Simplified envelope thermal modeling method based on the Design of Experiments

Issa JAFFAL
Université de La Rochelle, France

Christian INARD
Université de La Rochelle, France

Christian GHIAUS
INSA Lyon, France

ABSTRACT

The building sector is the first responsible of energy consumption in France (about 43%). Improving procedures, simulation tools and design methods should go in parallel with efforts to enhance the energy efficiency and to find optimal design solutions.

This paper provides a simplified linear correlation method to predict the impact of 11 envelope parameters on the heating annual demand of a single family house in 3 cities of France (Nancy, Agen and Nice).

The corresponding model is identified using the design of experiments techniques (Taguchi tables). After the validation of the results, the effects of each parameter are presented and discussed.

1. INTRODUCTION

The actual energy design building is often based on experience and intuition, without an objective comparison between the solutions to find the optimal one. However, the optimization should not focus on a particular component, but it should take into consideration the whole building design, in order to find a global optimal solution.

There are some barriers for using this optimization, like the lack of trust in simulation tools, time and high level of expertise needed to use them, especially when the number of parameters to study gets large. So finding the optimal design implies to compare the energy performance of a huge number of configurations corresponding to many coupled parameters.

Any optimization of the building envelope thermal design should have criteria. It should be based on a model that describes with sufficient accuracy the corresponding phenomena. Two classes of models can be used for building energy evaluation:

- Dynamic simulations that provide accurate and detailed results, but the preparation of the input data and the simulations need a large amount of time. The models used usually are based on heat transfer theory.
- Simplified procedures that are easier and faster, but less accurate.

The simplified method based on heating degree-days (degree-hours), which is the difference between the base temperature and the mean outdoor ambient temperature, is well known and widely used. Many authors as (Bolattürk, 2006) and (Jedrzejuk and Marcks, 2002) developped optimization methods based on the degree-days method. However, for low energy buildings, this method could lead to unrealistic results.

Other important simplified methods are the regression models that can provide more precise results than the degree-days method and in a faster and easier way than dynamic tools.

To indentify regression models, some engineering design and manufacturing techniques are well-known and widely used.

One of them is the design of experiments (DOE), a structured, organized method for determining the relationship between parameters affecting a process and the output of the process, allowing gaining the most information with the least effort.

Some studies like (Filfi, 2007) and (Chlela, 2008) proposed methods based on DOE techniques. They used parameters for the building envelope, heating and cooling systems. (Gratia and De Herde, 2002) identified a 7 parameters models using DOE techniques, but adopted only one parameter for thermal transmission losses.

In this paper, the DOE techniques are used to study the building envelope behavior taking into consideration detailed parameters.

2. BUILDING ENVELOPE AND THE PARAMETERS

The envelope of a building includes vertical walls, floors, roofs, windows and doors. The envelope is characterized by many functional parameters as thermal and acoustic insulation, indoor air quality, integration into the environment… The amount of energy required to heat a building depends largely on the envelope thermal performance.

The output of a simplified model, for instance the annual heating requirement, should be expressed in function of the key parameters of the envelope heat transfer. Each parameter varies between a low and high level.

A building is a complex system where all elements including the environment, envelope, technical installations and activities of occupants, interact. The interactions between each phenomenon and the corresponding parameters exist in a manner far from simple. For example, the thermal flow across the floor depends of the solar radiative heat flux through the windows and absorbed by the floor.

To identify models using the DOE techniques, it is necessary to use reduced parameters instead dimensional ones, with -1 as the low level and 1 as the high level.

We assume that the inertia of the building is well known; and that the same type of model can be applied to different classes of inertia.

In total, 11 factors (Table 1) are selected. For 11 factors, there may be 55 interactions of the first order; the interactions of the second order between 3 factors are generally neglected in the DOE. The thermally effective ventilation rate $\dot{V}_e$ is introduced as follow:

$$\dot{V}_e = (1-\eta_r)\cdot \dot{V}_{vent} \qquad (1)$$

Where:

η_r: Heat recovery efficiency

$\dot{V}_{vent}$: Ventilation rate.

Table 1: Parameters of the simplified model.

