A STATISTICAL METHOD TO IMPROVE THE ENERGY EFFICIENCY OF AN OFFICE BUILDING

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ABSTRACT

There is an increasing demand for energy efficient and environment-friendly buildings with a high thermal comfort. On the other hand, the Kyoto protocol binds the developed countries to reduce the emission of greenhouse gases at least by 5% by 2008-2012. Some of the measures of the governments to achieve this goal are to improve energy efficiency of buildings and energy systems, to develop sustainable building concepts and to promote renewable energy sources.

This paper presents an optimisation technique based on the design of experiments method (DOE) widely used in the industrial field for process quality improvement. This method is used to optimize the envelope characteristics of an office building in order to improve its energy performance.

KEYWORDS

Design of experiments, Taguchi method, low energy buildings, energy consumption reduction, energy efficiency.

INTRODUCTION

Lots of effort has been devoted to promote sustainable and energy efficient construction. For this purpose, many project and standards have been created. Thomsena et al (2005) presented the results obtained from measurements and experiences gained from interviews on 12 advanced solar low energy houses designed and built as part of the International Energy Agency Solar Heating and Cooling Programme (IEA-shc). An energy saving of 60% compared with typical houses was achieved. Buildings complying with the Passive House standard are rapidly spreading across Germany, Austria Switzerland and Belgium. Wolfgang et al (2005) introduces the Passive House standard and summarizes results of the EU project "Cost Efficient Passive Houses as European Standards" (Cepheus) with respect to energy indices and comfort. It has been confirmed that indoor temperatures at and above the design value can be maintained in Passive Houses with a combined ventilation and air heating system. Moreover, many research projects on zero energy buildings are initiated in the USA, Canada and Japan (CSTB 2007).

The underlying Passive building concept is based on a holistic approach, improving the building envelope to a degree that allows substantial simplifications of the heating and cooling system. The improvements to make on the building envelope depend on the climate characteristics. In cold climate for instance, the major energy demand will be for heating, thus building thermal insulation and air-tightness should be enhanced in priority. In hot climate, the major improvement should concern the cooling demand decreasing by using solar protection, smart building orientation, good thermal inertia coupled with night ventilation, etc.

A parametric study via simulation tools could help the engineers to choose the adapted solutions to the climate context. However, there is lot of parameters in the building envelope which has an impact on the building energy efficiency such as the building thermal insulation, the building orientation, the area of glazed surface, the windows type, the air-tightness, the thermal inertia and so on. Furthermore, there is an interaction between some parameters, which is not easy to quantify via a simple parametric study. Analyzing the influence of each parameter and the interaction between them with a simple parametric study is rather complicated and requires a large number of simulations.

In this paper an optimisation methodology based on a statistical method called the design of experiments (DOE) is proposed. The main advantage of this method is the limited required number of simulations to find the optimum solution and to assess the influence of each parameter and the interaction between them. This method was also used by Filfli (2006) to reduce the energy consumption of tertiary buildings using conventional techniques only. However the application of the design of experiments method (DOE) was only for conventional buildings and not for low energy buildings as the case of our study.

This work consists of a numerical analysis following the DOE method to optimize the envelope of an office building in order to design a very low energy building. First, a description of the DOE method is given. Then the office building and the climate context are described. Finally we will outline the effect of the envelope parameters and the interaction between them as well as the obtained optimal solution.

THE DOE METHOD

Definition

During an experiment, we deliberately change one or more process variables (factors) in order to observe the effect the changes have on one or more response variables. The statistical design of experiments (DOE) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions (Pillet 1997, Goupy 1999).

Process models for DOE

The statistical theory underlying DOE generally begins with the concept of process models. The studied system is considered as a black box (see Figure 1). Experimental data obtained from the DOE are used to derive an empirical approximation model linking the response and the factors. These empirical models generally contain first and second-order terms.

