Applied Energy 119 (2014) 537–556

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Automated metamodel generation for Design Space Exploration and decision-making – A novel method supporting performance-oriented building design and retrofitting

Philipp Geyer [a,*], Arno Schlüter [b]

[a] Centre for Energy Efficient and Sustainable Planning and Building, Technische Universität München, Arcisstraße 21, 80333 München, Germany
[b] Architecture & Sustainable Building Technologies (SuAT), Institute of Technology in Architecture/ITA ETH Zurich, Schafmattstrasse 32, 8093 Zurich, Switzerland

HIGHLIGHTS

- Automated exponent term composition for the Response Surface Method (RSM).
- Verification of the method by identification of mathematical test functions.
- Validation and illustration of use by application to building retrofit case.
- Improvement of RSM accuracy from 43% error to 7% error in exemplary case.
- Illustration of Design Space Exploration (DSE) and decision making support.

ARTICLE INFO

Article history:
Received 24 April 2013
Received in revised form 18 December 2013
Accepted 26 December 2013
Available online 7 February 2014

Keywords:
Metamodelling
Surrogate models
Response Surface Method
Building energy performance simulation
Design Space Exploration

ABSTRACT

Design and retrofitting of buildings for high performance in terms of low consumption of energy and exergy requires the examination of a large number of design variants, including time-consuming simulation. Metamodels (surrogate models) based on the Response Surface Method (RSM) can solve this time problem by shifting computational effort for simulation from within a design process to a prior time. However, traditional metamodelling by RSM with second-order polynomials performs well only for selected problems and requires mathematical and technical understanding and manual adjustment by the user. To generate models without user interaction, the paper presents a novel method for automatically generating a higher-quality mathematical structure of the metamodel. With minimal user interaction, the method searches for all degrees of interaction and allows for simple definition of high order polynomials. The primary component of this method is an algorithm that determines the mathematical structure of the metamodel by composing an exponent matrix step-by-step while minimising the modelling error. First, we employ standard mathematical test functions to demonstrate the method's ability to identify models with up to six interacting variables; these functions determine its performance and limitations. An important observation is that the number of simulation experiments needs to be 1.5 to 2 times the number of exponent terms. Second, we apply the method to the design decisions and respective simulation data of a parametric Design Space Exploration (DSE) for an example case of an office building retrofit. This application demonstrates that the method improves the accuracy in cross-validation to an error of 7.2% for the total energy consumption, whereas the standard static RSM leads to an error of 35.9% (26.8% with interactions). Additional analyses demonstrate the benefits and limitations of metamodels for separated heating and cooling loads, as well as exergy. One benefit of applying the method is a quick-responding performance model. The use of this model is illustrated with a tool mock-up. A second benefit is obtaining global knowledge of the design space, as derived from interpreting the mathematical structure of the metamodel, i.e., the exponent and coefficient matrices. This structure reveals the quantitative impacts of factors and their interactions, and it allows identifying different design strategies, which is valuable for high-performance building design and retrofitting.

* Corresponding author. Tel./fax: +49 89 289 23990.
E-mail addresses: p.geyer@tum.de (P. Geyer), schlueter@arch.ethz.ch (A. Schlüter).

0306-2619/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.12.064

1. Introduction

In the face of the actual demand for sustainable design, the use of simulation has attained high relevance in determining the energy performance of building designs. Simulation is required for examining the dynamic thermal effects of energy efficiency, such as the intermediate storage required for renewable energy sources, solar collectors, night-ventilation, and the day-to-night shift of waste heat. Energy-efficient designs increasingly apply such technologies to the intelligent use of energy, especially for passive designs using high-performance building envelopes; additionally, dynamic simulation is required to correctly represent solar heat gains, their storage by thermal capacity and the effects of different control strategies.

However, a major problem of applying dynamic building simulation in the design process is the long computation time and the resulting delayed response. In particular, in the early design phases, which examine many design variants in terms of their energy performance, a quick response to an analysis request is required. The use of simplified quasi-steady-state methods, such as those described by the DIN-EN 832, reduce the calculation times drastically but provide no alternative because they capture dynamic effects only to a limited extent. The integration of renewable energy sources, the use of energy storage, and the exchange of energy (waste heat, electricity) between buildings requires dynamic simulations. As a consequence, designers need both an accurate result of the energy consumption and a prompt response within the design process.

