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A metamodel for building energy performance

Issa Jaffal[a,*], Christian Inard[b]

[a] CMGPCE, Cnam, Paris, France
[b] LaSIE, University of La Rochelle, La Rochelle, France

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ABSTRACT

There is a growing use of metamodels to evaluate building energy performance. However, current metamodeling approaches lack a common foundation. The aim of this work was to develop a general metamodel for building energy performance. Based on the premise that each building element can have an impact on energy performance, our general metamodel assumes that the overall impact is a polynomial function of the individual impacts. The model includes time-dependent parameters such as the solar heat gain coefficient and energy system efficiency. A model derived from the general model was tested on an office located in Paris. Energy needs and consumption, the cost of energy consumption and the CO_2 emissions for heating and cooling were analyzed. The study highlighted the significant impact of the choice of the performance criteria in evaluating the efficiency of building design solutions. The metamodel represents a fast way to perform calculations with an accuracy close to that of dynamic simulations. It can be used as a basis to perform parametric studies and for future building energy regulations.

1. Introduction

Using a suitable model to evaluate energy performance is a key element in building energy design. Models should respect several criteria such as accuracy, speed and flexibility. Simplified models, generally based on the mean outdoor air temperature or degree-days, offer fast calculation times but may lack accuracy [1,2]. In addition, they have a limited capability to integrate the effect of thermal mass, and the time-dependency of design parameters such as infiltration rate, solar heat gain coefficient and energy system efficiency. Dynamic simulation, based on detailed building heat transfer analysis, provides acceptable accuracy but can be time consuming when studying a large number of building parameters.

Metamodels are a class of building energy performance models based on a statistical approach that creates a relationship between building design and environmental parameters on the one hand, and energy performance on the other. The coefficients used in these models are identified from dynamic simulations, typically by using multiple regression analysis. The main goal of these models is to combine the high speed calculation of simplified models and the accuracy of dynamic simulation. The metamodel, generally a polynomial function, is used for a rapid evaluation of building energy performance. Such models are highly suitable for preliminary design phases when the available data are limited [3,4].

Given the large number of parameters that influence different aspects of building energy performance, the number of dynamic simulations needed to fit a metamodel can be very high. The design of experiments method can be used to limit this number [5,6]. This statistical method is an efficient procedure for planning experiments. It allows establishing relationships between inputs and outputs of a system with a small number of runs.

Early research used multiple regression analysis to develop metamodels to study the energy annual use for heating and cooling and peak cooling load of commercial buildings as function of design parameters, especially window properties [7,8] and the daily energy use of institutional buildings as a function of the outdoor conditions [9]. Metamodels were also developed for the annual energy consumption of office buildings as a function of the building and HVAC systems design parameters [3], of single-family houses as a function of the environmental conditions and the heating season duration [10] and of buildings as a function of population and weather parameters [11].

In addition, there has been an increasing number of metamodeling approaches to building energy performance. The metamodels developed for building energy performance concern energy needs [4,12–17] and energy consumption [18–26] for heating and cooling. Moreover, several authors have studied the effect of climate change on energy consumption [27–29], urban heat islands [30] and energy

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* Corresponding author.
E-mail address: issa.jaffal@lecnam.net (I. Jaffal).

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consumption building stocks [31,32]. Metamodels have also been developed for daylight factor [33].

Recent approaches are also more diversified. Several models have been developed for building envelope components such as air-filled cavities [34], lightweight concrete hollow bricks [35], double-glazed windows [36], radiant barriers [37], phase change materials [38], thermo-active systems [39], and thermal bridges [40]. Some authors have also developed metamodels for HVAC systems such as mechanical heat pumps [41], desiccant wheels [42], earth to air heat exchangers [43], multifunction solar systems [44], solar-assisted cooling [45] and PV systems [46].

Occupant comfort has also been studied using criteria such as overall occupant satisfaction [47], thermal comfort [48] and indoor temperature [12]. Metamodels have been integrated into a computer-aided design environment [49]. Finally, metamodels have been developed for the Brazilian energy regulation [50].

The models are generally linear or quadratic polynomial functions, and it has been shown that metamodels offer high speed calculation with results that are generally in good agreement with those of dynamic simulation. However, the choice of parameters and their interactions varies widely, highlighting the absence of a common framework for these models. Moreover, the time-dependency of parameters such as infiltration rate and energy system efficiency was not considered in these models.

Based on the analysis of heat transfer in a building, we proposed a metamodel to evaluate energy needs for heating that encompasses overall building design with an accuracy close to that of dynamic simulations [51]. Nevertheless, there is a lack of approaches that consider whole building design and are applied to other aspects of building energy performance such as energy consumption and CO_2 emissions.

