

AUTOMATIC CALIBRATION OF A BUILDING ENERGY SIMULATION MODEL USING A GLOBAL OPTIMIZATION PROGRAM

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ABSTRACT

A simulation model used to analyze the energy performance of an existing building should be calibrated to measured consumption data from the building so the simulation output closely follows the measured time series energy consumption data and shows the same temperature dependence. This paper has used optimization software to show that a simple simulation program which is a coding of the ASHRAE 'Simplified Energy Analysis Procedure' can be automatically calibrated to "measured" data. The "measured data" used in this case study was simulation data to which a small amount of white noise had been added.

INTRODUCTION

Building simulation models have been used for many years to forecast and analyze a building's energy consumption. In order to analyze an actual building's energy performance, the simulation model should be calibrated to generate output trends similar to the energy consumption of the actual building both in magnitude and pattern. This paper introduces a new approach in the history of calibration methods for building energy performance models. The procedure for automatic calibration is a global optimization process minimizing the error between measured and simulated energy consumption. The "measured" data used in this case was generated by the simulation program and will be referred to as synthetic measured data. The accuracy of calibration is fairly good (Table 1.) and the calibration time is less than 5 minutes with an ordinary personal computer.

LITERATURE REVIEW

There are several notable developments in the evolution of model calibration. Akbari et al. (1988) identified weather-dependent parameters and non-weather dependent parameters. Hsieh (1989), and Griffith et al. (1994) proposed a sensitivity analysis. Carroll et al. (1993) introduced an iterative calibration method. Clarke et al. (1993) made experimental instruments to validate the calibration of simulations. Kaplan et al. (1990, 1992), Subbarao et al. (1990), Balcomb et al. (1993, 1994), Manke et al. (1996) proposed short term building monitoring and calibration. Wei et al. (1998) developed signatures showing the influence of different parameters on the heating and cooling energy consumption for use in calibration. Bronson et al. (1992) developed carpet plots and characterized input parameters as weather-dependent and non-weather-dependent when calibrating the DOE-2 simulation program. Haberl et al. (1992), Hinchey et al. (1991), and Bronson et al. (1992) used 2-dimensional and 3-dimensional time-series and scatter plots to visualize the errors between measured and simulated data. Recently, Reddy et al. (1999) developed an inverse method to estimate the overall building and ventilation parameters of large commercial buildings.

In hydrological science, an automatic calibration technique was developed in the 1980's to calibrate an underground water location prediction model. Sorooshian et al. (1980, 1981, 1983, 1993) developed the automatic calibration method. Duan et al. (1992, 1993, 1994), Gupta et al. (1985, 1998, 1999) and many other hydrological scientists worked together to stabilize the method more than 20 years.

Table 1. Automatic calibration results (average of 32 calibrations).

	Tcl	Tr	UA	Vsupply	OA(%)	RMSE
Units	(°F)	(°F)	(Btu/h-°F)	(cfm/sf)	(%)	(Btu/hr)
Correct Value	55.00	73.00	18880.00	1.20	10.00	5961.76
After Calibration	54.86	73.09	18843.80	1.18	10.11	5722.06
°F or (Cali.-Correct) / Correctx100 (%)	0.14°F	0.09°F	0.2%	1.3%	1.1%	4.0%

METHODOLOGY

Following the concept used in hydrology of using an optimization program for calibrating the simulation model, this paper describes an automatic method developed to calibrate a simple building energy performance model. The procedure for automatic calibration is a global optimization process minimizing the error between measured and simulated energy consumption. The following objective function, which uses the RMSE of the CHW and HW simulations, is used:

$$\text{ObjectiveFunction} = \text{Minimize } \frac{1}{2} \times \left(\frac{\sum_{i=1}^n \sqrt{(CHW_{sim} - CHW_{mea})^2}}{n-1} + \frac{\sum_{i=1}^n \sqrt{(HW_{sim} - HW_{mea})^2}}{n-1} \right)$$

The automatic calibration program (Figure 1)¹ uses the same heat transfer and thermodynamic equations, which are used in the simulation program as constraints for calibration (optimization process). In other words, the calibration process is directly guided by the mathematical relationships among various variables and constants in the simulation-model. This ensures that the calibration steps are performed considering all the variables at the same time, understanding the characteristics of a simulation model. The Solver® (Frontline Systems, 2000) package is one of the most advanced optimization tools available at relatively low cost. Multiple investigators have used this package to successfully avoid local minima that plague optimization procedures. Kahn-Jetter et al. (1997), Kane et al. (1997), Klukowski et al. (2001), Morrice et al. (2001), Nikitas et al. (2000, 2001) Okennedy et al. (1994), Thiriez (2001), and Walsh et al. (2001) also conducted research with Solver® in their own fields. Therefore this package was chosen to conduct an initial test of automatic calibration in the energy management field.

