IMPACTS OF ARCHITECTURAL DESIGN CHOICES ON BUILDING ENERGY PERFORMANCE APPLICATIONS OF UNCERTAINTY AND SENSITIVITY TECHNIQUES

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ABSTRACT

In this paper, a sensitivity analysis has been carried out on a set of variables identified during the building conceptual design stage.

The sensitivity analysis is performed on a simple intermediate floor of a typical multi-storey office representative of the office building sector for different Italian climatic zones.

The conclusions are drawn in terms of sensitivity indexes of energy performance indicators for a set of different design variables and for different climatic zones. A multi-linear regression analysis is carried out to develop the polynomial approximation of the energy performance indicators.

INTRODUCTION

During the last decades, a large research activity has been dedicated to the architectural design choices during the preliminary conceptual design stage for code compliance, energy saving, environmental impacts purposes. Traditionally, the used approach is based on a discrete number of alternative solutions – orientation, building envelope transmittance, window size and transmittance … – with a base case which plays the role of a reference against which the different solutions are compared (Shaviv E., 1978, Almeida P.F., 2007, Pushkar S. et al. 2005. Wildea P. et al., 2002). The results from the analysis are the best solutions in terms of energy or environmental impacts.

In this paper, we suggest a different approach based on continuous alternative solutions of design choices, applying uncertainty and sensitivity techniques, to analyze some indicators of building energy performance. The first part of the work concerns the identification and description of the design variables. Variables will be synthetic, simple and related to architectural significance. The second part is dedicated to the description of the case study: a simple intermediate floor of a typical multi-story office is used as a generic case study for office buildings sector. Uniform density probability functions (with upper and lower bounds) are assigned for the different design variables. In the third part, the Latin hypercube method is used for generating random values of design variables. Then, simulations are performed, repetitively with Monte Carlo technique, using the quasi-steady simplified monthly method, specified in ISO 13790:2008 (ISO, 2008), to calculate the energy needs for heating and cooling for the generates sample.

After that, the mean and the variance of the heating and cooling energy needs for the case study considering five sites representing five different climatic zones are calculated. The analysis of variance Fourier Amplitude Sensitivity Test (FAST) method is used for the sensitivity analysis to distribute the variance to the different design variables. A multilinear-regression analysis is used to find a polynomial approximation for the energy needs for heating and cooling.

DESIGN VARIABLES RELATIONSHIPS

The design variables in the conceptual design stage in building construction are defined as the variables that describe the building in the conceptual phase. Variables have to be synthetic, simple and meaningful either from thermal engineering or from architectural point of views: therefore architects can take rational conclusions easily.

The following aspects, related to the building, were considered in the analysis: shape, orientation, glazed facade area, external shading devices, outer color and internal thermal heat capacity (uncontrollable variables such as internal heat sources or air change rate are not considered as desing varaibles because they depend on inhabitant's behavior).

Building shape

At the preliminary design stage, the shape of buildings is often settled accordingly to aesthetics and landscape urbanism constraints. Energy performance criteria are less involved in this work step even though the building shape represents an important factor for building performance purposes. The building shape determinates how large is the surface exposed to the external environment and then provides information about the heat gain and loss through the envelope.

CEN standard EN 15217 (CEN, 2007) presents two parameters to identify the shape of a building:

- the ratio of thermal envelope area to volume, called compactness ratio (A_e/V_c [m^{-1}]);
- the ratio of thermal envelope area to the conditioned floor area, called the building shape factor (A_e/A_c [-]).

The building shape is used in the assessment of the heat transfer by transmission defined as:

$$\Phi_{\mathbf{tr}} = \sum_k A_k U_k \left(\theta_{\mathbf{i}} - \theta_{\mathbf{e,k}}\right) \quad (1)$$

where U_k is the thermal transmittance of the element k adjacent to a space or to an external environment at a temperature $\theta_{e,k}$ and θ_i is the set-point temperature.

Building orientation

The building orientation represents an important aspect in the preliminary design stage: usually, buildings are oriented for the best landscape urbanism and accessibility. The building orientation (φ [°]) has an impact on heating, cooling and lighting energy consumption. It affects the amount of solar radiation entering through the transparent and opaque elements determined by equations (2, 3).

