ceiling are assumed to be adiabatic internal surfaces. This captures the thermal mass of the concrete floor slabs, but ignores any temperature differences between one floor and the one directly above/below it. The office floor is divided into five thermal zones

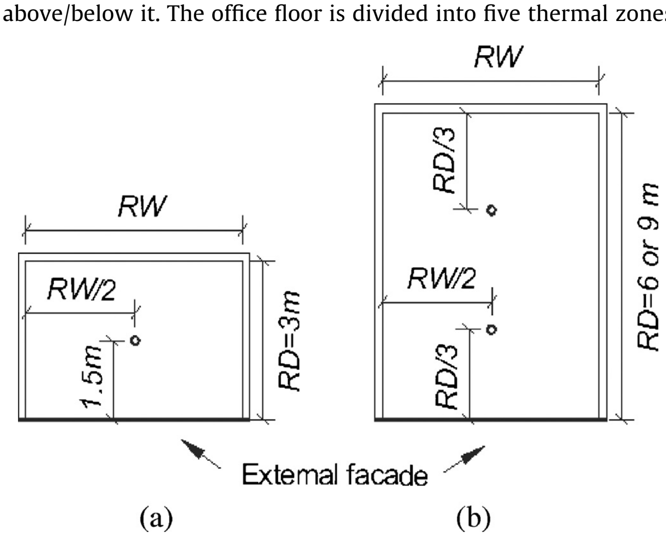


Fig. 2. Plan view of the generic cellular office rooms (a) room depth = 3 m, (b) room depth = 6 m or 9 m. 'o' represents the locations of the illuminance level reference points.

Table 4
Facade design variables for the generic cellular office room.

Input variable	Unit	Minimum value	Maximum value
Room geometry			
Room width (RW)	M	3	9
Room depth (RD)	M	3	9
Floor to ceiling room height (RH)	M	2.7	3.9
Façade parameters			
Window-to-wall ratio (WWR)	%	40[a]	100
Glazed portion U-value (U_g)	$W/m^2 K$	0.5[b]	3[c]
Glazed portion g-value (g)	%	0	78[d]
Glazed portion light transmittance (V_t)	%	0	82[d]
Opaque façade panel U-value (U_p)	$W/m^2 K$	0.5	2.5
Effective area of operable window (WS)	m^2/m^2 floor area	0.01	0.1
Initial capital cost of glazed portion (C_g)	€/m^2	610	735
Initial capital cost of opaque portion (C_p)	€/m^2	690	815
HVAC parameters			
Cooling set point temperature (CSPT)	°C	24	26
Heating set point temperature (HSPT)	°C	17	19
Infiltration rate (IR)	m^3/m^2 h at 50 Pa	3[e] [25]	10[f] [25]
Plant sizing factor (SF)	/	0.7[g]	1.0
Energy cost			
Electricity cost (EC)	€/kWh	0.15	0.3

[a] As the research focuses on predominantly glazed façades, a WWR of 40% is used as the lower boundary.
[b] Corresponds to centre-of-glazing U-value of triple glazing (4 mm glass + 12 mm Krypgon + 4 mm glass + 12 mm Krypgon + 4 mm glass), with Surface 2 and 5 low-e coated.
[c] Corresponds to the overall U-value of a 1 m × 1 m clear double glazing unit (4 mm glass + 10 mm air + 4 mm glass, centre-of-glazing U-value = 2.8 W/m^2 K) with a thermally broken aluminium frame (U-value = 2.22 W/m^2 K, frame width = 25 mm, linear heat transfer coefficient ψ = 0.08). This gives an overall U-value of 3 W/m^2 K.
[d] Corresponds to clear double glazing unit (4 mm glass + 10 mm air + 4 mm glass).
[e] Defined as a very tight building by Building Regulations Part L2A [26].
[f] Corresponds to a building that complies with Building Regulations Part L2A [26].
[g] Undersized by 30%.

(Fig. 4). The depth of the perimeter zones is fixed at 6 m. The occupancy density is assumed to be 6 m^2/person [13]. The internal heat gain from lighting and equipment are 12 W/m^2 and 25 W/m^2, respectively. Two illuminance level reference points are located at third points along the depth of the perimeter zones at a height of 0.8 m. The illuminance level set point is 500 lux. Automated continuous dimming lighting control is implemented. Assumptions on shading devices and operable window control strategies and the HVAC system are identical to the cellular office room described in Section 2.1. The 34 facade-intrinsic/extrinsic variables and 57 performance indicators are listed in Tables 6 and 7, respectively.

2.3. Calculation of energy demand and the corresponding energy cost

EnergyPlus 7.0 [11] was used to calculate the annual heating energy demand E_h, annual cooling energy demand E_c, and annual lighting energy demand E_l for all the cellular and open-plan office design scenarios. The total energy demand E_{tot} is calculated from:

$$E_{tot} = E_c + E_h + E_l \tag{1}$$

It is assumed that all the energy is provided by electricity at a rate of EC, and the discount rate is 4.35%. The service life of the façade is assumed to be 25 years. The total operational energy cost M_e(€) for 25 years is:

$$M_e = E_{tot} \times \sum_{n=1}^{n=25} \frac{\text{EC}}{(1+4.35\%)^n} \tag{2}$$

The energy demand (heating, cooling, lighting and total) and the total energy cost is normalised with respect to the office floor area.

