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STATISTICAL PROCESS CONTROL CONCERNING THE GLAZED AREAS INFLUENCE ON THE ENERGY EFFICIENCY OF BUILDINGS

BY

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Abstract. The aim of this paper is to present a statistical investigation, for analyzing the buildings characteristics from the energy efficiency point of view. The energy efficiency of buildings may be estimated by their capacity to ensure a healthy and comfortable environment, with low energy consumption during the whole year. The glazed areas have a decisive role in the building energy efficiency having in view the complex functions that they play in the system. A parametric study, based on the method of factorial plan of experience with two levels, allows us to emphasize the measure in which the geometric and energetic characteristics of glazed areas influence the energy efficiency, estimated by the yearly energy needs, to ensure a comfortable and healthy environment.

Key words: design of experiments, energy efficiency of building, response surface methodology

1. Introduction

The energy efficiency of buildings may be estimated by the yearly energy necessary for a comfortable and healthy indoor environment. This may be used as a criterion. It includes two different components, the energy necessary for heating during the cold season and the energy necessary for cooling, in the hot season.

The glazed areas influence in a sufficiently great measure the energy efficiency, because of the complex and apparently contradictory functions fulfilled in the system frame. Thus, the natural lighting and the solar energy use by means of green house effect require large glazed areas, while for purposes of energy saving and acoustic insulation, a reduction of glazed areas is necessary.

A parametric study, based on the factorial plan method of experience with two levels, allows the influence assessment of the main factors on the energy efficiency of building. In this frame of factors complex are included the geometric and thermal characteristics of the glazed areas.

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The criteria taken into account in the parametric study are: the yearly specific index of energy consumption for spaces heating and cooling. For the comfort assessment it was used the adaptive model.

The criteria values, that depend on the minimum and maximum values of the mentioned parameters, are obtained using some software that allow the whole building behavior simulation.

The parametric study results allow the delimitation of a values domain of parameters taken into account, in which are get optimum values of assessment criterion for the energy efficiency. It results in this way a useful instrument for designers that allow the optimization of the general conception of building from the energy efficiency and adaptability to the climate conditions point of view.

2. Process Optimization with Design of Experiments and Response Surface Methodology

The optimization of the manufacturing process is essential for the achievement of high responsiveness of production, which provides a preliminary basis for survival in today's dynamic market conditions. Process optimization refers to manipulating the most important process variables to levels or settings that result in the best obtainable set of operating conditions for the system. Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques for empirical model building [1]. By careful design of experiments, the objective is to optimize a response (output variables) which is influenced by several independent variables (input variables). Originally, RSM was developed to model experimental response [2] and then migrated into modeling of numerical experiments. The difference is in the type of error generated by the response.

An important aspect of RSM is the Design of Experiments [2], usually abbreviated as DoE. The objective of DoE is the selection of the point where the response should be evaluated. In a traditional DoE, screening experiments are performed in the early stages of the process, when it is likely that many of the design variables initially considered have little or no effect on the response. The purpose is to identify the design variables that have large effect for further investigation. To construct an approximate model that can capture interactions between N design variables, a full factorial approach [3] may be necessary to investigate all possible combinations. A factorial experiment is an experimental strategy in which design variables are varied together, instead one at a time. If the number of design variables becomes large, a fractional of a full factorial design can be used at the cost of estimating only a few combinations between variables. This is called fractional factorial design and is usually used for screening important design variables. Genichi Taguchi [4], proposed several approaches to experimental designs that are sometimes called "Taguchi Methods." "Taguchi" designs are similar to our familiar fractional factorial designs. However, Taguchi has introduced several noteworthy new ways of conceptualizing an experiment that are very valuable, especially in product development and industrial engineering, and we will look at two of his main ideas, namely Parameter Design and Tolerance Design [5].