Glazed building facades area

The glazed building façades are often applied in modern office buildings for aesthetics and daylighting purposes. The solar radiation, which penetrates through the windows, is absorbed by the interior furnishings and the internal partitions and after a certain time contributes to the heat load. The glazed building façades areas are characterized by:

- the ratio transparent area to thermal envelope area (A_t/A_e [-]);
- the ratio transparent area to the conditioned floor area (A_t/A_c [-]).

The glazed building façades ratio is used in the assessment of the heat transfer by transmission through windows equation (1) and for internal heat sources calculation defined by:

$$\Phi_{\mathbf{sol}} = \sum_k F_{sh,ob} . F_{sh,gl} . g . A_{tk} . I_k(\varphi) \quad (2)$$

where $F_{sh,ob}$ *and* $F_{sh,gl}$ are respectively the shading reduction factor for external fixed shading and movable and interior shading, g is the total solar energy transmittance and I is the average solar irradiance.

Building outer color

The building outer color is an important aspect in the building appearance. In energy terms, building outer color controls the absorption and emission of shortwave radiation. A white surface absorbs about 40% of the received solar irradiation, whereas dark green, brown and black surfaces absorb about 90%. The Building outer color is described through the absorptance (α [-]).

The building outer color is used in the solar heat gain through opaque elements as follow:

$$\Phi_{\mathbf{sol}} = \sum \alpha . R_{se} . U_k . A_{ek} . I_k(\varphi) . - F_r . \Phi_r \quad (3)$$

F_r is the form factor between the building element and the sky, Φ_r is the extra heat flow due to the thermal radiation to the sky form the building and R_{se} is the external surface heat resistance.

External shading reduction factor

The fixed exterior solar shading devices such as overhangs and vertical fins are designed by architects. They control the amount of sunlight entering to the indoor ambient and consequently contributing to an increase or decrease of the energy demand. The external shading reduction factor is characterized by the shading coefficient $F_{sh,ob}$ which represent the ratio of the solar irradiation reaching the window to the solar irradiation that would reach the window without any shading device.

Building internal effective heat capacity

The building effective heat capacity is related to internal partitions and furnishings. It plays an important role to reduce indoor temperature fluctuations and energy use: the thermal mass absorbs heat during the day when an overheating occurs and then releases back heat during the night. From an architectural design point of view, the building effective heat capacity is interpreted in terms the level of the open space. It is described through the C_i per unit of floor [kJ/°C m^2].

The building effective heat capacity is used in the calculation of the building time constant τ defined as:

$$\tau = \frac{C + C_i}{H} \quad (4)$$

Where H is the total heat loss coefficient and C is the building envelope effective heat capacity.

The time constant is used to calculate the gain/loss utilization factor defined as:

$$\eta_{\mathrm{H,gn/C,ls}} = \frac{1 - \gamma^{\pm a_{\mathrm{H/C}}}}{1 - \gamma^{\pm(a_{\mathrm{H/C}} + 1)}} \quad (5)$$

where γ is the heat balance ratio and $a_{H/C}$ is a dimensionless numerical parameter depending on the building time constant.

CASE STUDY

Mid-floor office description

A very simple intermediate floor of a typical multi-storey office building was used for the illustration of the suggested methodology. The first draft of the intermediate floor scheme consists on:

- the floor is planned to hold 20 persons with a useful area of 400 m^2 and a height of 3 m;
- the windows are distributed symmetrically and uniformly over the different lateral surface;
- the floor shape is rectangular;

- the opaque and light elements transmittances are set up to their limit values (Table 2) accordingly to energy Italian code compliance (Italian Parliament, 2005);
- the building envelope effective heat capacity per unit is equal to 40 kJ/°C m^2;
- the shading heating gain coefficients (not including the external reduction factor ratio) are set up to 0.65 and 0.36 respectively for the heating season and for the cooling season.

