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Development of a Multicriteria decision method for passive building refurbishment

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Abstract

In Europe, almost 75% of the existing buildings will always persist in 2050. In fact, the thermal refurbishment rate of the existing residential buildings which present a high potential in energy saving, is estimated less than 1% per year. In the aim of accelerating this renovation rate till 3% per year, seeking optimal technical solutions taking into account the economic, environmental and societal criteria is a very complex problem due to the high number of parameters to consider. The main objective of the present work is to propose a fast method to find the global optimum. This method is based on the development of polynomial models for the prediction of heating energy needs and thermal discomfort in summer period. To establish these models, we used the design of experiments method and dynamic thermal simulations using TRNSYS software. From these models, a sensitivity analysis has been achieved in order to identify the leading parameters on energy requirements. A database associating each parameter for its cost and environmental impact on its lifetime was generated from CYPE software and INIES database. Then, a detailed parametric study was performed using polynomial functions for determining a set of optimal solutions using the Pareto front approach. We implemented our method to a project of energy rehabilitation of an existing building located in La Rochelle (France). The developed multicriteria decision method showed a great potential for existing buildings rehabilitated with high energy efficiency. It allows a very fast operational optimization of sustainable and passive buildings at reasonable cost and environmental impact, low energy consumption and high thermal comfort.

Keywords - building refurbishment; building energy efficiency; multi-criteria decision method; sustainable buildings

1. Introduction

The building sector is the largest energy consumer in Europe for around 40% of total energy consumption and generates about 36% of total greenhouse gas emissions [1]. At the present time, the main challenge is the building's energy refurbishment because 92% of the building stock from

2005 will still be there in 2020 and 75% in 2050. This is due to the very low demolition rates (about 0.5% per year) and new built construction rates (about 1.0% per year) [2]. Also, among the commitments taken during the COP'21 is to reduce from 40% to 70% of greenhouse gas emissions as being necessary to avoid the risks of irreversible climate change. Therefore, to achieve Europe's decarbonisation, energy security and resource efficiency goals 3% of existing buildings should be renovated annually, leading to a significant reduction in energy consumption [3].

To achieve a sustainable buildings energy rehabilitation, the building envelope and ventilation may constitute very satisfactory technical solutions to improve the interior comfort conditions and increasing the energy efficiency in buildings [4,5]. Given the large number of parameters to consider, finding an optimal choice among the many possible solutions turns out to be a very complex problem. Solving multicriteria optimization problems has attracted a range of research efforts.

A literature survey [6,7] has shown that the evolutionary algorithms using building simulation software was the most frequently used. The main advantage of this method is it adaptation ability to a complex problem (linear, nonlinear ....) even with a large number of input parameters. However, this method has several drawbacks, such as the high computation time and it may have a tendency to converge towards local optima or even arbitrary points rather than the global optimum of the problem. For example Chantrelle et al [8] have developed 'Multiopt' which is a tool for multi-criteria optimization of the envelope in order to find the best compromise between energy consumption, summer comfort, the investment cost and gas emissions impact. This tool is based on genetic algorithms such as NSGA-II coupled with TRNSYS software for building energy simulation and economic and environmental databases. With a number of 6 parameters which represent the insulation of the various walls and window types, the discretization of these parameters leads to 51840 combinations. The optimal solutions are obtained via this method after 2 days and 12 hours.

In this paper, we present a novel approach to overcome these challenges. The objective of our study is to develop a fast multicriteria optimization method to obtain the global optimum for passive building refurbishment. Our approach is largely based on the coupling between statistical modeling ideas and Pareto efficiency concept. In order to contribute to a sustainable building refurbished we used four optimization criteria: heating energy needs, thermal discomfort, cost and environmental impact. An existing multistory building needing refurbishment is taken as a case study to demonstrate the feasibility of the proposed method in a real world situation.

2. Method proposed

The method proposed is based on the following steps:

- Identification of the envelope and ventilation parameters;

- Reduction of simulation number by implementing the design of experiments method;
- Metamodelling the heating energy needs by multi-regression analysis of the results of the simulations;
- Accuracy evaluation of the polynomial functions developed;
- Discretization parameters and generate a database of economic and environmental impact.
- Using the Pareto efficiency concept for multicriteria optimization and ranking the best result.