Parameter	Reduced parameter
U-value of the vertical walls U_{vw} (W/m². K)	UVW
U-value of the floor U_f (W/m².K)	UF
U-value of the roof U_r (W/m².K)	UR
Linear transmission coefficient of the thermal bridges Ψ_{th} (W/m.K)	PHTB
U-value of the windows U_w (W/m².K)	UW
Solar heat gain coefficient (SHGC) of the windows in the north direction $SHGC_{wn}$	SHGCWN
SHGC of the windows in the east direction $SHGC_{we}$	SHGCWE
SHGC of the windows in the south direction $SHGC_{ws}$	SHGCWS
SHGC of the windows in the west direction $SHGC_{ww}$	SHGCWW
Infiltration rate $\dot{V}_{inf}$ (ach)	INF
Thermally effective ventilation rate $\dot{V}_e$ (ach)	VE

3. THE METHOD

3.1 The model

The main goal is to build a linear correlation model assuming that the annual heating demand (the output of the simplified model) varies in a linear way as a function of the selected parameters. The annual heating demand H_{ad} (kWh/m².year) is expressed as follow:

$$\begin{aligned} H_{ad} &= c_0 + c_1 \cdot UVW + c_2 \cdot UF + c_3 \cdot UR + \\ &c_4 \cdot PHTB + c_5 \cdot UW + c_6 \cdot SHGCWN + \\ &c_7 \cdot SHGCWE + c_8 \cdot SHGCWS + \\ &c_9 \cdot SHGCWW + c_{10} \cdot INF + c_{11} \cdot VE \end{aligned} \quad (2)$$

Where:

c_0: Average of outputs

c_i (i=1, 10): Effect of each parameter

Low and high levels of the parameters (see Table 2) have been selected with respect to values recommended by the Passivhaus (higher performance) and the Minergie (lower performance) labels respectively. Passivhaus standards are discussed in (Feist et al. 2005). For the solar heat gain coefficients (glazing and frame), the values are selected according to existing windows of low energy buildings. Table 2 presents these values.

3.2 Tables of DOE

Table L_{12} (2^{11}) of Taguchi with 12 simulations is used to identify the coefficients of the equation 1 with a minimum number of simulations. This table (Table 3) is highly recommended by Taguchi himself (Taguchi and Konishi, 1987) because of its capability to investigate 11 main effects (columns)with only 12 simulations (rows).

Table 3: Table L_{12} (2^{11}) of Taguchi.

N°	1	2	3	4	5	6	7	8	9	10	11
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	1	1	1	1	1	1
3	-1	-1	1	1	1	-1	-1	-1	1	1	1
4	-1	1	-1	1	1	-1	1	1	-1	-1	1
5	-1	1	1	-1	1	1	-1	1	-1	1	-1
6	-1	1	1	1	-1	1	1	-1	1	-1	-1
7	1	-1	1	1	-1	-1	1	1	-1	1	-1
8	1	-1	1	-1	1	1	1	-1	-1	-1	1
9	1	-1	-1	1	1	1	-1	1	1	-1	-1
10	1	1	1	-1	-1	-1	-1	1	1	-1	1
11	1	1	-1	1	-1	1	-1	-1	-1	1	1
12	1	1	-1	-1	1	-1	1	-1	1	1	-1

Another identification could be done with the table L20 (2^{19}) of Taguchi which has the same properties than the table L12 (2^{11}). This table is presented in (Pillet, 2001).

4. CASE STUDY AND RESULTS

In the present study, a single dwelling is considered (see Figure 1). The lounge is oriented east and the dwelling is placed in three different locations in France, namely, Nancy, Agen and Nice in order to cover the range of French climates (cold, moderate and hot). The temperature set point is 19 °C and the internal loads are equal to 5 W/m². Regarding the 19°C degrees-hours 76404 °C.h for Nancy, 58299 °C.h for Agen and 40409 °C.h for Nice, the climates can be classified into three types: cold climate (Nancy), moderate climate (Agen) and hot climate (Nice).

Table 2: Low and high levels of each parameter.

	U_{vw}	U_f	U_r	Ψ_{tb}	U_w	$SHGC_{wn}$	$SHGC_{we}$	$SHGC_{ws}$	$SHGC_{ww}$	$\dot{V}_{inf}$	$\dot{V}_e$
	W/m².K	W/m².K	W/m².K	W/m. K	W/m². K					ach	ach
Low	0.1	0.1	0.1	0.01	0.7	0.3	0.3	0.3	0.3	0.09	0.06
High	0.2	0.2	0.2	0.1	1.0	0.6	0.6	0.6	0.6	0.19	0.18