The typical office intermediate floor is located between two similar conditioned modules. The internal heat sources are 5 W/m^2 and the ventilation change rate is 0.5 h^{-1}.

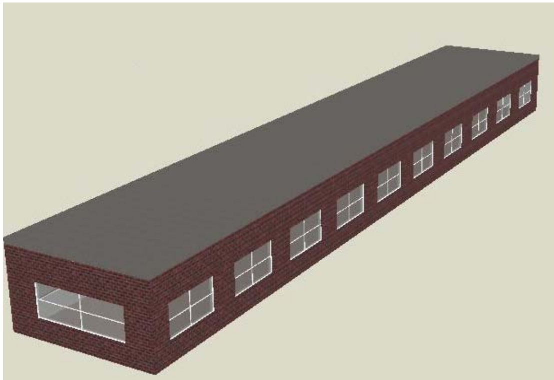

Figure 1 intermediate floor of a typical multi-story office

Design variables setting

All the design variables are distributed uniformly. We adopt the uniform distribution since we suppose that the architect made choices for every design variables independently of any constraints (energy environmental, aesthetics…). Below we set the upper and the lower limits for every design variables. Those bounds are chosen so that to generalize conclusions to office building sector. In Table 1, ranges and commnets about bounds are presented:

Climatic data

The simulations are performed for five towns situated in different climatic zones in Italy (Table 2). The yearly mean external temperature and the yearly mean daily irradiation on horizontal plan are shown in Figure 2 (UNI, 1994).

Table 2
U limit values for Italian climatic zones

Zone	Degree days	Town	$U_{limt,opq}$ (W/m^{2}K)	$U_{limt,W}$ (W/m^{2}K)
B	601-900	Palermo	0.48	3.0
C	901-1400	Bari	0.40	2.6
D	1401-2100	Roma	0.36	2.4
E	2101-3000	Turin	0.34	2.2
F	More than 3000	Cuneo	0.33	2.0

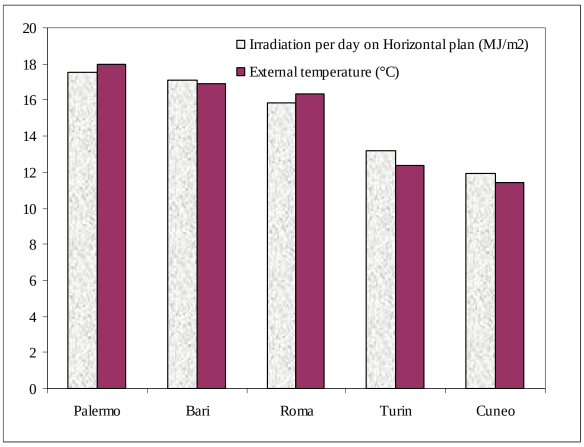

Figure 2 climatic data for the different towns

Table 1
Design variables

Design variable	Symbol	Unit	Range	Comments
Compactness ratio	A_e/V_c	[m^{-1}]	[0.2, 0.3]	0.2 refers to a square shape and 0.3 refers to a minimum width of the office floor of 6 m.
Orientation	ϕ	[°]	[0, 180]	0° refers to the South orientation for the main surface
Ratio of glazed building facades area to envelope area	A_t/A_e	[-]	[0.2, 0.9]	All possible values of the ratio A_t/A_e with a minimum value of 0.2.
Absorptance	α	[-]	[0.1, 0.9]	0.1 refers to lights colors and 0.9 to dark colors.
External shading reduction factor	$F_{sh,ob}$	[-]	[0, 0.3]	0 refers to no external fixed shading devices. 0.3 is the maximum value of $F_{sh,ob}$ in office buildings.
Internal heat capacity	C/A	[kJ/°Cm^2]	[10, 100]	10 corresponds to an open space floor and 100 to an office repartition of the floor.

SIMULATIONS

Method of calculation

The quasi-steady simplified monthly method, presented in ISO 13790:2008 (ISO, 2008) was used to calculate the energy needs.