RSM provides an approximate relationship between a true response y and p design variables, which is based on the ob-served data from the process or system [1], [2], [3], [6], [7], [8]. The response is generally obtained from real experiments or computer simulations, and the true response y is the expected response. Thus, numerical experiments are performed in this paper. We suppose that the true response y can be written as:

(1) $$y = F(x_1, x_2, \dots, x_p)$$

where the variables $x_1.\ x_2.\ \dots.x_k$ are expressed in natural units of a measurement. So they are called "natural variables". Usually, the approximating function, F, of the true response, y, is chosen to be either a first-order or a second-order polynomial model, which is based on a Taylor series expansion. In this study, the second-order is used namely:

(2) $$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \sum_{\substack{j=1 \\ i<j}}^{k} \beta_{ij} x_i x_j + e$$

where: β_0. β_I are called regression coefficients, and e represents the noise or the error observed in the response y [1], [3].

3. Case Study Results and Discussion

3.1 Building characteristics considered in this study

The case study has been made for a single family dwelling with a spatial configuration and constructive solving according to the saving energy requirements.

The main characteristics that determine the yearly energy consumption for ensuring an indoor environment quality are the following:

a) surface – volume ratio	0.7 1/m
b) U value of the walls	0,2W/m 2K
c) U value of the roof	0.15 W/m 2K
d) U value lower floor	0.25 W/m 2K

The microclimate parameters are:

a) natural ventilation rate	0.6h-1
b) indoor set temperature	20°C
c) overheating starts at an indoor temperature higher than	26.9°C.

3.2 Parametric Studies

In temperate area conditions, the yearly necessary energy for ensuring an indoor comfort has two components that result from:

a) space heating necessary during the cold period of the year;

b) space cooling necessary during the hot period of the year.

The parameters through which these components may be expressed are the yearly specific energy necessary for heating, q_h (W/m^{2}a) and the yearly specific energy necessary for cooling spaces, q_c (W/m^{2}a). The parameters values depend, in different measures, on the following factors:

a) glazed areas;

b) glazed areas orientation, respectively the solar radiation intensity;

c) thermal conductance of the glazed areas, *U*;

d) global coefficient of energy transmission, *g*.

In order to emphasize the measure in which each factor influences the value of the two factors, a parametric analysis based on a factorial plan with two levels was made. Out of the number of factors identified by their simplified notation (X_1, X_2, X_3, X_4, X_5 and X_6), the following ones were considered to be most important and necessary to control:

a) Window area (North) – X_1 (% fraction of wall),
b) Window area (South) – X_2 (% fraction of wall),
c) Window area (East) – X_3 (% fraction of wall),
d) Window area (West) – X_4 (% fraction of wall),
e) Thermal conductance of window (*U*-value) – X_5 (W/m^{2}K),
f) Global coefficient of energy transmission (*g*-value) – X_6 (-).

The input variables, chosen range for the study and their coded value, are given in Table 1.

Table 1 –Range of Variables and their Coded Form

Sample	Variables	Lower limit		Upper limit	
		Coded value	Real value	Coded value	Real value
1	X1	-1	9	1	18
2	X2	-1	19	1	38
3	X3	-1	19	1	38
4	X4	-1	24	1	48
5	X5	-1	1	1	6
6	X6	-1	0.5	1	1