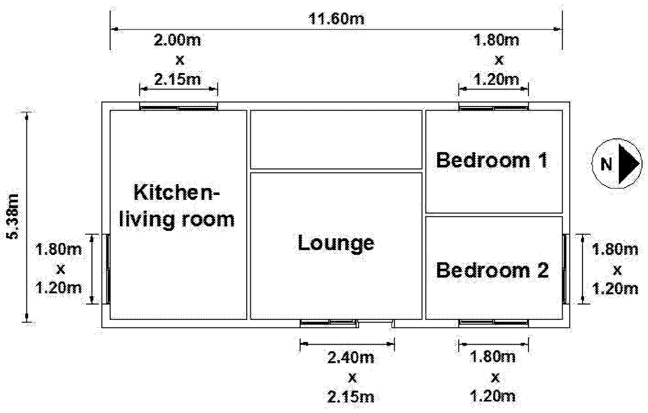

Figure 1: View of the simulated single family house.

The dynamic simulations are carried out with TRNSYS for a whole year with a simulation type step of 15 min.
The first step of the study consists in the identification of the coefficients c_i using the results of 12 or 20 TRNSYS simulations. Then, in order to check the accuracy of the simplified models, 50 additional simulations are carried out at random.

Figures 2-4 show the results for each location. Table 4 gives the mean and maximum values of the absolute errors for the heating demand between the simplified models and TRNSYS.

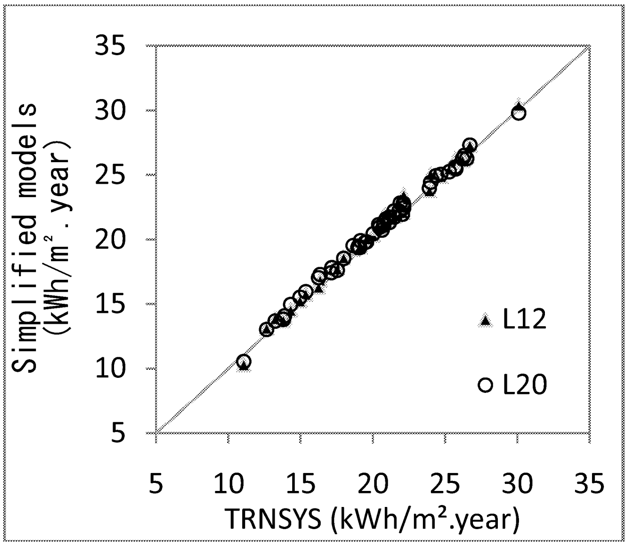

Figure 2: Annual heating demand computed with TRNSYS and the simplified models for Nancy.

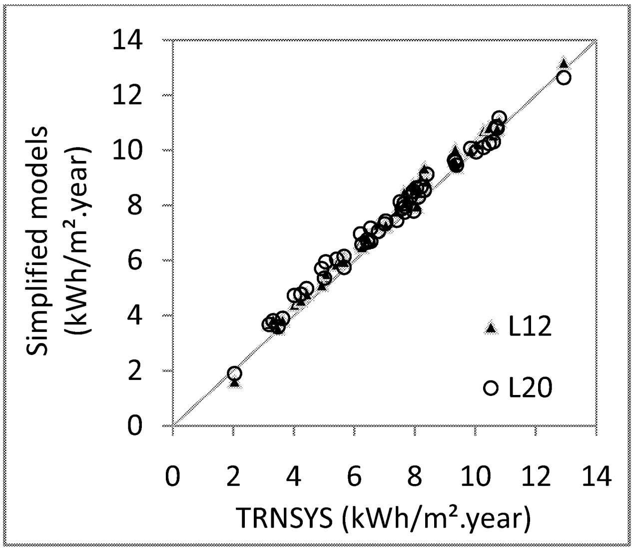

Figure 3: Annual heating demand computed with TRNSYS and the simplified models for Agen.