The energy needs for space heating is calculated, for each building zone and for each calculation period (month), as:

$$Q_{\mathrm{H,nd}} = Q_{\mathrm{H,ht}} - \eta_{\mathrm{H,gn}} Q_{\mathrm{H,gn}} \qquad (6)$$

where ($Q_{H,ht}$) is the heat transfer by transmission and ventilation, ($\eta_{H,gn}$) is the gain utilization factor for the heating mode and ($Q_{H,gn}$) is the heat gain from solar and internal sources during the heating season.

The energy need for space cooling is calculated, for each building zone and for each calculation period (month), according to:

$$Q_{\mathrm{C,nd}} = Q_{\mathrm{C,gn}} - \eta_{\mathrm{C,ls}} Q_{C,\mathrm{ht}} \qquad (7)$$

where ($Q_{C,ht}$) is the heat transfer by transmission and ventilation, ($\eta_{C,ls}$) is the loss utilization factor for the cooling mode and ($Q_{C,gn}$) is the heat gain from solar and internal sources during the cooling season.

A sample matrix, containing the six design variables, was generated using the Latin Hypercube sampling technique, while the Monte Carlo technique was used to evaluate the outputs of interest for each sample element.

The freeware Monte Carlo simulation software Simlab 2.2 (JRC, 2002) was used for the random sampling and post processing analysis.

MC-Latin Hypercube Sampling

The Monte Carlo analysis is based on repeated simulations; the outputs of interest are evaluated for each element of the sample matrix.

The Latin Hypercube Sampling technique achieves a better coverage of the sample space of the input factors. The sample space *S* of an input factor is partitioned into h disjoint intervals $S_1 \ldots S_h$ of equal probability *1/h*. One random input value is then selected from each interval S_i and the process is repeated *k* times, where *k* is the sample length.

The mean value and standard deviation of the vector outputs are calculated as:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad (8)$$

and the standard deviation using:

$$\sigma = \sqrt{\frac{\sum_i (y_i - \mu)^2}{(n-1)}} \qquad (9)$$

Variance decomposition – FAST technique

Variance decomposition techniques allow the computation of the contribution of each input factor to the output's variance (Fang, 2003). The variance is defined as the dispersion of the output to the mean value. The techniques are based on the decomposition of the model variance into:

- first order sensitivity index, S_i due to each input data;
- second order sensitivity index S_{ij} due interactions between any pair of input factors *i* and *j* ($\neq i$), which cannot be explained by the sum of the individual effects due the two factors. Analogously, we defined higher order sensitivity indexes ($S_{1..i...n}$) due to the interactions between more factors;
- total sensitivity index, S_{Ti} is the sum of the first order sensitivity index of the factor under investigation and the higher sensitivity index involving this factor.

Some input factor importance classifications have been suggested (Chan k., 1997):

- Very important: $0.8 < S_{Ti}$
- Important: $0.5 < S_{Ti} < 0.8$
- Unimportant: $0.3 < S_{Ti} < 0.5$
- Irrelevant: $S_{Ti} < 0.3$

The condition $S_{Ti} = 0$ is necessary and sufficient for X_i to be a non-influential factor. If $S_{Ti}=0$, then X_i can be fixed at any value within its range interval without appreciably affecting the output variance (Saltelli, 2008).

The calculation of the sensitivity indexes may be performed by ANalysis Of VAriance methods (ANOVA) such as the Fourier Amplitude Sensitivity Test (FAST) or the Sobol method.

The FAST method was introduced in the 70s by Cukier (Cukier, R. I, 1973). Preliminary, FAST classic computes only the main effects contribution and the first order sensitivity index S_i. The FAST classic method was improved by Saltelli in 2000 to an extended FAST method allowing the computation of the second order sensitivity index and the high order sensitivity index (Saltelli A., 1999). For more details about the assessment of the sensitivity indexes see the appendix.

Regression analysis

A muli-linear regression analysis was applied to a set of inputs and a set of outputs allowing the construction of a polynomial function that fitted a model's response *Y*.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \varepsilon \qquad (11)$$

where β_i are the regression coefficients or polynomial coefficients computed by least square regression analysis.