Table 2 – Two-Level Full Factorial Design of Experiments

Run	Variables						Run	Variables					
	X1	X2	X3	X4	X5	X6		X1	X2	X3	X4	X5	X6
1	-1	-1	-1	-1	-1	-1	33	-1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1	-1	34	1	-1	-1	-1	-1	1
3	-1	1	-1	-1	-1	-1	35	-1	1	-1	-1	-1	1
4	1	1	-1	-1	-1	-1	36	1	1	-1	-1	-1	1
5	-1	-1	1	-1	-1	-1	37	-1	-1	1	-1	-1	1
6	1	-1	1	-1	-1	-1	38	1	-1	1	-1	-1	1
7	-1	1	1	-1	-1	-1	39	-1	1	1	-1	-1	1
8	1	1	1	-1	-1	-1	40	1	1	1	-1	-1	1
9	-1	-1	-1	1	-1	-1	41	-1	-1	-1	1	-1	1
10	1	-1	-1	1	-1	-1	42	1	-1	-1	1	-1	1
11	-1	1	-1	1	-1	-1	43	-1	1	-1	1	-1	1
12	1	1	-1	1	-1	-1	44	1	1	-1	1	-1	1
13	-1	-1	1	1	-1	-1	45	-1	-1	1	1	-1	1
14	1	-1	1	1	-1	-1	46	1	-1	1	1	-1	1
15	-1	1	1	1	-1	-1	47	-1	1	1	1	-1	1
16	1	1	1	1	-1	-1	48	1	1	1	1	-1	1
17	-1	-1	-1	-1	1	-1	49	-1	-1	-1	-1	1	1
18	1	-1	-1	-1	1	-1	50	1	-1	-1	-1	1	1
19	-1	1	-1	-1	1	-1	51	-1	1	-1	-1	1	1
20	1	1	-1	-1	1	-1	52	1	1	-1	-1	1	1
21	-1	-1	1	-1	1	-1	53	-1	-1	1	-1	1	1
22	1	-1	1	-1	1	-1	54	1	-1	1	-1	1	1
23	-1	1	1	-1	1	-1	55	-1	1	1	-1	1	1
24	1	1	1	-1	1	-1	56	1	1	1	-1	1	1
25	-1	-1	-1	1	1	-1	57	-1	-1	-1	1	1	1
26	1	-1	-1	1	1	-1	58	1	-1	-1	1	1	1
27	-1	1	-1	1	1	-1	59	-1	1	-1	1	1	1
28	1	1	-1	1	1	-1	60	1	1	-1	1	1	1
29	-1	-1	1	1	1	-1	61	-1	-1	1	1	1	1
30	1	-1	1	1	1	-1	62	1	-1	1	1	1	1
31	-1	1	1	1	1	-1	63	-1	1	1	1	1	1
32	1	1	1	1	1	-1	64	1	1	1	1	1	1

The responses analysed in the study can be identified by their coded notation $Y_1 = q_h$ and $Y_2 = q_c$ (Table 3).

Table 3 – Two-Level Full Factorial Design of Experiments and Their Corresponded Responses

Run	Responses		Run	Responses	
	Y_1	Y_2		Y_1	Y_2
1	63.9	2.4	33	53	10.3
2	65.5	2.7	34	54	11.5
3	65	3.4	35	51.2	14.7
4	66.6	3.7	36	52.2	16.1
5	66	4.1	37	53.2	17.2
6	67.7	4.5	38	54.2	18.5
7	67.2	5.5	39	51.7	22.2
8	68.9	5.9	40	52.8	23.6
9	67.6	3.8	41	54.8	16.1
10	69.2	4.2	42	55.8	17.5
11	68.8	5.2	43	53.3	21
12	70.5	5.6	44	54.4	22.4
13	69.9	6.1	45	55.2	23.5
14	71.5	6.5	46	56.3	24.9
15	71.2	7.6	47	53.9	29
16	72.9	8	48	55.1	30.4
17	72.4	2.2	49	61.2	9.2
18	75.2	2.4	50	63.2	10.3
19	75.8	3	51	61.3	13.1
20	78.5	3.3	52	63.3	14.2
21	76.8	3.5	53	63.2	15.5
22	79.5	3.8	54	65.3	16.6
23	80.2	4.6	55	63.6	19.8
24	83	4.9	56	65.7	21
25	79	3.3	57	65.5	14.5
26	81.8	3.6	58	67.5	15.6
27	82.4	4.3	59	65.9	18.7
28	85.2	4.6	60	67.9	19.9
29	83.5	5.1	61	67.8	21.1
30	86.2	5.4	62	69.9	22.3
31	86.9	6.3	63	68.4	25.7
32	89.7	6.6	64	70.5	27

The influence of different factors on the two components of the yearly energy consumption may be emphasized using the Paretto diagram (Figs 1, 2) and analysis of variance (Tables 4,5).

Analysing the Pareto diagram enables to observe that:

a) all the considered factors are important for both situations;

b) the yearly specific energy necessary for heating is firstly determined by the global coefficient of energy transmission, *g*, followed by the thermal conductance, *U*, and the glazed area toward West;

c) the yearly specific energy necessary for cooling depends on the same manner by the global coefficient of energy transmission, *g*, followed by the glazed areas toward East, West, South and the interactions, the thermal conductance, *U*, being placed on the 8th place in importance order.