SIMULATION MODEL

The simplified simulation model used in this project is a coding of the ASHRAE ‘Simplified

Energy Analysis Procedure’ (Knebel, 1983). It is used to prove the possibility of automatic calibration through an optimization process. Synthetic ‘data’ was generated by the simulation program. This synthetic measured heating and cooling energy consumption data for the prototype building described below is then modified with 1% artificial random noise to represent some of the model deficiencies that will be present in a real building. By using synthetic measured data, the accuracy of the calibration result and the existence of local minimum could be judged much easier than if actual measured data were used.

The prototype building used for the simulation is assumed to have total conditioned area of 120,000 sf. Building length and width are 240 ft and 100 ft respectively. The height of the building is 65 ft with 5 stories. 13,260 sf of window (30 % of 4 façade areas of the building) has a U-value of 1.1 Btu/h-°F-sf. The remaining exterior sidewall area is 30,940 sf and the roof area is 24,000 sf. The wall U-value is 0.1 Btu/h-°F-sf and the roof U-value is 0.05 Btu/h-°F-sf. The occupancy of the building is 200 sf/person. Lighting and receptacle electrical loads correspond to daily average values of 1.0 W/sf and 0.5 W/sf respectively. The supply-air and outside-air flow rates are 1.2 cfm/sf and 0.12 cfm/sf respectively. The building was modeled with 50% of the area in an interior zone and 50% in an exterior zone. The room temperature setpoint is 73 °F. The HVAC system used is a single-duct-constant-volume (SDCV) terminal-reheat system.

MODEL CALIBRATION

The automatic calibration program uses the global optimization technique. This program is designed to calibrate the building energy performance model automatically. The number of parameters that that were changed to require calibration was restricted to five for the work done here. The variables calibrated are Tel (cooling coil leaving air temperature), Tr (room temperature), UA_{tot} (heat transfer rate for the building envelope), Vs (supply-air volume), and X_{oa} (outside-air flow fraction). UA_{tot} is the sum of UA_{window}, UA_{roof} and UA_{walls}. The boundaries of reasonable values of parameters (Table 2) limit the variation of parameters for calibration in program.

¹ Software copyright © 2002 by TEES

Table 2. The limiting values of parameters calibrated.

	Max	Min
Tcl	70	45
Tr	80	60
UA _{tot}	30000	5000
V _{supply}	2.0	0.5
OA(%)	80	5

The initial parameter sets were generated within the reasonable boundaries to test the calibration performance and identify any local minima. The 32 different initial-parameter-sets are composed of 5-parameter combinations of upper limit and lower limit values (Table 2), which correspond to extremely faulty initial input cases. To make the synthetic measured data more realistic, a small amount of artificial noise is introduced (Figure 2). The range of the random numbers is within 1% of average cooling or heating consumption. The presence of this noise results in an RMSE value of 5961.763 Btu/hr when the original input parameters were used.

LOCAL MINIMA

Incorrect sets of input parameters can produce simulated energy consumption values fairly close to the synthetic measured values. In terms of optimization these correspond to local minima. The program developed can filter out the local minimum solutions for the cases tested; these may be confused with the correct solution using only the conventional graphical method (Figure 3 and Table 3). This is one of the reasons why manual calibration results sometimes differ from one calibrating engineer to another if they are not checked with building measurements. In this paper parameter sets that result in local minima have been identified. A critical requirement for the automatic calibration process is the ability to escape from a local minimum and find the global optimum automatically. Without meeting these requirements, the calibrated model cannot be a correct representative of the real building. Therefore identifying the local minimum from which the automatic calibration process can escape is fairly meaningful for verifying the credibility of the program.