RESULTS

Variance assessment

The mean values and the standard deviations of the energy needs per unit of floor area for heating and cooling seasons, for the different sites, were calculated using MC-LHS with a sample of 100 data for every input. In Figure 3, the mid-point represent the mean point and the bar length is equal to two standard deviation.

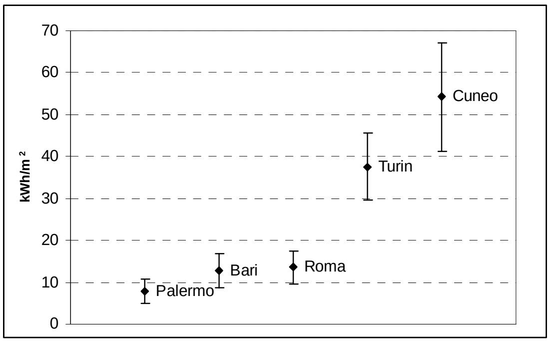

Figure 3 Mean and standard deviation of the energy needs for heating – five sites

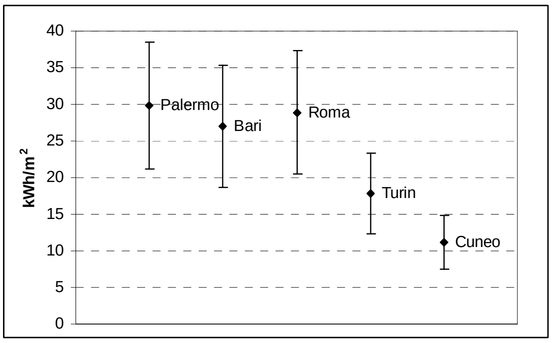

Figure 4 Mean and standard deviation of the energy needs for cooling – five sites

A large dispersion of energy needs, with a ratio of standard deviation to mean around 30 %, is noted for all the case studies.

A more elaborated analysis consists of a compliance check of the heating energy needs with the limits provided by the Italian energy code. Table 2 illustrates the limits of heating energy needs as a function of the compactness ratio enforced since 1st January 2010 for a celing height of 3 m (Italian Parliament, 2005). Table 3 provides the space heating limits for a compactness ratio between 0.2 and 0.3 obtained with a linear interpolation from the Table 2.

An overlapping between the results of Figure 3 and the limit values for A_e/V_c equals to 0.3 (Table 3) provides a good evidence that the value of the output is slightly crossing the limit for Palermo, Bari, Roma. However, in the cases of Cuneo and Turin, there is a high probability (around 50%) that the energy heating distribution is above the limit. Consequently, defining limit values for heating energy needs as a function of the compactness ratio is insufficient to ensure energy code compliance. Thus, there is a necessity to perform an analysis of variance to find which parameters have the biggest influence on the output variability.

Table 2
Limit values of heating energy needs per unit of floor[kWh/m^2] according to Italian energy code

	Climate Zone (HDD)					
	A	B	C	D	E	F
A_e/V_c	601	900	1400	2100	3000	
≤0.2	6	10.8	18	28.8	38.1	
≥0.9	24.6	38.4	51.9	67.5	93	
=0.3	8.7	14.7	22.8	34.3	45.9	

Table 3
Limit values of heating energy needs per unit floor [kWh/m^2]

	Palermo	Bari	Roma	Turin	Cuneo
A_e/V_c	751	1034	1415	2617	3012
0.2	8.4	12.7	18.2	34.1	38.1
0.3	11.7	16.9	23.1	41	45.9

Sensitivity index assessment

In tables 4 and 5, the first order sensitivity indexes are provided for the five sites and for energy needs for heating and for cooling. As the values are closed from a location to another, a pie graph is presented only for Palermo (Figures 5 and 6). In each pie the total variance of the case study is distributed among the different contributions due to the first-order effects of each input and to the interactions of all orders. Since the interactions do not explain a high amount of the variance they are summed up in a single term.