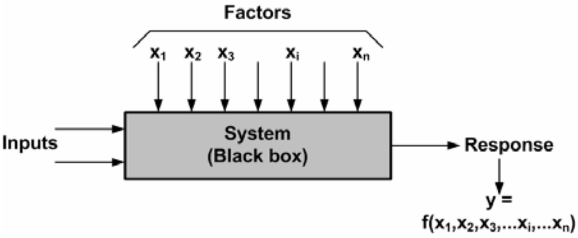

Figure 1: A black box process model schematic

The most common empirical models fit to the experimental data take either a linear form or quadratic form. A linear model with n factors, x_i, can be written as:

$$y = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i,j}^{n(n-1)/2} a_{ij} x_i x_j \qquad (1)$$

Here, y is the response for given levels of the main factors x_i. The $x_i x_j$ terms are included to account for a possible interaction effect between x_i and x_j factors. The a_i coefficients are the mean effects of the x_i factors on the process response. The a_{ij} coefficients represent the interaction between x_i and x_j factors. The a_0 coefficient corresponds to the response in the centre of the experiment domain (when the x_i factors are equal to zero).

Full factorial design

A common experimental design is one with all input factors set at two levels each. These levels are called "high" and "low" or "+1" and "-1", respectively. The use of two level factors is only possible if the process response is linear between the two levels. A design with all possible high/low combinations of all the input factors is called a full factorial design in two levels. Table 1 represents the design table of a 4 runs experiment. Each factor is set to high or low during a run according to whether the matrix had a +1 or -1 set for the factor during that trial. If the experiment had more than 2 factors, there would be an additional column in the matrix for each additional factor. Full factorial designs allow computing all the possible interactions.

Table 1: Full factorial design table for a 2 factor experiment

	x_1	x_2
Run 1	-1	-1
Run 2	+1	-1
Run 3	-1	+1
Run 4	+1	+1

If there are k factors, each at 2 levels, a full factorial design has 2^k runs. When the number of factors is 6 or greater, a full factorial design will require a large number of runs and is not very efficient In this case, the use of fractional factorial design is recommended.

Fractional factorial design - The Taguchi method

Fractional factorial design is defined as a factorial experiment in which only an adequately chosen fraction of the treatment combinations required for the complete factorial experiment is selected to be run.

Even if the number of factors, k, in a design is small, the 2^k runs specified for a full factorial can quickly become very large. For example, $2^7 = 128$ runs are for a two-level, full factorial design with seven factors. To this design we need to add a good number of centre point runs and we can thus quickly run up a very large resource requirement for runs with only a modest number of factors. The solution to this problem is to use only a fraction of the runs specified by the full factorial design. The chosen fractional factorial design for experiments should respect some properties among them, the orthogonality. The orthogonality means that the sum of the products of the corresponding elements of any two vectors in the design table is equal to zero.

The Taguchi method, after the name of its author, the Japanese engineer and statistician, Dr. Genichi

Taguchi, offers a ready to use orthogonal design arrays (or tables) for fractional factorial design of experiments. The design tables exist for different numbers of runs and different factors level (Pillet 1997). The application of this technique had become widespread in many US and European industries after the 1980s.

The process model coefficients calculation

The coefficients of the linear model (see equation 1) could be calculated via a simple matrix multiplication (Goupy 1999).

Let's consider the example of the Table 1. If we add an "I" column and an "x1.x2"column to the matrix of 4 trials, we will obtain what is known as the model or analysis matrix for this simple experiment (see Table 2).

Table 2: Analysis Matrix for a 2 factor experiment

I	x_1	x_2	$x_1.x_2$
+1	-1	-1	+1
+1	+1	-1	-1
+1	-1	+1	-1
+1	+1	+1	+1

The model for this experiment is expressed by the following equation:

$$y = a_0 + a_1 x_1 + a_2 x_2 + a_{12} x_1 x_2 \tag{2}$$

The "I" column of the design matrix has all +1's to provide for the a_0 term. The $x_1.x_2$ column is formed by multiplying the x_1 and x_2 columns together, row element by row element. This column gives interaction term for each trial.