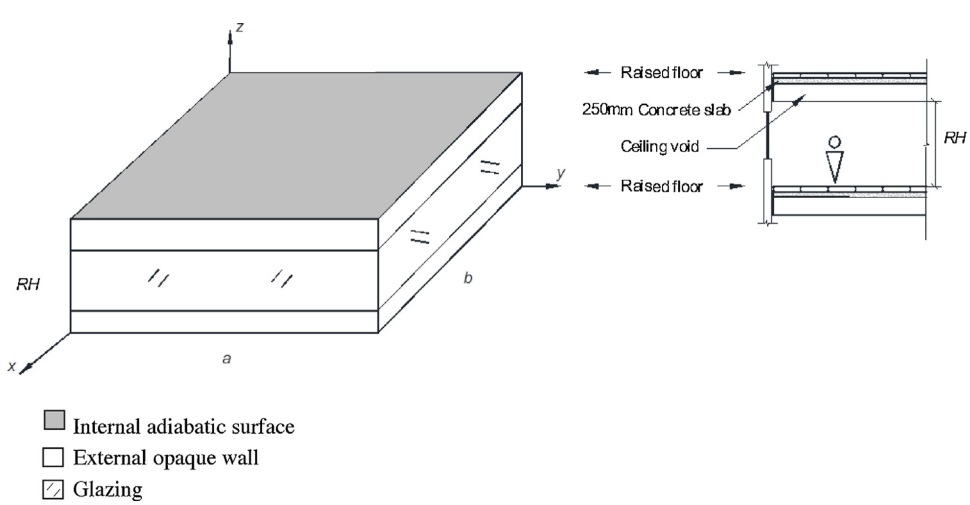


Fig. 3. 3-D view and plan section of the generic open-plan office floor.

Table 5
Facade performance indicators for the generic cellular office room.

Output variable	Unit
Energy demand	
Heating (E_h)	kWh/m^2 of floor area
Cooling (E_c)	
Lighting (E_l)	
Total (E_{tot})	
Comfort	
Acceptance of thermal comfort (C_{therm})	%
Acceptance of air quality (C_{air})	
Acceptance of light level (C_{light})	
Overall acceptance of indoor environment quality (IEA)	
Economic cost	
Initial capital cost—façade (M_f)	€/m^2 floor area
Initial capital cost—plant (M_p)	
Operational energy cost (M_e)	
Loss of productivity (M_{IEQ})	
Whole life cost (sum of the four above) (M_{WLC})	

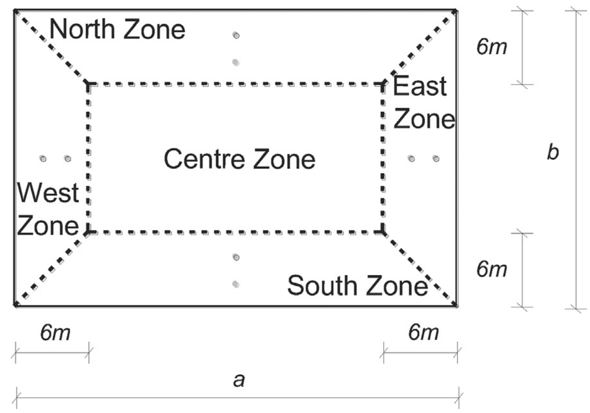


Fig. 4. Plan view of the generic open-plan office floor. 'o' indicates the locations of the illuminance level reference points.

2.4. Calculation of comfort indicators and the corresponding employment cost

The comfort indicators proposed by Wong et al. [15] are adopted in this analysis, namely: acceptance of thermal comfort (C_{therm}_N, C_{therm}_E, C_{therm}_S, C_{therm}_W, C_{therm}_C), air quality (C_{air}_N, C_{air}_E, C_{air}_S, C_{air}_W, C_{air}_C), light level (C_{light}_N, C_{light}_E, C_{light}_S, C_{light}_W), and the overall indoor environmental quality (IEA_N, IEA_E, IEA_S, IEA_W, IEA_C) to determine the comfort levels for all the cellular and open-plan office scenarios. The inputs required for quantifying acceptance values are occupancy-weighted annual average PPD, CO_2 concentration ζ_1 and light level ζ_2, which are calculated in a two-step process:

(1) EnergyPlus 7.0 [11] is used to calculate the hourly PPD, hourly CO_2 concentration, and hourly light level by adopting the following assumptions. It is assumed that the work efficiency of the human body for office work is 0, i.e., all the energy produced in the body is converted to heat and none is converted to mechanical energy, and the air velocity is assumed to be 0.05 m/s [16]. The metabolic rate of people for office work is 1.2 met [25]. The clothes level is assumed to be 0.7 for summer (May–Sep) 0.85 for winter (Jan–Apr, Oct–Dec) [25]. The indoor noise level is constantly at 41 dBA [25]. The CO_2 level in the atmosphere is 390 ppm [37].