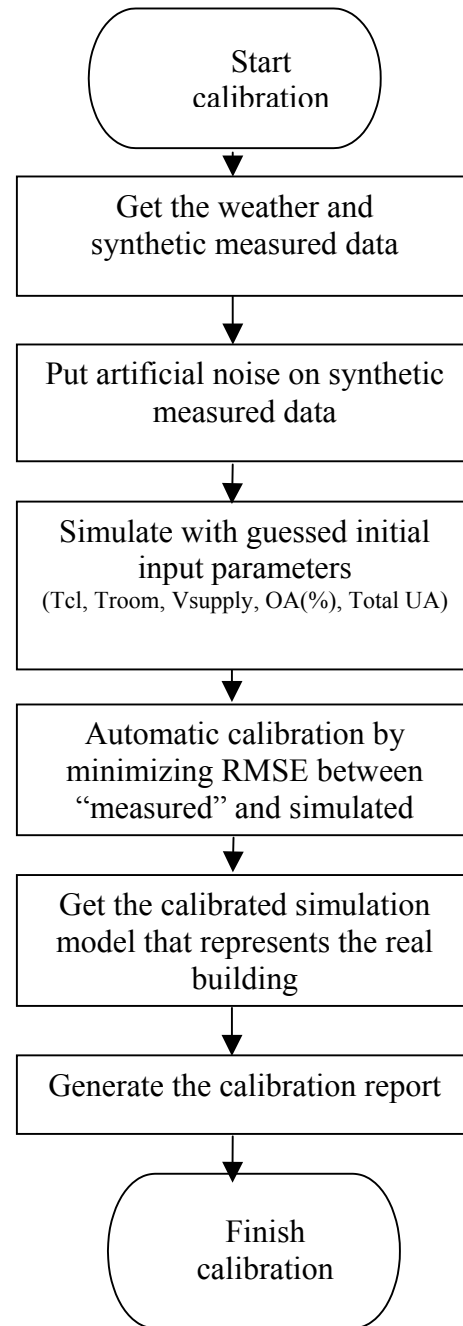


Figure 2. Procedure for calibration

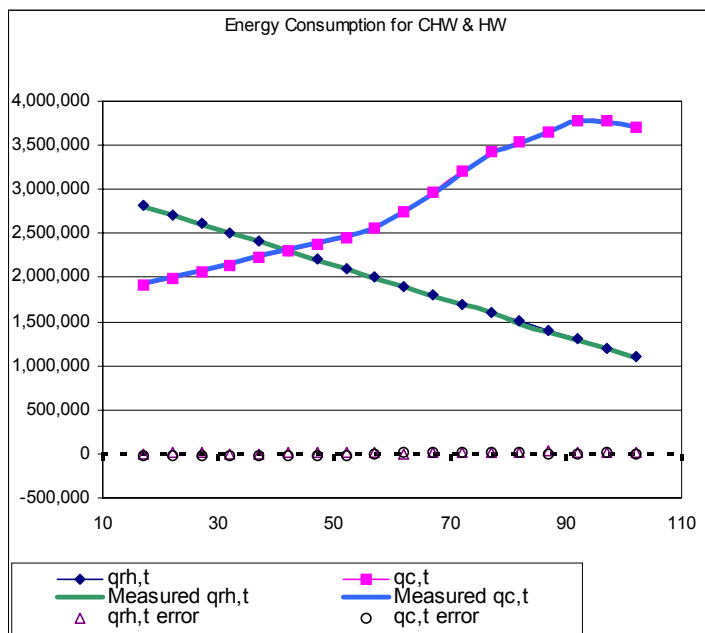


Figure 3. Local minimum solution. The agreement is excellent.

Table 3. Local minimum solution of (Figure 3.) The actual input parameters are far from accurate.

	Tcl	Tr	UA	Vsupply	OA(%)	RMSE
Correct Value	55.00	73.00	18880.00	1.20	10.00	5961.76
Before Calibration	45.00	80.00	5000.00	2.00	5.00	6380175.85
After Calibration	60.51	71.44	18897.76	2.00	6.68	19897.20
°F or (Cali.-Correct) / Correctx100 (%)	5.51°F	1.56°F	0.1%	66.7%	33.2%	233.7%

CONCLUSIONS

An automatic calibration method using an optimization technique has been programmed and tested with the commercial optimization add-in software Solver®. The automatic calibration method has been shown to provide objective (free from local minima), accurate, and fast calibration to the synthetic measured building HVAC energy consumption data with which it was tested. The automatic calibration program uses the simulation program as constraints in the optimization process. This program opens the door for the possibility for adding an autocalibration feature to simulation programs. This may permit objective, fast and reliable calibrated simulation.

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