In matrix notation, equation (2) is summarized by:

$$[Y] = [X] \cdot [A] \tag{3}$$

X is the 4 by 4 design matrix of 1's and -1's shown above, A is the vector of unknown model coefficients (a_0, a_1, a_2, a_{12}) and Y is a vector consisting of the four trial response observations.

The unknown elements of the A vector are calculated as following:

$$[A] = (\mathrm{tr}[X] \cdot [X])^{-1} \cdot \mathrm{tr}[X] \cdot [Y] \tag{4}$$

A limited number of experiments allow identifying the empirical process model. This model could be used to analyse the effect of each factors and the interaction between them as well as to optimize the process response.

THE CLIMATE CONTEXT

This study was carried out for the climate of the French city Nice, located in the south of France on the Mediterranean Sea.

The climate of Nice is rather hot. Table 3 gives some key data of the climate characteristics. Figure 2 shows the cumulative frequency distribution of the outside air temperature (RT, 2005).

Table 3: Climate characteristics

T_{min} [°C]	3.0
T_{max} [°C]	30.3
$DH_{(19\,°C)}$ [°C.h]	38078
$DH_{(26°C)}$ [°C.h]	435
$DH_{(20\text{-}26°C)}$ [°C.h]	5750
Φ_{solar}[kWh/m²]	1482

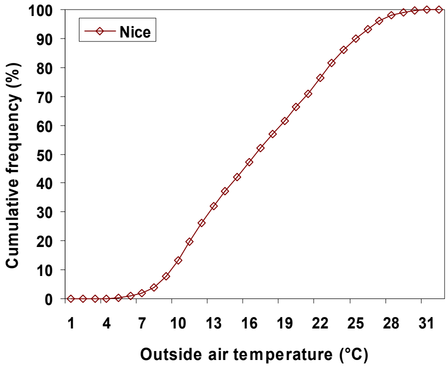

Figure 2: Cumulative frequency distribution of the outside air temperature

OFFICE BUILDING DESCRIPTON

The studied building is a three-storey office building with a total floor area of 540 m². Figure 3 to Figure 5 show the top view of the building.

The office building has a total floor area of 540 m² and a volume of 1620 m³. The ventilation air change rate is equal to $0.68h^{-1}$. The infiltration air change rate is $0.72h^{-1}$ under 4Pa of pressure difference. The envelope average heat transfer coefficient value is equal to 0.95 W/m²K. These characteristics were chosen according to the French thermal regulation (RT, 2005). The internal heat gain due to occupancy and equipments is equal to 10.6W/m². The average artificial lightning power is 11.1W/m².