(2) The occupancy-weighted annual average PPD, CO_2 concentration ζ_1 and light level ζ_2 are calculated using Eqs. (3)–(5):

$$\text{weighted annual average PPD} = \sum_{h=0}^{h=8760} w_h \text{PPD}_h \tag{3}$$

$$\text{weighted annual average } \zeta_1 = \sum_{h=0}^{h=8760} w_h \zeta_{1,h} \tag{4}$$

Table 6
Facade design variables for the generic open-plan office floor.

Input variable	Unit	Minimum value	Maximum value
Floor geometry			
Floor dimensions when aspect ratio is 1:1 (FD)*	M	16	60
Aspect ratio (a:b in Fig. 4) (AR)*		1:3	3:1
Floor to ceiling room height (RH)	M	2.7	3.9
Façade parameters			
Window-to-wall ratio of the north (WWR_N), east (WWR_E), south (WWR_S), and west (WWR_W) facades	%	40	100
Glazed portion U-value for the north (U_g_N), east (U_g_E), south (U_g_S), and west (U_g_W) facades	W/m^2 K	0.5	3
Glazed portion g-value of the north (g_N), east (g_E), south (g_S), and west (g_W) facades	%	0	78
Glazed portion light transmittance for the north (V_t_N), east (V_t_E), south (V_t_S), and west (V_t_W) facades	%	0	82
Opaque façade panel U-value for the north (U_p_N), east (U_p_E), south (U_p_S), and west (U_p_W) facades	W/m^2 K	0.5	2.5
Effective area of operable window for the north (WS_N), east (WS_E), south (WS_S), and west (WS_W) facades	m^2/m^2 of floor area	0.01	0.1
Initial capital cost of glazed portion (C_g)	€/m^2	610	735
Initial capital cost of opaque portion (C_p)	€/m^2	690	815
HVAC parameters			
Cooling set point temperature (CSPT)	°C	24	26
Heating set point temperature (HSPT)	°C	17	19
Infiltration rate (IR)	m^3/m^{2}h at 50 Pa	3	10
Plant sizing factor (SF)	/	0.7	1.0
Energy cost			
Electricity cost (EC)	€/kWh	0.15	0.3

Table 7
Facade performance indicators for the generic open-plan office floor.

Output variable	Unit
Energy demand	
Heating for each zone and total (E_h_N, E_h_E, E_h_S, E_h_W, E_h_C, E_h_tot,)	kWh/m^2 floor area
Cooling for each zone and total (E_c_N, E_c_E, E_c_S, E_c_W, E_c_C, E_c_tot)	
Lighting for each perimeter zones and total (E_l_N, E_l_E, E_l_S, E_l_W, E_l_tot)*	
Total energy demand each zone and total (E_t_N, E_t_E, E_t_S, E_t_W, E_t_C, E_t_tot)	
Comfort	
Acceptance of thermal comfort for each zone (C_{therm}_N, C_{therm}_E, C_{therm}_S, C_{therm}_W, C_{therm}_C)	%
Acceptance of air quality for each zone (C_{air}_N, C_{air}_E, C_{air}_S, C_{air}_W, C_{air}_C)	
Acceptance of light level for each perimeter zone (C_{light}_N, C_{light}_E, C_{light}_S, C_{light}_W)	
Overall acceptance of indoor environment quality for each zone (IEA_N, IEA_E, IEA_S, IEA_W, IEA_C)	
Economic cost	
Total initial capital cost of façade (M_f)	€/m^2 floor area
Initial capital cost of plant for each zone and total (M_p_N, M_p_E, M_p_S, M_p_W, M_p_C, M_p_tot)	
Total operational energy cost (M_e_tot)	
Cost of occupant productivity loss for each zone (M_{IEQ}_N, M_{IEQ}_E, M_{IEQ}_S, M_{IEQ}_W, M_{IEQ}_C, M_{IEQ}_tot)	
Total whole-life cost (sum of the above) (M_{WLC})	

*E_c_C omitted as artificial lighting is required continuously in centre zone.

$$\text{weighted annual average } \zeta_2 = \sum_{h=0}^{h=8760} w_h \zeta_{2,h} \tag{5}$$

where w_h is the weight of the occupancy in hour h.

The employment cost for commercial offices in Inner London in 2010 is taken as €58,841 [18]. Discounted at 4.35% for 25 years, the present value is €869,815 per occupant. The productivity loss due to suboptimal indoor environmental quality (M_{IEQ}_N, M_{IEQ}_E, M_{IEQ}_S, M_{IEQ}_W, M_{IEQ}_C, M_{IEQ}_tot) are calculated from:

$$M_{IEQ} = \left(1 - \frac{\text{Maximum occupant productivity}}{\text{occupant productivity in current design}}\right) \times 724,846 \tag{6}$$

where the maximum occupant productivity is 90.6% [19], and the occupant productivity for a facade design scenario is obtained using the 'multi-variant IEQ-productivity' relationship proposed by Jin et al. [20], which provides a quantitative relationship between indoor environmental quality and occupant productivity. The employment cost is expressed in €/m^2 of office floor area.