2.1 Parameters selection

The variables under consideration in this study and their corresponding ranges are listed in Table 1. We will focus in the context of our work on the building envelope optimization since it allows for a sustainable building retrofit. Regarding opaque walls, the heat transmission coefficient of the external walls U_{ew} "$W/m^2.K$", the heat transmission coefficient of the floor U_{fl} "$W/m^2.K$", the heat transmission coefficient of the roof U_{rf} "$W/m^2.K$", the heat transmission coefficient of the windows U_w "$W/m^2.K$", the heat transmission coefficient of the windows frame U_f "$W/m^2.K$"and the linear heat transmission coefficient of the thermal bridges Ψ_{tb} "W/m.K" are selected as design parameters. The upper limit of these coefficients is given by typical multistory buildings built between 1948 and 1974 in France. The lower limit is given by the best practice [9]. The windows are also characterized by the solar factor noted g-value. This coefficient used to measure the solar energy transmittance of glass which represents the maximum amount of solar energy passing through the windows. The maximum value of this coefficient corresponds to a single glazing and the minimum value corresponds to a window associated with a sunscreen. The coating of opaque walls is also taken into account by the solar absorption coefficients of external walls α_{ew}, roof α_{rf} and windows frame α_f. Their limits are defined by the absorption characteristics of usual coating materials. The properties of the glazing materials are obtained from the LBNL Windows 7 software [10], which contains a database of 2695 types of glass available from manufacturers. In order to respect the air sanitary rules, a ventilation rate q_{vent} is set. This rate takes it maximum value when using simple flow mechanical ventilation and its minimum value when using double flow mechanical ventilation with 90% of air change efficiency [11]. The upper limit of infiltration rate q_{inf} corresponds to old leaky houses [12] and lower limit is given by the label limit [9]. In order to improve the summer thermal comfort a night mechanical-ventilation can be switched on. The minimum and maximum values of the air change rate in this case varied between 0 and 5 ‘‘v/h’’.

Table 1. The variable space for optimal building envelope design, and the ranges of the variables.

Parameter	Lower limit	Upper limit	Unit
U_{ew}	0,15	1,83	W/m².K
α_{ew}	0,1	0,9	-
U_{rf}	0,15	0,33	W/m².K
α_{rf}	0,1	0,9	-
U_{fl}	0,15	1,34	W/m².K
Ψ_{tb}	0,01	1	W/m.K
$U_{w\text{-}south}$	0,1	5,8	W/m².K
$g\text{-}value_{south}$	0,05	0,9	-
$U_{w\text{-}Est}$	0,1	5,8	W/m².K
$g\text{-}value_{Est}$	0,05	0,9	-
$U_{w\text{-}west}$	0,1	5,8	W/m².K
$g\text{-}value_{west}$	0,05	0,9	-
$U_{w\text{-}north}$	0,1	5,8	W/m².K
$g\text{-}value_{north}$	0,05	0,9	-
U_f	1,3	4,3	W/m².K
α_f	0,1	0,9	-
q_{inf}	0,11	T1 : 0,56 T5 : 0,49	v/h
q_{vent}	T1 : 0,125 T5 : 0,062	T1 : 1,25 T5 : 0,62	v/h
$q_{survent}$	0	5	v/h

2.2 Criteria

For our case study we used four optimization criteria: heating energy needs, thermal summer discomfort, cost and environmental impact. The annual heating energy needs criterion is calculated by TRNSYS software [13]. The summer thermal comfort criterion is based on the adaptive approach to thermal comfort [14]. In order to evaluate this criterion, we use the summer discomfort rate which represents the percentage of busy time during which the temperature is above the upper limit of the operative temperature as it defined in EN 15251[15].

The economic criterion is the initial investment cost, the life cycle cost which is the sum of the initial investment cost, the annual on-going charges for a lifetime of 50 years and the maintenance cost over the same period, and payback period. A price database has been established from Cype software [16].

In order to assess the impacts on the environment, eight indicators (Table 1) are used in assessing environmental impact over the life cycle of the building materials. The reference data was procured from a database, INIES [17].