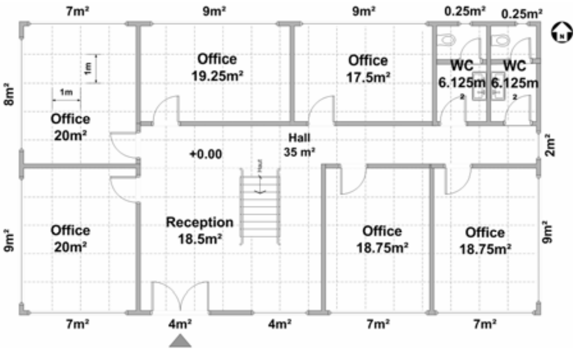

Figure 3: Top view of the building ground floor

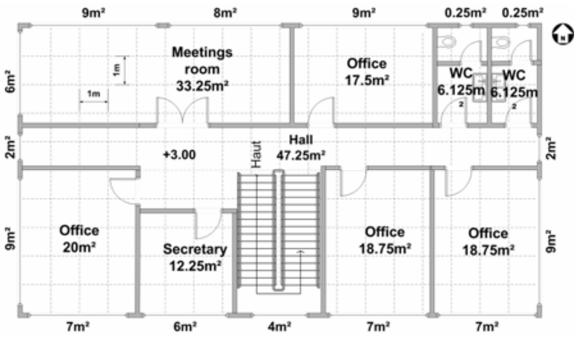

Figure 4: Top view of the building first floor

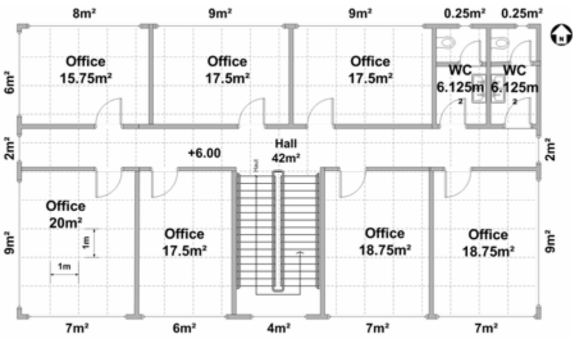

Figure 5: Top view of the building second floor

The annual energy performance of the office building with these envelope characteristics and internal gains will be evaluated and considered as a "reference case" to which the energy performance of the improved office building will be compared.

MODELS USED FOR THE SIMULATIONS

Simulations were carried out using SIMBAD Toolbox (SIMBAD, 2005), developed by the CSTB in Matlab/Simulink environment (SIMULINK, 2005).

Before the application of the DOE method to the office building, annual simulations were performed in order to evaluate the energy performance of the office building (reference case). The energy performance concerns the heating and cooling demand of the building, the total final energy consumptions and the annual performance of the HVAC system. The HVAC system consists of a mechanical extract ventilation system for building air renewing and a reversible heat pump coupled to a fan coil system for building heating and cooling. The yearly performance of the heat pump system was used in the DOE method application.

The models used to perform the simulations are described in the following sessions.

The building model

The building thermal behaviour is simulated using the multizone building model of SIMBAD developed by EL Khoury et al (2005). This model was validated against experimental data and other building models (EL Khoury et al. 2005, Neymark et al 2004, Neymark 2004).

Thermal zone

The multizone building model in SIMBAD is a transient model with one air node per zone, representing the thermal capacity of the zone air volume. Each air zone is assumed to be homogeneous in temperature. The heat balance equation of an air node takes into account the convective heat exchange between the air and the walls, the convective gains due to ventilation, infiltration and air flow from other zones, and the internal convective gains (from people, equipments, etc.). It is expressed as following:

$$\begin{aligned}\rho_a V_i \frac{dT_{a,i}}{dt} &= \sum_p h_{con,p} A_p \left(T_{w,p} - T_{a,i}\right) \\ &+ \sum_j \dot{m}_{vent,j} cp_a \left(T_{vent,j} - T_{a,i}\right) \\ &+ \sum_j \dot{m}_{ji} cp_a \left(T_{a,j} - T_{a,i}\right) \\ &+ \dot{m}_{inf,i} cp_a \left(T_{a,out} - T_{a,i}\right) \\ &+ \left(\sum_t \psi_t L_t\right)\left(T_{a,out} - T_{a,i}\right) + P_{gc}\end{aligned} \tag{5}$$

The radiation heat balance of each zone enables the evaluation of the mean radiant temperature:

$$\sum_p h_{rad,p} A_p \left(T_{w,p} - T_{mr,i}\right) = 0 \tag{6}$$

Walls model

Multilayer walls are modelled using constant thermo-physical properties of each layer. The heat transfer process across the wall is considered as one dimensional. It is described by the following one dimensional heat diffusion equation:

$$\rho cp \cdot \frac{\partial T_w(x,t)}{\partial t} = \lambda \cdot \frac{\partial^2 T_w(x,t)}{\partial x^2} \tag{7}$$

The boundary conditions on the two surfaces of the wall are:

$$-\lambda \cdot \left.\frac{\partial T_w(x,t)}{\partial x}\right|_{x=0} = h_{c,1}\left(T_{a,1} - T_w(0,t)\right) + P_{rad,1} \tag{8}$$

$$-\lambda \cdot \left.\frac{\partial T_w(x,t)}{\partial x}\right|_{x=L} = h_{c,1}\left(T_{a,2} - T_w(L,t)\right) + P_{rad,2} \tag{9}$$

Windows model

The window is described using a two-node model. It is thermally considered as an external wall with no thermal mass, partially transparent to solar radiation and opaque to long-wave radiation. The model takes into account the variation of the solar optical properties such as solar transmissivity and absorptivity with respect to the incident angle of the solar radiation.