3. Sensitivity analysis

Two fundamentally different sensitivity analyses methods are adopted, namely: (1) standardised regression analysis [21], which is a sampling-based method and (2) Sobol's method [22], which is a variance-based method. Both methods provide quantitative measures of the sensitivity of the output variables.

Standardised regression analysis [21] performs regression analyses on the input and output variables. It eliminates the effects of different units of the input variables by standardising the input and output variables by the ratio of the standard deviation to the mean. For example, a standardised regression coefficient (SRC) of 0.5 indicates that a change of one standard deviation in the input variable will result in a change of 0.5 standard deviations in the output variable. The positive/negative sign of an SRC indicates that the input variable is positively/negatively correlated to the output variable. For example, the SRC between visible transmittance of the window and lighting energy demand is negative, which means that a higher visible transmittance of the window leads to a lower lighting energy demand.

Sobol's method [22] determines the importance of input variables using a ratio of the input variable-related variance to the output variable variance. Two sensitivity indices can be computed from Sobol's method. One is Sobol's first index S_f that accounts for the first order effect of the input variable on the output variable, the other is the Sobol's total index S_t, which accounts for both the direct effect of the input variable and its interaction with other input variables. Therefore, an S_f of 0.2 indicates that the variation in the input variable (e.g. g-value) alone leads to a 20% variation in the output variable (e.g. cooling energy demand); whereas an S_t of 0.1 shows that the variation in the input variable and its interaction with other input variables, (e.g. the interaction between g-value and visible transmittance) leads to a 10% variation in the output variable (e.g. cooling energy demand). S_f and S_t are calculated using multi-dimensional Monte Carlo integration [23].

The sensitivity analysis was carried out using the Simlab software [24], which is interfaced with Matlab 7.10 [17]. The process (Fig. 5) is automated and consists of: (1) a sensitivity analysis method is selected in Simlab; (2) Simlab generates the required number of input variable samples according to the sensitivity analysis method; (3) Matlab send the sets of input variables to EnergyPlus for evaluation, and the output variables are generated directly by EnergyPlus or further calculations are performed as described in Sections 2.3 and 2.4; (4) Matlab sends the input and output variables to Simlab for sensitivity analyses; (5) the sensitivity indices are generated by Simlab.

The analysis was carried out on a Windows-based PC with a 2.66 GHz processor and 3.25 GB of RAM. For the cellular office room scenarios, the standardised regression analysis required 300 samples (i.e., 300 combinations of input variables) to be evaluated by EnergyPlus, with a run time of 1 h. The Sobol's method required 9000 samples to be evaluated, with a run time of 34 h. For the open-plan office floor scenario, the standardised regression analysis required 1000 samples and a run time of 11 h. The Sobol's method required 18,000 samples and a run time of 200 h.

4. Results and discussion

4.1. Visualisation and rationalisation of results

The SRCs and Sobol's total indices are tabulated and shaded according to their absolute values. Darker shades indicate higher sensitivities. The input variables that have |SRC| < 0.05 or Sobol's total coefficient <0.02 across the board indicate very low sensitivities and have therefore been omitted for brevity.

4.2. Cellular office scenarios

The results for a cellular office facing south in London from standardised regression analysis and the Sobol's methods are summarised in Table 8. The results for the other three orientations are not included in the paper for brevity, but they can be accessed in the Supplementary Data (Table A.1, Table A.2 and Table A.3). The pairs of tables show very similar shaded patterns. This means that the two sensitivity analysis methods produce a similar ranking of influencing input variables for a particular output variable. For example, both methods indicate that heating energy demand

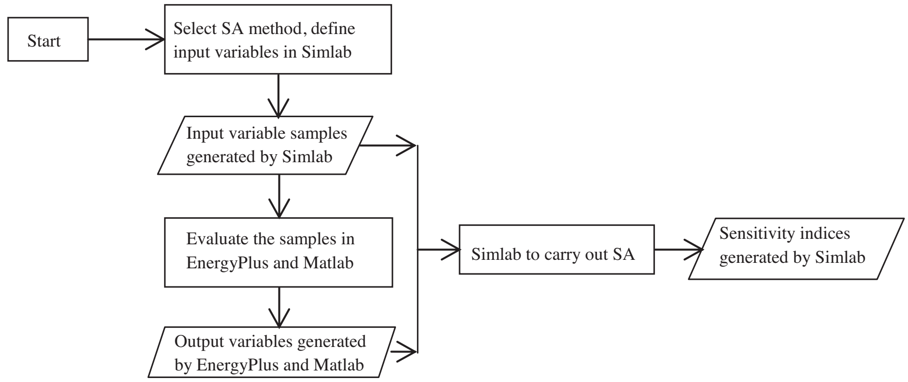


Fig. 5. Sensitivity analysis process (SA = sensitivity analysis).

is governed by the same three input variables (i.e., room depth, glazing *U*-value, and infiltration rate).