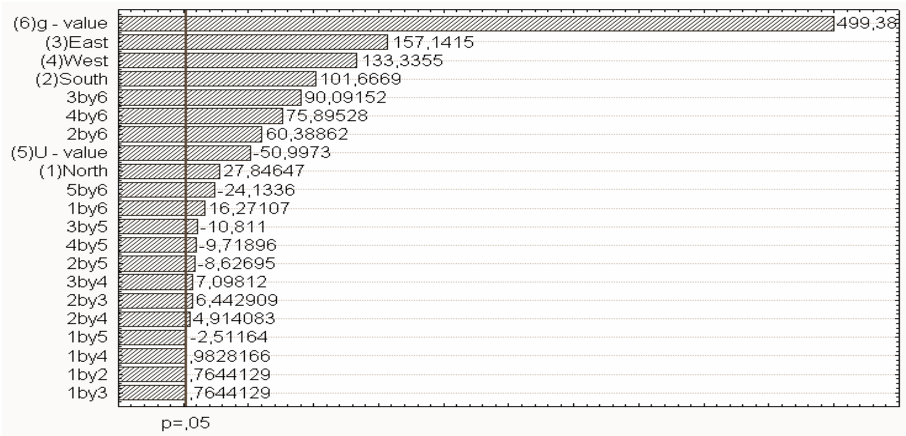

Fig. 1 – Pareto chart for cooling demand

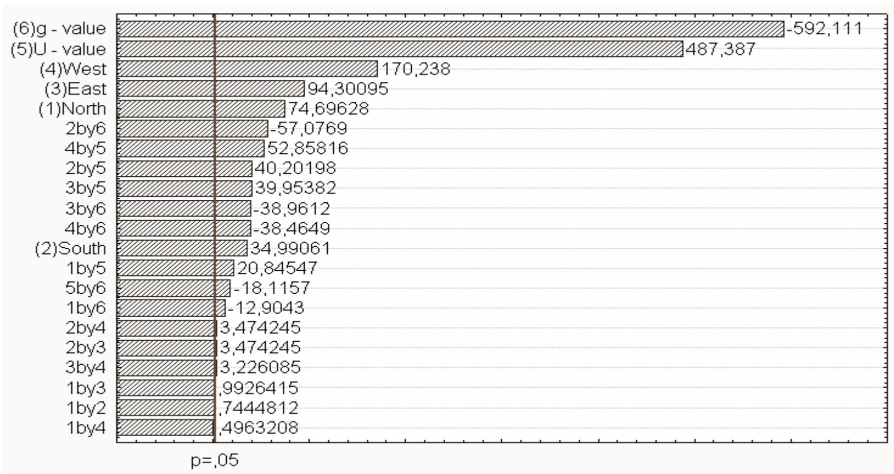

Fig. 2 – Pareto chart for Heat energy demand

Table 4 – Analysis of Variance

ANOVA – Variable – Cooling demand R-sqr= 0.99987; Adj= 0.99981					
(1)North	10.160	1	10.160	775.4	0.000000
(2)South	135.431	1	135.431	10336.2	0.000000
(3)East	323.550	1	323.550	24693.4	0.000000
(4)West	232.944	1	232.944	17778.3	0.000000
(5)U	34.076	1	34.076	2600.7	0.000000
(6)g	3267.551	1	3267.551	249380.4	0.000000
1 by 2	0.008	1	0.008	0.6	0.448895
1 by 3	0.008	1	0.008	0.6	0.448895
1 by 4	0.013	1	0.013	1.0	0.331326
1 by 5	0.083	1	0.083	6.3	0.015949
1 by 6	3.469	1	3.469	264.7	0.000000
2 by 3	0.544	1	0.544	41.5	0.000000
2 by 4	0.316	1	0.316	24.1	0.000014
2 by 5	0.975	1	0.975	74.4	0.000000
2 by 6	47.783	1	47.783	3646.8	0.000000
3 by 4	0.660	1	0.660	50.4	0.000000
3 by 5	1.531	1	1.531	116.9	0.000000
3 by 6	106.348	1	106.348	8116.5	0.000000
4 by 5	1.238	1	1.238	94.5	0.000000
4 by 6	75.473	1	75.473	5760.1	0.000000
5 by 6	7.631	1	7.631	582.4	0.000000
Error	0.550	42	0.013		
Total SS	4250.342	63			