The requirement of an instant response becomes more critical in case of the application of Design Space Exploration (DSE). We understand DSE as a method of providing a parametric design model and systematically searching for good solutions. The term design space in this context describes the combinatorics of the possible configurations that the selected parameters or factors and their levels allow. This search can be performed manually by changing the parameters and observing the results or automatically by using an experiment plan or directed search methods. The methods used for this purpose include parametric studies, design of experiments (DoE) [1,2] and multidisciplinary design optimisation (MDO) [3,4]. For performance-oriented design, these methods require a parameterised simulation model that is able to determine the performance of a design artefact depending on the configuration of its defining parameters. Eskin and Türkmen [7] present a study of the heating and cooling loads depending on building's conditions and control strategies based on simulation and measurements. Ourghi et al. [8] examine the influence of the building's compactness and windows area and type on the cooling loads using simulation. Aksoy and Inalli [9] vary the building shape and orientation position to observe the heating demand in a cold climate by simulation. Papamichael et al. [10] present modelling environment for early design phases with parametric capabilities for lighting and thermal energy. Caldas and Norford [11] apply Genetic Algorithms the generate good design solutions in terms of thermal performance and lighting. Lu et al. [12] optimize an HVAC system. Mara and Tarantola [13] show the application of ANOVA to thermal building simulation. Ghiaus [14] builds a regression model of heating and cooling energy consumption based on outdoor temperatures of different locations. The search procedure usually involves many evaluations of the performance models. In the case of simulations of building designs, this can cause considerable computation times, e.g., the 20 h reported by Welle et al. [5,6] or the 60 h reported by Chantrelle et al. [7].

Metamodelling, also called surrogate modelling, offers a solution in this situation.[1] Due to its ability to provide quick responses compared to other methods (cf. [36]) and its close relation to engineering interdependencies, the Response Surface Method (RSM) is chosen in this approach for metamodelling. In the best case, physical dependencies directly map to terms of the metamodel, and engineers can interpret the revealed dependencies without any diagrams. The RSM, which generates a mathematical surrogate model from sample points, has been used in scientific studies in many different contexts of engineering to derive rapid-response models mostly by second-order polynomials with first-order interactions (see background). To develop a metamodelling method that designers can apply for broad DSE without mathematical and technical knowledge, it is necessary to investigate the steps of metamodelling to identify where manual interventions currently occur. The procedure of metamodel generation consists of three steps:

(1) Sampling of the design space to generate supporting points of the metamodel mostly on the basis of design of experiments (DoE).
(2) Generation of the metamodel from the resulting data, including manual model selection, i.e., composing terms for factors and interactions, and fitting, i.e., regression analysis.
(3) Validation of the metamodel against the simulation results by additional simulations that were not included in the fitting data (cross validation).

There are two steps that require user interactions based on technical-mathematical understanding. Step one requires the selection of an appropriate DoE table. This, however, relies on the complexity of the problem and the structure of the metamodel. Given the metamodel structure selected, automated table selections seems possible; Sections 3.1 and 4.3 will examine criteria for this purpose. Step two requires the manual setup of the mathematical structure of the metamodel, which involves significant technical knowledge. To overcome this drawback, this paper develops an automated method of model composition to complement the RSM in step (2) so that it does not need a manual model selection and broadly searches for well-fitting model structures. This automated method improves the accuracy of the metamodel significantly. By these automations, user intervention is reduced and decoupled from mathematical experience in RSM. This allows broad application of RSM by building designers in individual design cases.

Section 2 describes the theory for this main innovation, which is the automated generation of the mathematical structure of the metamodel, i.e., the composition of polynomial terms by a selection and composition algorithm. The evaluation of the method by standard mathematical test functions with known exponents and coefficients in Section 3 serves to verify the method. This section also includes important observations of the performance of the method and of the required size and structure of the DoE table. Section 4 reports the application of the method to an exemplary retrofit case of an office building. This application shows the use and benefit of an individual retrofit case. It determines the quality of the metamodel for different real-world performance indicators, such as site energy, thermal heating and cooling energy, and exergy, by cross-validation and compares it with the results of the traditional RSM. Furthermore, it shows how to derive strategies for low-energy building design for individual cases by interpreting the structure of the metamodel and its coefficients.

1.1. Background of metamodelling

A prominent method of metamodelling, which forms the basis of this paper, is the Response Surface Methodology (RSM).

[1] Please note that the term metamodelling is used in the engineering sense of a surrogate model and not in the sense of computer science referring to a model of higher order.