As expected, different orientations also lead to different rankings of input variables, e.g., Table 8 and Table A.1 show that the most effective strategy for reducing heating energy demand is to reduce the glazing *g*-value of the south facade rather than to change the heating set-point temperature, whereas the effectiveness of these two variables is reversed for the north facade. Glazing properties, room geometry, infiltration, and temperature control strategies have a high impact on the energy demands and thermal comfort. Some other key dependencies are apparent for the cellular office in London, namely: (i) unsurprisingly, infiltration rate is essential for air quality. (ii) WWR, visible transmittance, and room depth are important for improving daylighting. (iii) Apart from room geometric variables, the operational energy demand for south, east, and west orientation are very sensitive to the *g*-value of glazing. (iv) Whole-life cost and IEQ cost have almost identical sensitivity indices, indicating that IEQ cost is a good indicator of whole-life cost. Therefore, it is essential to create a comfortable indoor environment in order to achieve the highest possible value during the whole service life of a facade. The complete sensitivity coefficient charts for Helsinki and Rome are not included in this paper for

Table 8
Sensitivity coefficient charts for south orientation cellular office in London (a) SRC and (b) S_t. (Darker shades indicate higher sensitivity).

(a)		Output variables												
		E_l	E_h	E_c	E_{tot}	C_{therm}	C_{air}	C_{light}	IEA	M_f	M_p	M_e	M_{IEQ}	M_{WLC}
Input variables	*RW*	-0.08	0.00	0.08	0.05	-0.11	-0.15	0.07	-0.09	0.00	-0.62	-0.01	0.48	0.48
	RD	0.41	-0.56	-0.22	-0.49	0.32	-0.23	-0.40	0.23	-0.93	-0.70	0.33	0.15	0.13
	RH	-0.12	0.18	0.02	0.11	-0.05	0.22	0.12	-0.03	0.31	-0.01	0.07	0.04	0.05
	WWR	-0.37	0.01	0.24	0.25	-0.23	0.06	0.39	-0.10	-0.07	0.03	0.20	0.13	0.13
	U_g	-0.03	0.50	-0.18	0.03	-0.06	-0.09	0.02	-0.13	0.00	-0.01	-0.02	0.15	0.15
	g	-0.04	-0.23	0.83	0.66	-0.41	0.30	0.05	-0.31	-0.01	0.10	0.41	0.23	0.23
	V_t	-0.75	0.06	-0.04	-0.12	0.03	-0.03	0.74	0.24	0.00	0.01	-0.11	-0.16	-0.16
	U_p	0.02	0.11	0.02	0.07	-0.06	-0.01	-0.02	-0.08	0.00	0.01	0.02	0.07	0.07
	C_g	0.00	0.00	-0.01	-0.01	-0.02	0.00	0.01	-0.01	0.08	0.01	-0.01	0.00	0.00
	CSPT	-0.01	-0.01	-0.17	-0.17	-0.61	-0.08	-0.01	-0.56	0.00	-0.03	-0.10	0.45	0.45
	HSPT	0.01	0.23	-0.01	0.09	0.26	-0.01	-0.01	0.40	0.00	-0.02	0.02	-0.39	-0.40
	IR	0.01	0.38	-0.12	0.04	-0.05	0.79	-0.02	0.02	0.00	-0.01	0.06	0.03	0.03
	SF	-0.02	-0.03	0.04	0.02	0.02	-0.07	0.02	0.03	0.01	0.05	0.03	-0.02	-0.02
	EC	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	-0.01	-0.01	-0.01	0.36	0.02	0.02