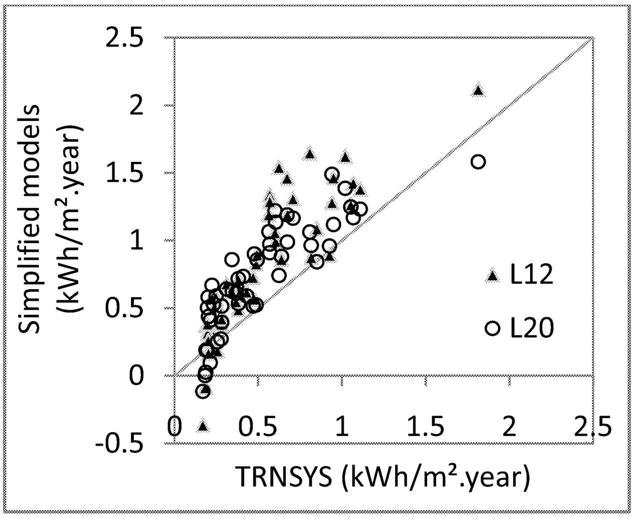

Figure 4: Annual heating demand computed with TRNSYS and the simplified models for Nice.

Table 4: Mean and maximum absolute errors between the simplified model and TRNSYS in kWh/m².year.

	Nancy		Agen		Nice	
Model	L12	L20	L12	L20	L12	L20
Mean error	0.46	0.42	0.38	0.27	0.32	0.26
Max. error	1.32	0.93	1.05	0.90	0.92	0.62

Obviously, the model identified with 20 simulations is more accurate than the one identified with 12 simulations.

Figures 2-4 show that the relative errors increase from Nancy to Nice, but Table 4 shows the opposite for the absolute errors. A simple linear model could be sufficiently precise to estimate the heating demand for low energy levels in Nancy (cold climate) which could be also valid for Agen (temperate climate). However, for very low heating demand zones like Nice the results are not enough precise; this is because the non-linear behavior of the outputs and the interactions between the parameters get more influence in the annual heating demand values. The accuracy of the DOE model could be improved by coupling several conventional DOE designs (Box-Behnken, D-optimal…) and adding new terms to the model.

The effect of each factor are shown in the Figure 5-7.

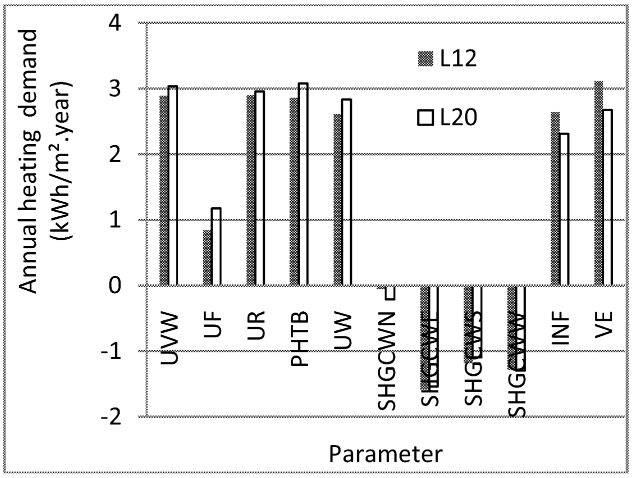

Figure 5: Effect of each parameter in Nancy.

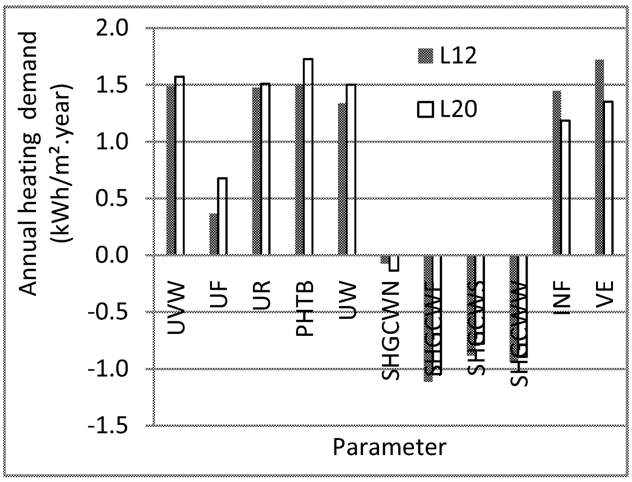

Figure 6: Effect of each parameter in Agen.

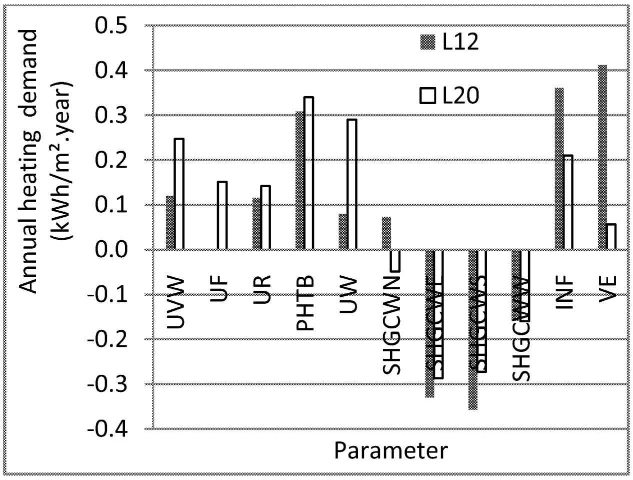

Figure 7: Effect of each parameter in Nice.