In this study, we provide a general metamodel that is designed to be used as a common framework for evaluating the different aspects of building energy performance. The model is based on the study of the individual impacts of the building element and takes into account the time-dependency of its design parameters. The approach is customized to the energy needs and consumption for heating and cooling, the cost of energy and CO_2 emissions. We then studied the energy performance of an office located in Paris. Specific metamodels for this case study were deduced from the general model and fitted from dynamic simulation. Their accuracy was shown by comparing the results with those of dynamic simulation.

2. Method

2.1. General metamodel

The general metamodel we developed assumes that, for a given energy performance, the overall impact of a building I_b is a function, to be determined, of the individual impacts $\mathbf{I} = (I_1, I_2, \ldots, I_n)$ of its elements.

The second-order Taylor expansion of this function around the point $\mathbf{I} = (0, 0, \ldots, 0)$ gives the following expression of the impact:

$$I_b = a_0 + \sum_{i=1}^{n} a_i I_i + \sum_{i=1}^{n} a_{ii} I_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} a_{ij} I_i I_j + \varepsilon \quad (1)$$

where I_i and I_j are two individual impacts, a_i, a_{ii}, and a_{ij} are the metamodel coefficients to be identified and ε is the residual error.

When all the individual impacts of the building elements are null, at the point $\mathbf{I} = (0, 0, \ldots, 0)$, there are no impacts of the building elements on the energy performance; consequently the overall impact of the building I_b is also null, which implies that $a_0 = 0$.

The individual impacts of the building elements are determined in a simplified steady state calculation. The identification of the metamodel coefficients from dynamic simulations allows considering the transient behavior of the building and consequently the effect of the thermal mass. These coefficients, which are constant in the model, are assumed to depend on the climate of the location, the thermal mass of the building, the building use (residential, commercial, etc.) and the type of energy system.

Table 1
The considered reference and the dimensionless time-dependent components of metamodel parameters.

Parameter	Symbol	Reference component	Time-dependent component
U-value	U	U_r	$U(t)$
Area	A	A_r	$A(t)$
Adjustment factor for transmission	b_{tr}	$b_{tr,r}$	$b_{tr}(t)$
Adjustment factor for air change	b_{ac}	$b_{ac,r}$	$b_{ac}(t)$
Air change rate	$q_{v,ac}$	$q_{v,ac,r}$	$q_{v,ac}(t)$
Solar heat gain coefficient	$SHGC$	$SHGC_r$	$SHGC(t)$
Shading reduction factor	F	F_r	$F(t)$
Efficiency of the energy system equipment	η_{sys}	$\eta_{sys,r}$	$\eta_{sys}(t)$
Energy price	EP	EP_r	$EP(t)$
CO_2 emission factor	EF_{CO_2}	$EF_{CO_2,r}$	$EF_{CO_2}(t)$

The main energy performance indicators used to evaluate the overall building impact are the energy needs for heating and cooling Q_h and Q_c and the corresponding energy consumption E_h and E_c, the cost of energy consumption C_h and C_c, and the CO_2 emissions $m_{CO2,h}$ and $m_{CO2,c}$. The related individual impacts are discussed below.

2.2. Individual impacts

2.2.1. Energy needs for heating and cooling

In terms of the energy needs for heating and cooling, the individual impact of a building element i is an individual energy need Q_i (kWh).

A transmission energy need Q_{tr} is calculated, in a quasi-steady-state assumption as

$$Q_{tr} = \sum b_{tr} UA \left(\theta_{is} - \theta_{eo}\right) \Delta t \quad (2)$$

where U and A are the U-value and the area of the wall, respectively; θ_{is} is the indoor set-point temperature; θ_{eo} is the equivalent outdoor temperature to which the wall is exposed, which can be the air-soil temperature for an opaque wall or the mean weighted temperature of the air and sky for a window; b_{tr} is the temperature adjustment factor for transmission (equal to 1 when the wall is exposed to the external environment) [52] and Δt is the time step.

We assume that a design parameter x such as U, A and b_{tr} can be computed from (Table 1)

$$x = x_r x(t) \quad (3)$$

where x_r and $x(t)$ are the constant reference and the dimensionless time-dependent components of x, respectively.

Thus, a transmission energy need Q_{tr} can be expressed as

$$Q_{tr} = b_{tr,r} U_r A_r \sum b_{tr}(t) U(t) A(t) \left(\theta_{is} - \theta_{eo}\right) \Delta t \quad (4)$$

An energy need due to air change Q_{ac} by infiltration or ventilation is given by

$$Q_{ac} = \sum b_{ac} \rho_a c_{pa} q_{v,ac} \left(\theta_{is} - \theta_{oa}\right) \Delta t \quad (5)$$

where $q_{v,ac}$ is the air flow rate, ρ_a and c_{pa} are the air density and specific heat capacity, respectively, θ_{oa} is the outdoor air temperature and b_{ac} is the temperature adjustment factor for air change