Table 4
First order sensitivity index - heating energy needs

	Palermo	Bari	Roma	Turin	Cuneo
A_e/V_c	0.15	0.16	0.15	0.19	0.18
ϕ	0.07	0.06	0.08	0.04	0.05
A_t/A_e	0.54	0.56	0.54	0.65	0.69
α	0.00	0.00	0.00	0.00	0.00
F	0.05	0.06	0.07	0.05	0.03
C	0.16	0.14	0.13	0.04	0.02
Others	0.02	0.02	0.03	0.03	0.03

Table 5
First order sensitivity index - cooling energy needs

	Palermo	Bari	Roma	Turin	Cuneo
A_e/V_c	0.07	0.07	0.07	0.06	0.06
ϕ	0.09	0.10	0.06	0.06	0.05
A_t/A_e	0.79	0.79	0.82	0.82	0.80
α	0.00	0.00	0.00	0.00	0.01
F	0.04	0.04	0.04	0.05	0.07
C	0.00	0.00	0.00	0.00	0.02
Others	0.00	0.00	0.00	0.00	0.00

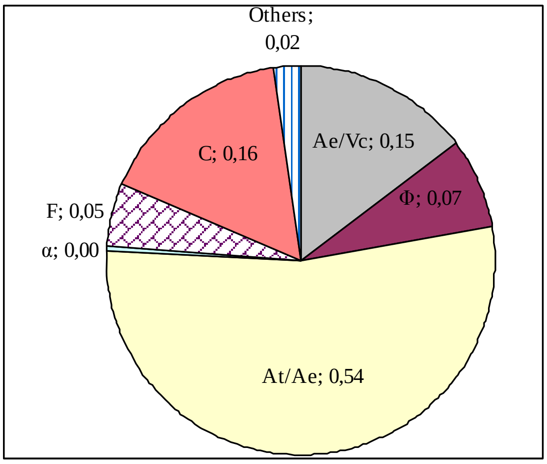

Figure 5 Decomposition of the total variance of the energy needs for heating – case Palermo (interactions of all orders are grouped in a single term)

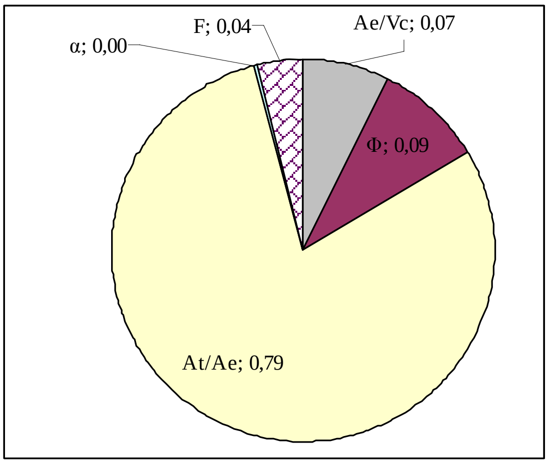

Figure 6 Decomposition of the total variance of the energy needs for cooling – case Palermo

Figure 5 and Table 4 stress that the variance of energy needs for heating is mainly influenced by the glazed building façade area and by the building shape with a large contribution of the ratio A_t/A_e; more than 50% for the different locations.

Besides, Table 4 highlights that climatic data have an effect on the sensitivity index of A_t/A_e and C: the contribution of the ratio A_t/A_e on the variance is significant in cold zones at the opposite of the variable *C* whose contribution is significant in hot climates. The reduction shading factor and the building orientation have closed values of first sensitivity index and are not important. The outer color can be fixed at any value of its range (S_T=0.01).

As regards the sensitivity indexes for the cooling energy needs, important differences are stressed in comparison to the heating mode: an intensive contribution of the A_t/A_e ratio and a negligible value for the internal thermal heat capacity sensitivity index. The building shape, the building orientation and the reduction shading factor are unimportant and have sensitivity indexes values around 0.07 (Figure 6 and Table 5).