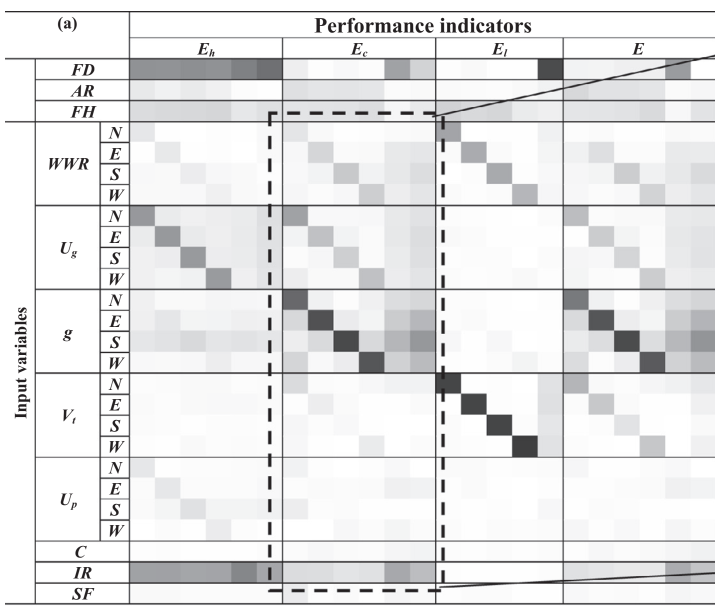
(b)		Output variables												
		E_l	E_h	E_c	E_{tot}	C_{therm}	C_{air}	C_{light}	IEA	M_f	M_p	M_e	M_{IEQ}	M_{WLC}
Input variables	*RW*	0.00	0.00	0.01	0.01	0.04	0.03	0.01	0.06	0.00	0.49	0.01	0.38	0.38
	RD	0.09	0.44	0.24	0.42	0.13	0.08	0.14	0.11	0.91	0.60	0.82	0.14	0.13
	RH	0.01	0.06	0.01	0.03	0.01	0.06	0.01	0.01	0.10	0.00	0.01	0.01	0.01
	WWR	0.11	0.03	0.19	0.16	0.09	0.01	0.18	0.09	0.01	0.00	0.06	0.06	0.06
	U_g	0.00	0.29	0.05	0.02	0.04	0.02	0.00	0.05	0.00	0.00	0.01	0.04	0.04
	g	0.00	0.10	0.72	0.48	0.32	0.12	0.00	0.37	0.00	0.01	0.23	0.32	0.32
	V_t	0.79	0.00	0.00	0.02	0.01	0.00	0.66	0.08	0.00	0.00	0.01	0.07	0.07
	CSPT	0.00	0.00	0.02	0.02	0.42	0.01	0.00	0.40	0.00	0.00	0.01	0.40	0.40
	HSPT	0.00	0.05	0.00	0.01	0.08	0.00	0.00	0.15	0.00	0.00	0.01	0.09	0.09
	IR	0.00	0.12	0.02	0.01	0.01	0.70	0.00	0.01	0.00	0.00	0.00	0.01	0.01
	EC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00

Table 9
Sensitivity coefficient charts for south and north facing cellular office in Rome, London, and Helsinki (SRC).

	Rome						London						Helsinki					
	E_{tot}		C_{therm}		M_{WLC}		E_{tot}		C_{therm}		M_{WLC}		E_{tot}		C_{therm}		MWLV	
	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N	S	N
WWR	0.19	0.11	-0.17	-0.13	0.12	0.02	0.25	0.12	-0.23	-0.15	0.13	0.00	0.13	0.06	-0.14	-0.10	0.06	0.03
U_g	-0.09	-0.06	0.03	-0.04	0.06	0.14	0.03	0.22	-0.06	-0.22	0.15	0.28	0.28	0.37	-0.26	-0.33	0.26	0.29
g	0.80	0.61	-0.48	-0.20	0.27	0.01	0.66	0.31	-0.41	-0.03	0.23	-0.10	0.22	0.08	-0.02	0.10	-0.05	-0.10
V_t	-0.15	-0.32	0.05	0.03	-0.20	-0.26	-0.12	-0.26	0.03	-0.06	-0.16	-0.15	-0.08	-0.10	-0.03	-0.04	-0.07	-0.08
CSPT	-0.19	-0.37	-0.75	-0.83	0.61	0.52	-0.17	-0.22	-0.61	-0.51	0.45	0.24	-0.09	-0.06	-0.31	-0.18	0.09	0.02
HSPT	0.05	0.11	0.08	0.19	-0.15	-0.29	0.09	0.18	0.26	0.45	-0.40	-0.60	0.14	0.15	0.71	0.74	-0.62	-0.65
IR	-0.03	0.05	0.03	-0.02	-0.04	-0.02	0.04	0.20	-0.05	-0.11	0.03	0.04	0.30	0.37	-0.07	-0.10	-0.01	0.00

brevity, but they can be accessed in the Supplementary Data. A selection of the results are also listed and compared with London in Table 9. Similar to London, both sensitivity methods indicate that heating energy demand is governed by the same three input variables (i.e., room depth, glazing U-value, and infiltration rate). Three major differences can be identified between Rome, Helsinki, and London. Firstly, the impact of heating set-point temperature on energy demands, thermal comfort, and whole-life cost in Rome is much smaller than that in London (the opposite applies for the cooling set-point temperature). Compared to London, the heating set-point temperature in Helsinki has a larger influence on the energy demands and occupant comfort (the opposite applies for the cooling set-point temperature). Secondly, the impact of glazing U-value on the total energy demand and thermal comfort for different orientations in London vary considerably from one orientation to another, i.e., a larger impact for the north orientation and a smaller impact for the south orientation. In contrast, glazing U-value has similarly small impacts for all orientations in Rome

Table 10
Sensitivity coefficient charts for energy demand output variables for open-plan office in London (a) SRC, (b) S_t, (c) an expanded portion of (a).