Figures 5-6 show for Nancy and Agen that:

- The effect of the insulation of the vertical walls, roof, thermal bridges, windows, infiltration and ventilation are of the same order of magnitude.
- Although the surface of the windows in the south direction is much lower than those in the east and west directions, the effect of SHGCWS parameter is of the same order of magnitude that SHGCWE and SHGCWW parameters. Furthermore, increasing the value of SHGCWN parameter in the north direction has a very low effect on the heating demand.
- The effect of each parameter decreases considerably between the cold climate (Nancy) and the temperate climate (Agen).

For the hot climate (Nice), Figure 7 shows that some effects appear unrealistic, as the positive effect on the annual heating demand of SHGCWN parameter (L12 model) and the huge difference in the effect of VE parameter between both models. These results confirm that the linear model should be improved for this type of climate in the way explained previously.

By using these graphs, the designer can find a way to answer to familiar energy questions like: is it thermally worse to more insulate vertical walls or roof?

For example, equation (3) gives the values of the coefficients c_0 and c_i for the annual heating demand for Nancy obtained with the L_{12} (2^{11}) table:

$$H_{ad} = 20.85 + 2.89 \cdot UVW + 0.84 \cdot UF + 2.90 \cdot UR + 2.86 \cdot PHTB + 2.61 \cdot UG - 0.06 \cdot SHGCWN - 1.59 \cdot SHGCWE - 1.18 \cdot SHGCWS - 1.28 \cdot SHGCWW + 2.64 \cdot INF + 3.11 \cdot VE \quad (3)$$

Furthermore, 11 parameters were considered for the annual heating demand. The number of possible combination for 11 parameters is 2048 (2^{11}) if we consider two levels for each parameter and 177147 (3^{11}) if we consider 3 levels. Using the DOE method, a suitable linear model is developed by performing 12 or 20 numerical simulations. The simplified model could be then used to calculate rapidly all the possible combinations and choosing the desired ones.

5. CONCLUSION

The purpose of this study was to develop a simplified linear correlation model for annual heating demand of building that could help designer to identify the effect of building envelope key parameters.

The identified models are very simple and easy to use with a minimum number of data needed. The model shows directly the impact of each parameter on the annual heating demand. It can be a base for a new design tool.

The simplified models show a good agreement with the dynamic simulations of TRNSYS for the cold and moderate climates (Nancy and Agen). For the hot climate (Nice) the model must be revised. It could be done by adding quadratic terms and/or interactions between factors. It will also be interesting to expand the study with others parameters like the geometry and the thermal mass of the building.

Using the design of experiments, the effects of the parameters are identified in an easy way and the number of simulations is significantly reduced.

REFERENCES

Bolattürk A. (2006). Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. Applied Thermal Engineering 26 (11-12): 1301-1309.

Chlela, F. (2008). Développement d'une méthodologie de conception des bâtiments à basse consommation d'énergie, PHD Thesis, La Rochelle: Université de La Rochelle.

Feist ,W. & Schnieders J. ; Dorer V. ; Haas, A. (2005). Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. Energy and Buildings. 37 (11): 1186- 1203

Filfi, S. (2007). Optimisation Bâtiment/système pour minimiser les consommations dues à la climatisation, PHD Thesis. Paris: Ecole des Mines de Paris.

Jedrzejuk, H. & Marks, W. (2002). Optimization of shape and functional structure of buildings as well as heat source utilization. Basic theory. Building and Environment 37(12): 1379-1383.

Gratia,E. & De Herde, A. (2002). A simple design tool for the thermal study of an office building. Energy and Buildings. 34(3): 279-289.

Pillet M. (2002). Les plans d'éxpériences par la méthode de Taguchi. Paris: les Editions d'Organisation.

Taguchi G. & Konishi S. (1987). Taguchi methods. Orthogonal arrays and linear graphs. Michigan: American Supplier Institute, Inc