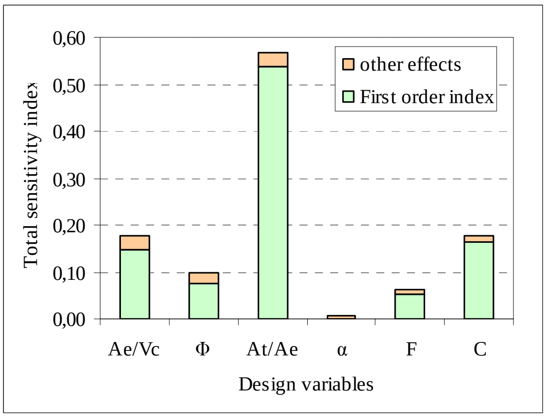

Figure 6 Sharing of the total order index S_T for the different design variables - Energy needs for heating – Case Palermo.

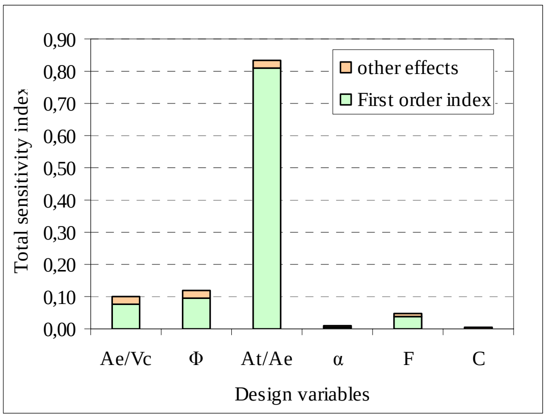

Figure 4 Sharing of the total order index S_T for the most important design variables - Energy needs for cooling – Case Palermo.

Regression analysis

The regression analysis aimed to perform a simple polynomial approximation for heating energy needs and for cooling energy needs. Thus, architects can substitute equations (6, 7) with more simple equations using only the design variables as polynomial variables for the different climatic zones to defined energy needs for heating and cooling as:

$$Q_{\mathrm{H,nd}} = \beta_0^h + \beta_1^h . \frac{A_e}{V_c} + \beta_2^h . \phi + \beta_3^h . \frac{A_t}{A_e} + \beta_4^h . \alpha + \beta_5^h . F + \beta_6^h . C \tag{12}$$

$$Q_{\mathrm{C,nd}} = \beta_0^c + \beta_1^c . \frac{A_e}{V_c} + \beta_2^c . \phi + \beta_3^c . \frac{A_t}{A_e} + \beta_4^c . \alpha + \beta_5^c . F + \beta_6^c . C \tag{13}$$

Table 5
Polynomial coefficients - heating energy needs

	Palermo	Bari	Roma	Turin	Cuneo
β_0^h	-5.21	-6.04	-5.07	-7.02	-17.69
β_1^h	37.89	52.75	53.06	116.32	188.01
β_2^h	-0.009	-0.01	-0.001	-0.013	-0.022
β_3^h	9.18	12.82	12.7	29.06	48.27
β_4^h	-0.70	-0.94	-1.01	-1.83	-3.08
β_5^h	10.60	15.42	14.95	27.07	35.32
β_6^h	-0.046	-0.06	-0.059	-0.070	-0.095
R^2_{adj}	92.6 %	93.7 %	91.8 %	95.0 %	95.2 %

Table 6
Polynomial coefficients - cooling energy needs

	Palermo	Bari	Roma	Turin	Cuneo
β_0^c	2.67	-2.44	-3.36	-1.37	-0.663
β_1^c	87.45	80.58	82.99	50.72	32.031
β_2^c	-0.0163	-0.02	-0.0067	-0.0042	-0.00149
β_3^c	35.29	33.54	34.74	22.77	14.93
β_4^c	1.44	1.06	0.973	0.80	1.02
β_5^c	-35.19	-5.05	-33.94	-25.69	-18.35
β_6^c	-0.0183	-0.02	-0.0125	-0.0153	-0.0211
R^2_{adj}	89.0 %	87.9 %	91.6 %	91.1 %	91.5 %

Using Minitab tool (Minitab, 2009) and inputs and the outputs provided by MC-LHS already performed, the different polynomial coefficients, β_i^h, β_i^c and the adjusted residual R^2_{adj} are calculated and presented in Tables 5 and 6.