The infiltration model

An infiltration model was developed basing on the norm prEN 15242 (2005). This method is suitable to be used for applications such as energy calculations, heat and cooling load calculation, summer comfort and indoor air quality evaluation. It consists of solving the mass balance equation for one air zone. The air zone corresponds to one building floor. We have thus three air zones.

The mass balance equation for an air zone is expressed by:

$$\dot{m}_{extr} + \sum_{c} \dot{m}_{comp}(p_{in,z}) = 0 \qquad (10)$$

$\dot{m}_{extr}$ is the air flow rate due to the mechanical extract ventilation system, $\dot{m}_{comp}$ is the air mass flow rate through a ventilation component such as air openings and infiltration cracks. $P_{in,z}$ inside pressure at the zone floor level.

The air volume flow rate thought an air opening is calculated as following:

$$\dot{Q}_{open} = \begin{cases} 1.1 \cdot M \cdot \text{signe}(\Delta P)\sqrt{\dfrac{|\Delta P|}{20}}; & \Delta P \le 20 \\ 0{,}55 \cdot M \cdot \dfrac{\Delta P}{80} + 77 \cdot \dfrac{M}{80}; & \Delta P \ge 20 \end{cases} \qquad (11)$$

The air volume flow rate through an infiltration crack is:

$$Q_{crack} = Q_{crack,0} \times \text{signe}(\Delta P) \times \left|\frac{\Delta P}{\Delta P_0}\right|^{2/3} \qquad (12)$$

Where $Q_{crack,0}$ is the reference crack mass flow rate and Δp_0 is the reference pressure difference taken equal to 4 Pa.

The mass air flow rate is obtained by multiplying the volume flow rate by the air density:

$$\dot{m}_{comp} = Q_{comp} \times \rho_a \qquad (13)$$

The pressure difference Δp is due to the combined actions of wind and thermal buoyancy:

$$\Delta P = \left(C_p \rho_{a,out} \frac{v_a^2}{2} - \rho_{a,out} gH + \rho_{a,in} gh \right) - P_{in,z} \qquad (14)$$

The heat pump and fan coil model

The developed heat pump model is an empirical model which calculates the performance of the heat pump based on three rating points, and the temperatures of the hot and cold sources (Morisot and Marchio 2002, Morisot et al. 2002). The model was validated against manufacturer data and other heat pump models (Alessandrini el al. 2002).

The fan coil model developed models the performance of a dry heating coil or a dehumidifying cooling coil. This model was validated against manufacturer data and detailed model (Morisot 2002, Morisot and Marchio 1999).

THE OFFICE BUILDING ENERGY PERFORMANCE (REFERENCE CASE)

The "reference case" corresponds to the office buildings with the envelope characteristics and the internal gains previously mentioned.

Yearly simulations were carried out to evaluate the energy performance of the building. Figure 6 shows the building heating and cooling demand, the mechanical ventilation auxiliary consumption as well as the lightning and the equipments electricity consumption. The cooling demand and the electricity consumptions for lightning are more important than the heat demand.

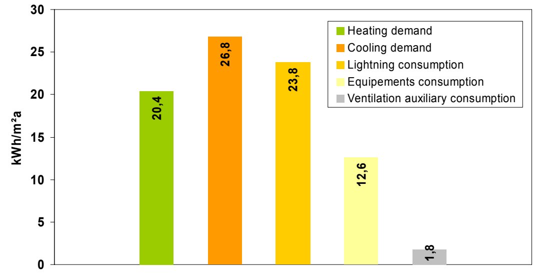

Figure 6: Building energy performance (reference case)

The annual final energy consumption of the building when it is heated and cooled by a reversible heat pump and fan coil system is 68.7kWh/m²a. The annual coefficient of performance (COP) of the heat pump for heating and cooling modes is respectively 3.11 and 3.33. These performance coefficients were used in the calculation of the process response of the DOE method which is described in the next session.