Table 2. Selected environmental indicators

Environmental indicators	Unit	Symbol
Water pollution	m^3/m^2	WP
Primary energy	kWh/m^2	PE
Embodied energy	kWh/m^2	EmE
Total water consumption	L/m^2	TWC
Resource depletion	Kg Sb eq./m^2	RD
Global warming potential	Kg CO_2 eq./m^2	GWP
Air pollution	m^3/m^2	AP

2.3 Design of Experiments method

In order to metamodeling the heating energy needs and thermal discomfort, we use the polynomial regression analysis. The objective of this approach is to approximate the response by a set of independent variables (19 parameters defined previously) and to determine the best fitting coefficients of the model from the given data. In order to evaluate both interaction and quadratic effect of selected parameters a full quadratic model was generated (Eq.(1)):

$$\hat{Y} = a_0 + \sum_{i=1}^{n} a_i \times x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij} x_i x_j + \sum_{i=1}^{n} a_{ii} x_i^2 \qquad (1)$$

With:

$\hat{Y}$ is the response estimated by the metamodels.

x_i and x_j are the input parameters,

a_0, a_i, a_{ii} and a_{ij} are the coefficients of the metamodel that we must identify,

Using the least square method, the system of equations to be solved is written in matrix notation as follows (Eq.(2)):

$$[Y] = [X][A] \qquad (2)$$

$[Y]$ is the output vector calculated for several combinations by numerical simulations using TRNSYS,

$[A]$ is the vector of the metamodel coefficients, it is computed as follows (Eq.(3)):

$$[A] = \left([X]^t\,[X]\right)^{-1}\,[X]^t\,[Y] \tag{3}$$

$[X]$ is the matrix calculation, it is chosen according to the number of parameters and the polynomial function type. In order to choose a matrix with the least number of calculations, we use the design of experiments method.

For 19 selected parameters, the number of possible combinations is more than a billion if we consider 3 levels for these parameters. Since the dynamic simulation of the building is time consuming, performing this huge number of simulations is not realistic. A reduced number of dynamic simulations may be obtained by using the design of experiments method (DOE). This method uses orthogonal tables which have been established by mathematical theory and ready to use [18–20]. Many standards DOE design are available. It has been found that the D-optimal design provides a greater accuracy with a small number of simulations to achieve compared to other plans studied. It also allows evaluating any interactions between parameters. It is generated by an iterative search algorithm and seeks to minimize the covariance of the parameter estimates for a specified metamodel. This is equivalent to maximizing the determinant $D = [X]^t\,[X]$, where $[X]^t$ is the transposed matrix of $[X]$. The total number of simulation is reduced to 210.

2.4 Model accuracy

Before starting the optimization procedure, at first we must check the accuracy of the metamodels developed and therefore a comparison with random simulations must be performed. Indeed, the quality of metamodels was measured against various statistical parameters such as the mean absolute error (MAE) (Eq.(4)), and the multiple determination coefficients (R^2) (Eq.(5)):

$$MAE = \frac{\sum_{i=1}^{m} \left| Y_i - \hat{Y}_i \right|}{n} \tag{4}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{m} \left(Y_i - \hat{Y}_i \right)^2}{\sum_{i=1}^{m} \left(Y_i - \overline{Y} \right)^2} \tag{5}$$

Where: Y_i is the random sample simulation output, $\overline{Y}$ is the mean of the whole output data,

m is the number of random sample. Low value of the MAE and a high value of R^2 prove that the metamodels are sufficiently accurate and therefore can be used for predicting the heating energy needs and thermal discomfort for optimization process.

2.5 The multicriteria optimization process

After having conducted a sensitivity analysis and identified the most influent parameters on the outputs, a discretization of the building envelope and ventilation parameters is carried out. From this database and in order to determine the optimal solutions we use the Pareto efficiency concept [21]. The so-called optimal solutions are those which pass through the front Pareto P(Y), which may be more formally described as follows. Consider a system with function $f : \Re^n \to \Re^m$, where X is a compact set of feasible decisions in the metric space $\Re^n$, and Y is the feasible set of criterion vectors in $\Re^m$, such that

$Y = \{y \in \Re^n : y = f(x), x \in X\}$.

We assume that the preferred directions of criteria values are known. A point $A \in \Re^m$ is preferred to (strictly dominating) another point $B \in \Re^m$, written as B>A. The Pareto efficiency is thus written as:

$$P(Y) = \{y \in \Re^m : (B \in Y : B > A, B \neq A) = \phi\} \tag{10}$$

Figure 1 resumes the multicriteria optimization processes used in this study.