A standard statistical technique to carry it out is represented by the analysis of variance (ANOVA), it is routinely used to provide a measure of confidence. ANOVA results for the analysed responses are shown in Tables 4 and 5. By this way it can observe the importance of interaction effect of all leading factors, which is expressed by the coefficient R-sqr = 0.99987 (Table 4) and R-sqr – 0.9999 (Table 5). This coefficient shows an adequate fit for the predictive response surface model of the responses (Cooling demand and Heat specific) investigated.

Table 5 – Analysis of Variance.

ANOVA – Variable – Heat specific R-sqr= 0.99993; Adj= 0.9999					
(1)North	56.626	1	56.626	5579.5	0.000000
(2)South	12.426	1	12.426	1224.3	0.000000
(3)East	90.250	1	90.250	8892.7	0.000000
(4)West	294.122	1	294.122	28981.0	0.000000
(5)U	2410.810	1	2410.810	237546.1	0.000000
(6)g	3558.123	1	3558.123	350595.1	0.000000
1 by 2	0.006	1	0.006	0.6	0.460731
1 by 3	0.010	1	0.010	1.0	0.326569
1 by 4	0.002	1	0.002	0.2	0.622256
1 by 5	4.410	1	4.410	434.5	0.000000
1 by 6	1.690	1	1.690	166.5	0.000000
2 by 3	0.122	1	0.122	12.1	0.001202
2 by 4	0.122	1	0.122	12.1	0.001202
2 by 5	16.402	1	16.402	1616.2	0.000000
2 by 6	33.063	1	33.063	3257.8	0.000000
3 by 4	0.106	1	0.106	10.4	0.002433
3 by 5	16.201	1	16.201	1596.3	0.000000
3 by 6	15.406	1	15.406	1518.0	0.000000
4 by 5	28.356	1	28.356	2794.0	0.000000
4 by 6	15.016	1	15.016	1479.5	0.000000
5 by 6	3.331	1	3.331	328.2	0.000000
Error	0.426	42	0.010		
Total SS	6557.024	63			

4. Conclusions

The parametric analysis based on the factorial plan of experience allows the identification with a higher precision degree of the measure in which different involved factors influence the behavior of a certain component or the whole building from the point of view of rational use of energy.

Analysing the influence of different factors on those two components of the yearly energy necessary for ensuring the thermal comfort during the whole year, it results that certain conditions cannot be simultaneously fulfilled.

The parametric studies emphasize the importance of *g* coefficient which adds the optical transmittance and the secondary heat flux normalized by the incident irradiance, that may be firstly taken into account in selected constructive solutions, having in view the energy efficiency.

For the temperate climate conditions, with a temperature increasing tendency during the hot period of the year, a rational dimensioning of the glazed areas is necessary, having in view a simultaneously fulfilling of the requirements concerning the natural lighting and the operation energy consumption.

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ANALIZA STATISTICĂ PRIVIND INFLUENȚA SUPRAFEȚELOR VITRATE ASUPRA EFICIENȚEI ENERGETICE A CLĂDIRILOR.

(Rezumat)

Se propune o metodă statistică pentru analiza caracteristicilor clădirilor din punctul de vedere al eficienței energetice. Aceasta poate fi estimată prin capacitatea clădirilor de a asigura un mediu interior sănătos şi confortabi,l cu un consum anual de energie scăzut.

Suprafața vitrată a anvelopei joacă un rol decisiv în stabilirea eficienței energetice, având în vedere funcțiile complexe ale acesteia în sistem. Un studiu parametric bazat pe metoda planului factorial de experiență cu doua niveluri permite evidențierea măsurii în care caracteristicile geometrice şi energetice ale suprafeței vitrate influențează eficiența energetică estimată prin necesarul anual de energie pentru asigurarea unui mediu sănătos si confortabil.