THE DOE METHOD APPLIED TO THE OFFICE BUILDING

Description of the process variables

The design of experiments method was used to improve the energy efficiency of the office building by improving its envelope characteristics.

A two level factors design was adopted. Table 4 gives the list of the considered factors and their corresponding low "-1" and high "+1" levels.

Uwalls and *Ψ* represents, respectively, the heat transfer coefficient of the walls (including floor and ceiling) and the thermal bridges. The low level corresponds to the usual heat transfer coefficient value for the passive houses (Wolfgang et al 2005). The high level was chosen according to requirements of the French thermal regulation (RT 2005).

Table 4: Low and high level of the studied factors

Factors	(-1)	(+1)	Unit
Uwalls	0.1	0.3	W/m²K
Ψ	0.01	0.6	W/mK
Win-type	TG	DG	-
%Win	50	70	%
Inertia	Low	High	-
Ori	N/S	E/W	-
Air_tight	0.07	0.72	h^{-1} under 4Pa
Night-ventil	0	5	h^{-1}
AI-light	6	11	W/m²
Sunshades	0	1	-

Win-type represents the window type. The low level corresponds to a triple glazed window (TG) and the high level corresponds to a double glazed window (DG). Table 5 gives some characteristics of the two types of windows.

Table 5: Windows characteristics

	Ug (W/m²K)	Uw (W/m²K)	$\tau_{(0)}$ (-)
TG	0.64	0.77	0.408
DG	2.8	2.6	0.725

%Win is the percentage of the glazed surface area of the office building. *Inertia* represents the building thermal inertia. The low and high inertia levels were chosen according to the French thermal regulation (RT 2005). *Ori* is the building orientation. The office building is orientated North/South (N/S) or East/West (E/W).

Air_tight is the building air tightness under a pressure difference of 4Pa. $0.07h^{-1}$ is the air tightness of passive houses obtained with the best practice (Wolfgang et al 2005). $0.72h^{-1}$ is the standard value for office buildings according to the French thermal regulation (RT 2005). *Night-ventil* is the night ventilation air flow rate. *AI-light* is the internal heat gains due to the artificial lightning. The *Sunshades* factor represents the office building horizontal sunshades.

Choosing an experimental design

A full factorial design for 10 factors has $2^{10} = 1024$ runs (or simulations). A fractional factorial design is thus necessary. In this study, the Taguchi method for fractional design experiments was used. The Taguchi orthogonal design table of 32 runs L_{32} was chosen (Pillet 1997).The empirical process model consists of a linear form model containing 10 factors and 15 interactions. Figure 7 shows the linear graph of the process model. The white circles represent the factors and the lines represent the interactions. The numbers indicate the corresponding column for each factor and interaction in the L_{32} design table.

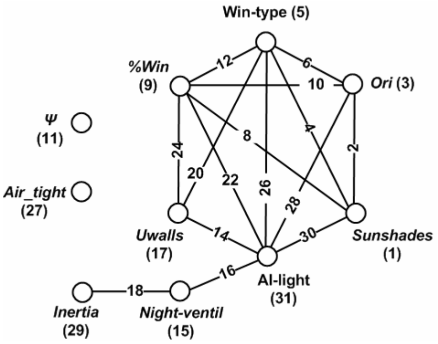

Figure 7: The process model linear graph

Process response & Linearity verification

The process response is the building final energy consumption. It comprises the energy consumption for heating and cooling, the ventilation auxiliary consumption and the electricity consumption for artificial lightning and equipments. It's expressed by the following equation:

$$E_F = \frac{E_{heat}}{COP} + \frac{E_{cool}}{EER} + E_{mv} + E_{nv} + E_{light} + E_{eqp} \quad (15)$$

COP and EER are, respectively, the annual coefficient of performance and the annual energy efficiency ratio of the heat pump.

