Energy Conversion and Management 174 (2018) 705–718

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Uncertainty and sensitivity analysis of energy assessment for office buildings based on Dempster-Shafer theory

Wei Tian[a,b,*], Pieter de Wilde[c], Zhanyong Li[a,b], Jitian Song[a,b], Baoquan Yin[d]

[a] Tianjin Key Laboratory of Integrated Design and On-line Monitoring for Light Industry & Food Machinery and Equipment, College of Mechanical Engineering, Tianjin University of Science and Technology, Tianjin 300222, China
[b] Tianjin International Joint Research and Development Center of Low-Carbon Green Process Equipment, Tianjin 300222, China
[c] Chair of Building Performance Analysis, Environmental Building Group, University of Plymouth, Plymouth, Devon PL4 8AA, United Kingdom
[d] Tianjin Architecture Design Institute, 300074 Tianjin, China

ARTICLE INFO

Keywords:
Uncertainty analysis
Building performance
Dempster-Shafer theory
Sensitivity analysis
Machine learning

ABSTRACT

Uncertainty and sensitivity analysis of building energy has become an active research area in order to consider variations of input variables and identify key variables influencing building energy. When there is only limited information available for uncertainty of building inputs, a specific probability for a given variable cannot be defined. Then, it is necessary to develop alternative approaches to probabilistic uncertainty and sensitivity analysis for building energy. Therefore, this paper explores the application of the Dempster-Shafer theory (DST) of evidence to conduct uncertainty and sensitivity analysis for buildings. The DST method is one of imprecise probability theories to allow combining uncertainty from different sources in terms of interval-valued probabilities in order to construct the belief and plausibility (two uncertainty measures) of system responses. The results indicate that the DST uncertainty analysis in combination with machine learning methods can provide fast and reliable information on uncertainty of building energy. It is recommended that at least two inherently different learning algorithms should be applied to provide robust simulation results of building energy. A spectrum of distributions should be implemented in global sensitivity analysis with the DST method because there are no specific distributions for intervals of input factors. Moreover, the stability of results from uncertainty and sensitivity analysis should be assessed when applying the DST method in building energy analysis.

1. Introduction

Building energy is affected by a number of inherently uncertain variables, including weather conditions, internal heat gains, and occupant behaviours [1,2]. Therefore, uncertainty analysis of building energy has become an active research field [3–5]. Most previous studies have implemented probabilistic uncertainty methods to consider the influences of these uncertain parameters [6–8]. Urbanucci and Testi [9] use the Monte Carlo risk analysis to estimate the long-term uncertainty of energy demands for a hospital facility in order to optimize the size of CHP (combined heat and power) system. Tian et al. [10] consider the influences of variations of building form on energy performance of buildings located at Harbin (China) based on the Monte Carlo sampling method. Faggianelli et al. [11] implement sampling-based sensitivity analysis by regarding input factors as uniform or normal distributions. Hopfe and Hensen [12] assume the normal distributions for input factors to assess energy performance of an office building using the Latin hypercube sampling method. These examples demonstrate that probabilistic uncertainty and sensitivity analyses have become very popular and widely used in the field of building performance simulation. However, variations of building variables are difficult to obtain and it can be a challenge to gather sufficient information for the definition of a specific probability (such as uniform, normal, triangle, and lognormal) when predicting energy use, especially in the stage of building

Abbreviations: BPA, basic probability assignment; CBF, cumulative belief function; CCBF, complementary cumulative belief function; CCPF, complementary cumulative plausibility function; CDF, cumulative density function; CHP, combined heat and power; CL, cooling set-point temperature (°C); CPF, cumulative plausibility function; CSWD, Chinese standard weather data; DST, Dempster-Shafer theory; ED, equipment peak value (W/m^2); FT, infiltration rate (ACH); HT, heating set-point temperature (°C); LD, lighting power density (W/m^2); MARS, multivariate adaptive regression splines; OD, occupancy density (people/m^2); RMSE, root mean square error; SHGC, solar heat gain coefficient; SVM, support vector machine; VAV, variable air volume system

* Corresponding author at: Tianjin Key Laboratory of Integrated Design and On-line Monitoring for Light Industry & Food Machinery and Equipment, College of Mechanical Engineering, Tianjin University of Science and Technology, Tianjin 300222, China.

E-mail address: tjtianjin@gmail.com (W. Tian).

https://doi.org/10.1016/j.enconman.2018.08.086
Received 16 April 2018; Received in revised form 30 July 2018; Accepted 22 August 2018
0196-8904/