(c)	E_c_N	E_c_E	E_c_S	E_c_W	E_c_C	E_c_tot
WWR_N	0.11	0.03	0.00	0.01	0.02	0.03
WWR_E	0.03	0.18	0.02	0.02	0.10	0.11
WWR_S	0.03	0.05	0.24	0.06	0.10	0.15
WWR_W	0.04	0.02	0.03	0.22	0.08	0.11
U_g_N	-0.44	-0.03	-0.03	-0.03	-0.09	-0.13
U_g_E	-0.05	-0.28	-0.05	-0.02	-0.10	-0.14
U_g_S	-0.01	-0.03	-0.21	-0.02	-0.09	-0.14
U_g_W	-0.07	-0.02	-0.02	-0.28	-0.08	-0.11
g_N	0.73	0.06	0.01	0.07	0.15	0.18
g_E	0.18	0.83	0.09	0.05	0.23	0.33
g_S	0.08	0.16	0.86	0.17	0.34	0.49
g_W	0.19	0.03	0.08	0.81	0.20	0.31
V_t_N	-0.15	-0.01	-0.01	-0.03	-0.05	-0.05
V_t_E	-0.01	-0.07	-0.02	0.00	0.00	-0.02
V_t_S	-0.03	-0.01	-0.03	0.00	0.00	0.00
V_t_W	-0.03	0.00	0.00	-0.08	0.00	-0.01
U_p_N	-0.05	0.00	0.00	0.01	0.03	0.00
U_p_E	-0.01	-0.02	-0.01	-0.02	-0.06	-0.05
U_p_S	-0.07	0.02	-0.01	0.00	0.00	0.00
U_p_W	0.00	0.00	-0.03	-0.01	-0.04	-0.01
C_g	-0.01	-0.03	-0.02	-0.02	-0.04	-0.05
IR	-0.15	-0.15	-0.11	-0.13	-0.40	-0.30

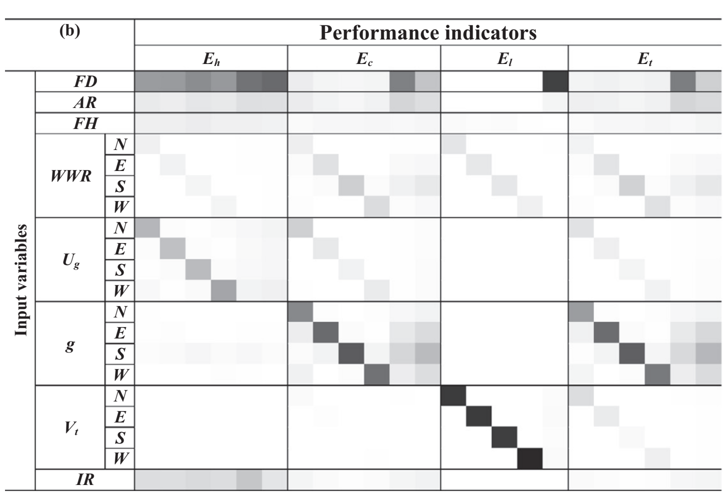


Table 11
Sensitivity coefficient charts for open-plan office floor in Rome, London, and Helsinki (SRC).

		Rome			London			Helsinki		
		E_L tot	IEA_N	IEA_S	E_L tot	IEA_N	IEA_S	E_L tot	IEA_N	IEA_S
WWR	***N***	0.02	0.12	0.03	0.02	0.02	0.00	0.04	-0.07	0.01
	E	0.16	-0.04	0.01	0.09	0.00	0.01	0.15	-0.01	0.01
	S	0.16	0.01	-0.02	0.16	0.01	-0.06	0.18	0.00	-0.05
	W	0.11	0.00	-0.03	0.11	0.02	0.01	0.11	-0.03	-0.02
U_g	***N***	-0.03	-0.39	-0.06	-0.10	-0.49	-0.06	0.01	-0.57	-0.06
	E	-0.08	-0.03	-0.05	-0.12	-0.08	-0.08	-0.01	-0.07	-0.05
	S	-0.08	-0.05	-0.37	-0.12	-0.05	-0.45	-0.03	-0.05	-0.58
	W	-0.08	-0.07	-0.03	-0.09	-0.06	-0.05	-0.04	-0.03	-0.03
g	***N***	0.21	0.21	0.00	0.18	0.19	0.02	0.18	0.14	0.01
	E	0.40	0.04	0.01	0.35	0.10	0.06	0.33	0.07	0.03
	S	0.40	0.04	0.17	0.50	0.07	0.19	0.40	0.04	0.30
	W	0.37	0.02	0.05	0.31	0.04	0.05	0.29	0.03	0.03
V_t	***N***	-0.10	0.49	0.02	-0.10	0.10	0.02	-0.11	0.04	0.02
	E	-0.02	0.01	-0.02	-0.06	0.00	0.01	-0.03	0.00	0.00
	S	-0.08	0.00	0.52	-0.02	-0.01	0.24	-0.08	0.01	0.09
	W	-0.03	0.02	0.00	-0.06	-0.02	-0.01	-0.06	-0.01	0.00

and Helsinki. Thirdly, the key variable for reducing total energy demand in London and Rome is glazing *g*-value, furthermore, the total energy demands in Rome are more sensitive to glazing *g*-value than those in London. In comparison, the key design variable for reducing total energy demand in Helsinki is glazing *U*-value and infiltration rate. These differences can be attributed to the generally warmer weather and higher solar heat gain in Rome than those in London.