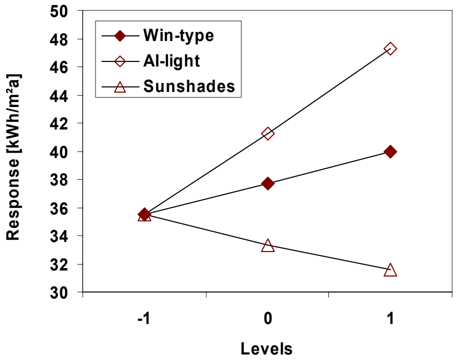

Figure 8: Checking out the response linearity

Using two level factors design is only possible if the response behaviour is linear as function of factor settings. Yearly simulations were thus carried out to check out the linearity of the process response. It was found that the final energy consumption has a linear form as function of all the factors. Figure 8 shows the behaviour of the final energy consumption as function of the *Win-type*, *AI-light* and *Sunshades* factors. The "0" level is the mean of the low and high levels.

Experiment results and discussions

32 simulations (or runs) were carried out following the Taguchi orthogonal design table L_{32}. It allows identifying the empirical model describing the behaviour of the office building final energy consumption as a function of the 10 factors described in Table 4.

Figure 9 shows a comparison between the empirical model and the simulation results for a set of random cases. The empirical model gives good agreement. The simulation of the centre point run (all the factors are set to zero) gives 44.76W/m²K. The empirical model gives 44.99W/m²K.

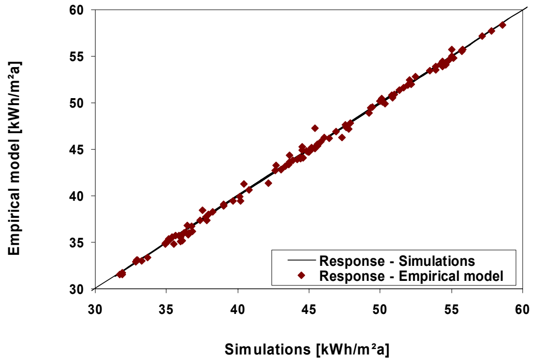

Figure 9: Empirical model validation for a set of random cases

Figure 10 shows the factors mean effects. The factor which has the biggest impact on the final energy consumption is the internal heat gains due to the artificial lightning (*AI-light*) then comes the windows type (*Win-type*), the sunshades (*Sunshades*) and the percentage of glazed surface area (*%Win*). The effect of the thermal inertia is marginal.

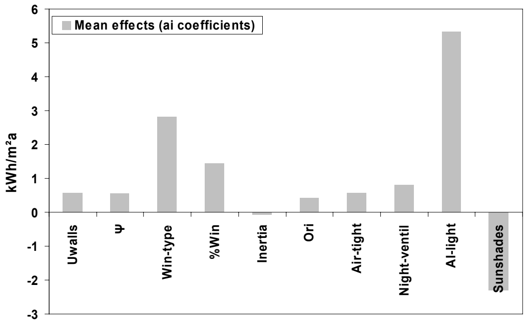

Figure 10: Variables mean effects

Figure 11 gives the factors interactions. The must significant interaction is the one between the percentages of glazed surface and the windows type (*%Win.Win-type*). Then comes the sunshades and the percentages of glazed surface (*Sunshades.%Win*) and the sunshades and windows type (*Sunshades.%Win-type*).

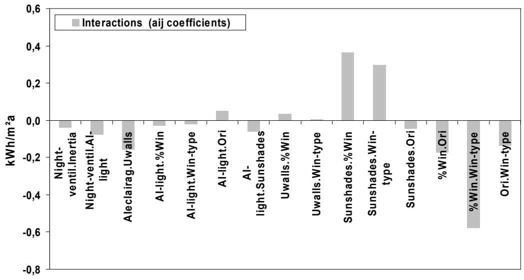

Figure 11: Variables interactions

Table 6 gives a set of variables configurations for which the final energy consumptions is low. The minimum final energy consumption is obtained for the first configuration.