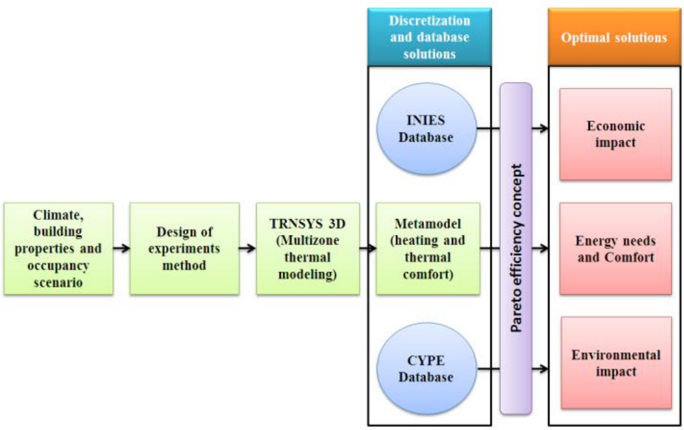


Figure 1. Modeling process and optimization scheme

3 Case study

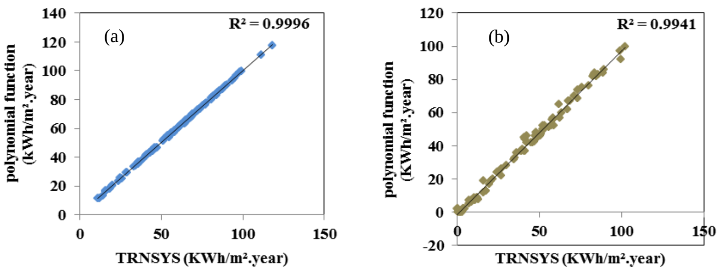
The building studied is a four-story existing building with a total floor area of 960 m^2. It represents typical French building stock built in 1954 located in La Rochelle. Figure 2 shows schematic views of the building model. The building is oriented East-West. The internal heat gains are 5 W/m². The temperature set-point in winter is 19°C in winter. The airtightness of the building is 0.52 ach at 4 Pa. In these buildings the walls are built with concrete blocks without insulation, the roof is insulated by 12 cm of rock wool and floor is built with 15 cm of hollow blocks.

Figure 2. Schematic views of the building model.

4 Results and discussion

4.1 Metamodels validation

After identification of the metamodels coefficients for the polynomial models, checking the accuracy is performed by comparing them with the results of a set of dynamic simulations randomly selected. For this purpose, 100 new random building simulations were carried out for heating energy needs estimation (Figure 3-a) and summer thermal discomfort (Figure 3-b).



The results are very encouraging. The regression coefficient of the polynomial model for predicting heating energy needs, was 0.9996, the maximum and average difference between the simulations and the polynomial model is respectively 0.98 kWh/m².year and 0.38 kWh/m².year.

Regarding the prediction of summer discomfort, it is found that the results obtained are satisfactory. The maximum and average errors are 7.66% and 2.49% respectively.

4.2 Multicriteria optimization results

In order to proceed with the optimization process, discretization parameters are performed to match technical solutions that exist in the construction market. The calculation time was about 7 hours. The results show that the heating energy needs is reduced by approximately 83.7% compared to the reference case and is equal to 15 kWh/m².year. The discomfort level is also reduced to 20% less than the reference value.

In this case, the building refurbished meets regulatory requirements and also those of MINERGIE-P and PASSIVHAUS labels. The optimum technical solutions are:

- 20 cm of mineral wool for external walls insulation,
- Tripe glazed with low emissivity for East facing windows,
- Double glazing for West facing windows,
- Double flow ventilation with a recovery efficiency of 0.9,
- Night ventilation in summer with an air change rate of 5 v/h.

The investment cost generated by the implementation of these solutions is 204 euros per m². The payback time is about 18 years. The overall cost of the building life cycle is 379 euros per m².

For optimal solutions, the overall environmental impact is significantly reduced (Table 3).

Table 2. Optimal environmental indicators

WP	PE	EmE	TWC	RD	GWP	AP
34	261 358	1 261 318	643	0,35	49	7 616

5 Conclusions

The aim of the study presented in this article was to develop multicriteria decision method that would optimize the renovation of buildings across a range of objectives, with contributions from databases and assessment software. It was developed and validated metamodels of heating energy needs and summer thermal discomfort for multistory building located in La Rochelle (France). From this metamodels and economic and environmental database a multicriteria optimization of the building envelope and ventilation parameters is performed. Optimal solutions should satisfy 12 criteria representing the energy requirements, thermal comfort, economic and environmental impacts. We have shown that with a reduced number of simulations, the multicriteria optimization is performed successfully and the use of metamodel allows for global optimum results with a low statistic error.

This methodology offers rapidity and flexibility could provide important support for architects and engineers.

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