CONCLUSIONS

In this study, an office floor was taken as a case study to investigate the importance of some design variable in the early building conceptual stage. A set of design variables was selected, a range of variability was assigned for every variable. The selections of the variability ranges were made as to encompass the office building sector in order to generalize the conclusions.

The conclusions of the study are the followings:

- the dispersions of the energy needs are very significant;
- complying with the Italian energy code defining the limits for thermal transmittance is not enough for heating energy code compliance;
- as regards the heating energy needs, the most significant factors are the building glazed façade area, with a contribution from 0.54 to 0.69, and building shape, with a contribution around 0.17;
- as regards the cooling energy needs, the most significant factors are the building glazed façade area, with a contribution around 0.8, the building shape, the building orientation and the reduction shading factor, with a contribution around 0.07;
- the building outer color has no influence and can be fixed at any value of its range.

It is important to note that sensitivity index values depend on the range width: for instance if we increase the upper limit of the building shape ratio to 1.0 the first order sensitivity index of A_e/V_c increases from 15% to 60%.

APPENDIX

The sensitivity indexes are defined through the expected value *E* and the variance *V*.

$$S_j = \frac{V\left[E(Y / X_j = \tilde{X}_j)\right]}{V(Y)}$$

$$S_{ij} = \frac{V\left[E(Y / X_i = \tilde{X}_i, X_j = \tilde{X}_j)\right]}{V(Y)} - \frac{V\left[E(Y / X_i = \tilde{X}_i)\right] - V\left[E(Y / X_j = \tilde{X}_j)\right]}{V(Y)}$$

$$S_{Tj} = S_j + \sum_{\substack{i=1 \\ i \neq j}}^{k} S_{ji} + \sum_{\substack{i=1 \\ i \neq j,m,j<m}}^{k} S_{jim} + \ldots + S_{j1\ldots k}$$

$$\sum_{j=1}^{n} S_j + \sum_{\substack{i=1 \\ i \neq j}}^{k} S_{ji} + \sum_{\substack{i=1 \\ i \neq j,m,j<m}}^{k} S_{jim} + \ldots + S_{j1\ldots k} = 1$$

Where Y denotes the model output, X_j denotes an input factor, $E(Y/X_j)$ is the expectation of Y conditional on an X_j and the variance V is taken over all the possible values of X_j.

The variance is given by:

$$V(Y) = \int_{D_1} \ldots \int_{D_k} [E(Y) - f(X_1, X_2, \ldots, X_k)]^2 . \prod_{i=1}^{i=k} P(X_i) dX_i$$

The expected value is given by:

$$E(Y) = \int_{D_1} \ldots \int_{D_k} f(X_1, X_2, \ldots, X_k) . \prod_{i=1}^{i=k} P(X_i) dX_i$$

The FAST method is based on the transformation that converts the variance of a variable Y, which is a k-dimensional integral, to a single dimensional integral with respect to a scalar variable s, by transforming each input factor X_i to be of the form $X_i = G_i(\sin(\omega_i s))$, for an appropriate set of transformations G_i and integer frequencies ω_i (Campolongo F.1997). The transformation for FAST analysis is:

$$E(Y) = \int_{D_1} \int_{D_2} \ldots \int_{D_k} f(X_1, X_2, \ldots, X_k) . \prod_{i=1}^{i=k} P(X_i) dX_i =$$

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} f(G_1 \sin(\omega_1 s), \ldots, G_k \sin(\omega_k s)) . \prod_{i=1}^{i=k} P(G_i \sin(\omega_i s)) ds$$

NOMENCLATURE

A_e/V_c : building shape;

Φ : heat flow;

ϕ : orientation;

A_t/A_e : glazed building facades area;

α : solar absorptance;

$F_{sh,ob}$: external shading reduction factor;

C : internal effective heat capacity;

A_e: thermal envelope building;

A_c: conditioned area;

A_t: transparent area;

V_c: conditioned volume;

$U_{limt,opq}$: limit value of thermal transmittance for opaque elements;

$U_{limt,W}$: limit value of thermal transmittance for windows;

S_i: Sensitivity index.

μ : Mean value

σ : Standard deviation

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