Table 6: A set of optimal configurations

Config.	**1**	**2**	**3**	**4**	**5**
Uwalls	0.1	0.1	0.2	0.3	0.2
Ψ	0.01	0.01	0.3	0.01	0.01
Win-type	TG	TG	TG	TG	TG
%Win	50%	50%	50%	50%	50%
Inertia	High	High	High	High	High
Ori	N/S	N/S	SW/NE	N/S	SW/NE
Air_tight	0.07	0.07	0.07	0.07	0.4
Night-ventil	0	0	0	0	0
AI-light	6	6	6	6	6
Sunshades	1	1	1	1	1
$E_{F\text{ - model}}$	**31.70**	**31.92**	**32.92**	**32.86**	**32.94**
$E_{F\text{-simulations}}$	**31.52**	**31.63**	**33.11**	**32.87**	**33.09**

Figure 12 shows the office building energy performance for the first configuration. The reduction in heating and cooling demand as well as in electricity consumption for lightning is very significant comparing to the reference case (see Figure 6). It is 81% for heating demand, 63% for cooling demand and 45% for lightning consumption.

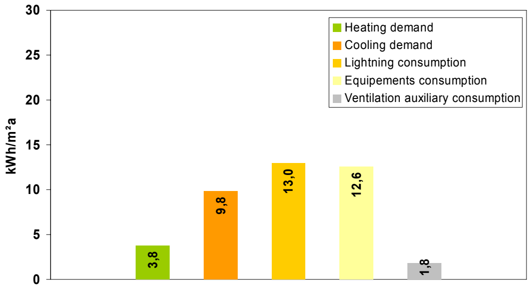

Figure 12: Building energy performance

This work could be associated to an optimisation of the ventilation system, by using solutions such as balanced ventilation systems with heat recovery and earth to air heat exchanger. These ventilation systems, widely used in low energy buildings, present a big potential for improving the energy efficiency of buildings with respect to the French climates (Chlela et al 2006).

CONCLUSIONS

The design of experiments (DOE) was used to improve the energy efficiency of an office building. This method, widely used in the industrial field, is very efficient for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. It allows deriving an empirical approximation model linking the process response and the process variables.

The main advantage of the design of experiments method (DOE) is the limited number of simulations required to find the optimum solution and to assess the influence of each variable and the interaction between them. Two types of experiment design could be used depending on the number of process variables. In this study a fractional factorial design was adopted following the Taguchi orthogonal design table L_{32}. The process variables concerned the building envelope characteristics, the internal heat gains due to the artificial lightning and the night ventilation. The process response was the final energy consumption. The obtained empirical model showed very satisfying agreements with the simulation results. This model was then used to quantify the influence of each factor on the final energy consumption of the office building as well as to find the factors settings which give the minimum final energy consumption.

NOMENCLATURE

A	surface area (m²)
Cp	specific heat capacity (J/kgK)
cp	pressure coefficient (-)
COP	coefficient of performance (-)
DH	number of degree-hours (°C.h)
E	energy (kWh/m²a)
EER	energy efficiency factor (-)
h	heat transfer coefficient (W/m²K) or internal height of the zone (m)
H	height of the zone with respect to the soil (m)
L	length (m)
M	air opening module (m^3/h)
$\dot{m}$	mass flow rate (kg/s)
P	power (W), heat flux (W/m^2) or pressure (Pa)
T	temperature (°C)
t	time (s)
U	heat transfer coefficient (W/m²K)
V	volume (m^3)
v	velocity (m/s)
x	co-ordinate (m)

Greek Symbols

Φsolar	global solar radiation on horizontal (kWh/m²)
ρ	density (kg/m^3)
λ	thermal conductivity (W/mK)
Ψ	thermal bridges heat transfer coefficient (W/mK)
Δ	difference
τ	solar transmissivity

Subscripts

a	air
con	convective
comp	component
extr	extract
F	final energy
g	glazed surface
gc	convective gain
i	zone i
in	inside
mv	mechanical ventilation
nv	night ventilation
eqp	equipments
out	outside
inf	infiltration
ji	from the zone j to the zone i
p	wall p
rad	radiative
t	thermal bridges
vent	ventilation air
w	wall or window

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