4.3. Open-plan office scenarios

The results calculated by standardised regression analysis and the Sobol's method for the energy demand output variables of a generic open-plan office in London are summarised in. The full sensitivity coefficients are omitted for brevity, but can be accessed from in the Supplementary Data (Table A.4–A.6). The output variables are arranged in the following order left to right: north, east, south, west, centre zones and total. The lighting-related performance indicator E_C_C for the centre zone is omitted from, because it is assumed that the centre zone is completely artificially lit continuously during working hours and hence the input variables have no impact on the lighting-related performance indicators. Good agreements between the two methods are observed.

Table 10 shows that the energy demands for the open-plan office in London are sensitive to glazing properties, room geometry, and infiltration rates. The heating energy demand depends mainly on floor size, *U*-value, and infiltration rate. Cooling energy demand depends is mainly influenced by WWR, *U*-value and *g*-value. Since the open-plan office floor in London is cooling dominated, the sensitivity coefficient chart for total energy demands and cooling energy demand are similar. For any given floor area, glazing *U*-value, infiltration rate and *g*-value are the three variables that have the highest influence on cooling energy demand (c). The infiltration rate has a negative effect on thermal comfort, but a positive effect on air quality. The net effect of infiltration rate on overall IEQ is negative (Table A.5), therefore if the design objective is to improve overall IEQ, the infiltration rate should be minimised. This is because the thermal comfort dominates the overall comfort. Both methods suggest that the sensitivity indices of whole-life cost and IEQ cost are almost identical (Table A.6), indicating that IEQ cost is a good indicator of the whole-life cost. Some interactions between the zones are worth noting. For example, a change of one standard deviation in window *g*-value on the south façade account for a change of 0.16 and 0.17 standard deviations in the cooling energy demand in the east zone and the west zone, respectively (c). The full sensitivity coefficient charts for Helsinki and Rome are not included in this paper for brevity, but they can be accessed in the Supplementary Data (Tables A.11–A.13, A.18–A.20). According to Table 11, window-to-wall ratio and glazing *g*-value are the key factors for controlling total energy demand in the three locations. The influence of glazing *U*-value on total energy demand in Helsinki is much lower than that in London or Rome. This is probably because a low *U*-value keeps undesirable heat from dissipating from the buildings in London and Rome, which leads to a high cooling energy demand. But this effect is beneficial in Helsinki which unlike London and Rome is heating dominated. In Rome, glazing visible transmittance makes a significant contribution to the acceptance of IEQ, because a lower visible transmittance leads to more artificial lighting, which generates more undesirable internal heat gain. This effect has a significantly lower influence in the cooler climate of Helsinki.

A notable difference between the cellular office room and open-plan office floor is that the former is more sensitive to the HVAC parameters (Table 4), while the latter is more sensitive to the façade parameters (Table 6). This can be seen from two observations: (1) in London the thermal comfort indicators of the open-plan office floor are most sensitive to the façade *U*-value, *g*-value and visible transmittances (Table A.5), while the thermal comfort in the cellular office room is more sensitive to the heating and cooling set point temperatures (Table 8, Table A.1, Table A.2, Table A.3); (2) the façade infiltration rate has a large impact on the energy demand and comfort indicators (except for the lighting associated ones) for the open-plan office, but the impact is much lower in the cellular office. This is probably because the cellular office has lower internal heat gain and much smaller volume, which makes it easier to control. In contrast, the open-plan office floor has much higher volume and internal heat gain, making it more difficult to control. Therefore, the facades play a more significant role in the performance of the open-plan office space.

5. Conclusions

This paper describes the sensitivity analyses performed on a generic cellular office room and a generic open-plan office floor in three locations: London, Helsinki, and Rome. The results are presented in the form of sensitivity coefficient charts that provide quantitative relationships between a comprehensive list of early-stage design variables (room/building geometry, façade properties, HVAC parameters, energy price) and façade performance indicators (including energy demand, comfort, and costs). The charts can be used to identify the design variables that have highest impacts on the performance indicators. For example, for the office spaces considered in this paper, g-value plays an essential role in affecting the cooling energy demand. A notable difference between the cellular office room and the open-plan office floor is that the former is more sensitive to HVAC parameters while the latter is more sensitive to the facade parameters. Similar results obtained from standardised regression analysis and Sobol's method increase the confidence in the validity of these results. The sensitivity coefficient charts 396 may therefore provide a guide for allocating the limited design 397 time and construction budget to the design variables that will 398 generate largest impacts on the performance indicator of interest. The sensitivity charts can be readily applied in the façade design of cellular office room/open plan office floor in locations with similar climates to London/Helsinki/Rome, but extrapolating the results to other building types and climates may lead to incorrect conclusions.However, similar charts cold be produced for other building scenarios or locations. Further experimental validation of the sensitivity coefficient charts would be particularly useful, but this would clearly involve considerable experimental resources.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2014.03.038.

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