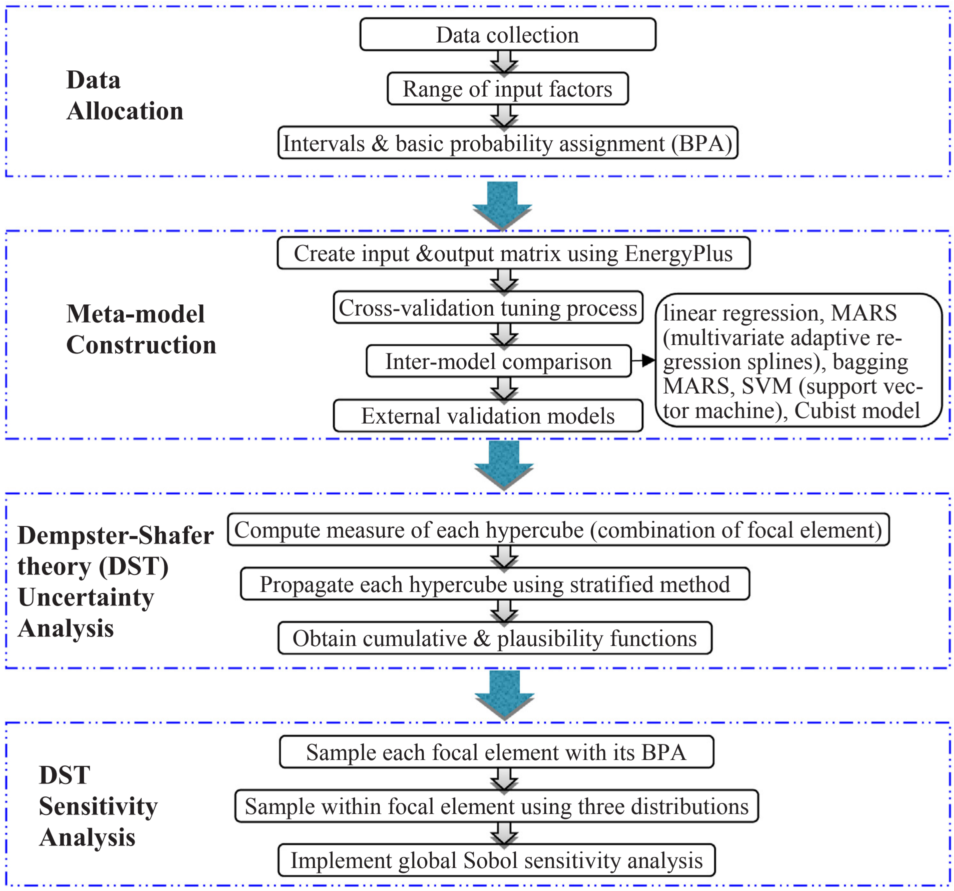

Fig. 1. Flow chart used in this research.

design [13]. Hence, the alternative approach to probabilistic analysis is needed to handle the imprecise building data in properly estimating energy performance of buildings.

The Dempster-Shafer theory (DST) of evidence can be regarded as a generalization of classical probability theory that allows one to deal with the imprecise information on data, often in the form of interval-valued data. The mathematical foundations of DST analysis have been well established [14] and the DST approach has been used in various fields, including studies on reliability of pressure vessels [15], petroleum engineering [16], urban environment [17], and computer voice detection [18]. More recently, the DST analysis is also being applied to the analysis of building energy. Tian et al. [3] implement the DST to assess uncertainty of energy performance for an office building using the EnergyPlus program. Four scenarios are used in their research to represent the level of availability for uncertain inputs from the simple to detailed information. Chaney et al. [19] use the DST to add multiple-sensor data in a house simulation model. They found that the evidence theory is a reasonable approach for providing rich information about occupant interaction with systems in the house. Kim et al. [20] report that the DST can be used to effectively combine uncertainties from five experts into single uncertainty when predicting energy use for a 33-storey office building in Seoul, Korea.

These previous studies provide valuable information on the implementation of DST analysis in building energy assessment. However, there are several issues that have not been explored when applying the DST method in building energy assessment. One issue is how to reduce high computational cost of DST analysis in building simulation using engineering-based energy models. A large number of simulation runs are usually required to provide the minimum and maximum output values in order to obtain the stable results of output range for the DST method. Another issue is how to implement sensitivity analysis within the context of DST analysis in assessing building energy performance. The sampling-based sensitivity analysis requires the structured distributions of input variables to obtain a matrix of inputs and outputs. The DST method, however, does not include specific distributions for the data within the intervals.

Therefore, this paper explores a systematic approach towards implementation of the DST method in uncertainty and sensitivity analysis of building energy when only limited information on building input variables is available. An office building located in Tianjin (China) is used as a case study to demonstrate the suitability of DST method in assessing building energy performance. The building energy simulation is carried out with the EnergyPlus program [21]. The originality of this paper is two-fold: (1) implementation of global sensitivity analysis in conjunction with the DST analysis in assessing building energy performance; (2) demonstration of using machine learning models to reduce high computational cost of building energy simulation for both uncertainty and sensitivity analysis within the DST analysis. Moreover, this research discusses two important issues in the application of DST analysis: how to choose reliable machine learning models and how to assess the stability of uncertainty and sensitivity analysis. This provides practical guidance in applying the DST method into building energy assessment. The combination of DST and machine learning algorithm can significantly expedite computation, which can make DST analysis feasible in building energy assessment. However, a number of machine learning models should be evaluated to choose suitable ones for replacing building energy models on a case-by-case basis. More discussion on the method used will be presented in Section 2.

The remaining parts of this paper are structured as follows. Section 2 describes the statistical methods applied in this research, including