Building Thermal Performance Optimization using GA and ANN

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ABSTRACT

The optimization of building thermal performance has traditionally been based on designers' experience. However, optimization algorithms such as Genetic Algorithms (GA) have lately been used extensively in order to find the optimization configuration of a building, where the building performance is determined either from a simplified function embedded in the algorithm or from an elaborate energy software tool. In this paper, GA is coupled with Artificial Neural Network (ANN) in order to minimize the energy consumption and maximize the occupants' thermal comfort; the energy simulation tool ESP-r is used to determine the building thermal performance. The resulting scheme was applied to an existing office building, showing the robustness, effectiveness and the value added from resorting to such tools in the construction industry.

KEYWORDS

Whole-building optimization, ANN, genetic algorithm, simulation, energy

INTRODUCTION

Traditionally, the choice of a given design alternative has been made based on the designer's experience and on an exhaustive trial-and-error approach. However, due to the complex interactions between the building elements (building structure, HVAC system, and control strategies), finding the optimal configuration of a building proves to be a very tedious process, which cannot be achieved by such means. Consequently, optimization techniques were introduced in the design process at different levels.

For the sake of simplifying the problem, these optimization approaches will be classified in this paper under three main categories: (1) the optimization of the design process itself; (2) the optimization of the building energy system (building structure, HVAC system, control strategies, or any combination of these); and (3) ongoing simulation, which basically consists in continuously altering some features of the building so that it may adapt to ever-changing operational conditions. The first category deals with optimizing the interactions between the numerous professions involved in building design (e.g. Choudhari 2003). Hobbs et al (2003) also documented the benefits of sensitizing architects to the use of energy tools. The second optimization level has been explored much more and numerous studies are available. Wright and Loosemore (2001) carried out a multi-criterion optimization of the design and control of a building. They used parameters reflecting the three sub-systems aforementioned (characteristics of the envelope, dimensions of the HVAC system, and set-point control temperatures). Wang et al (2005) proposed the optimization of a green building envelope design, based on the measure of the building's exergy. Finally, ongoing optimization studies aim at adapting a building, or an element thereof, to the changing conditions it is subject to, or to the effect of usage on the performance of the element under consideration. Yang et al (2005) investigated different ways to train ANN's for the prediction of the energy consumption of an HVAC system. Madhavi et al (2005) carried out extensive work on model-based control of lighting systems.

Genetic algorithms (GA) are one of the best techniques for building-related optimization problems. Due to their stochastic nature, they have the potential to find near-optimal solutions but at a high computational cost. Hence, if a significant level of detail is required on the performance of the building, computation time rapidly becomes a major barrier. The idea proposed in this paper to overcome this problem is to use an artificial neural network (ANN) whose purpose is to mimic the response pattern of the building when subject to exterior forcing. Towards that end, a number of simulations are required to construct the ANN, which involves choosing an experimental design to sample the region of interest within the design space of the variables. The design of experiments (DOE) is a necessary step, which has to represent the whole design space with as few simulations as possible. Once the ANN is trained, it can be used by the GA in order to evaluate the performance of the buildings generated by the optimization algorithm, thus mitigating the computation time otherwise involved by the use of an external energy tool. The present study aims to show the applicability of this methodology.

METHODOLGY

The building selected for this study is an office building located in Ottawa, Canada. An ESP-r model of the building is available from the ESP-r database. Despite the typical harsh Canadian winter, this building, as so many others in Canada, requires cooling load when the outside temperature is more than 6°C. Clearly there might be room for improvement in terms of energy consumption. Based on this simple observation, a couple of parameters were chosen in a view to determine their impact on the total energy consumption and on the occupants' thermal comfort, and consequently to explore the best tradeoffs between a minimum annual energy consumption and a maximum thermal comfort satisfaction.

This is a multi-objective optimization problem, whose objectives are: 1) the minimization of the annual heating demand; 2) the minimization of annual cooling demand; 3) the minimization of average lighting energy consumption; and 4) the maximization of occupants' thermal comfort in each room.

The optimization objective is a weighted sum of all individual objectives and it takes the following form:

$$F_{obj}(X) = Min \left(\begin{array}{l} C_1\left(\frac{\sum_{i=1}^{n} HE_i * Days_i}{totdays}\right) + C_2\left(\frac{\sum_{i=1}^{n} CE_i * Days_i}{totdays}\right) + C_3\left(\frac{\sum_{i=1}^{n} LE_i * Days_i}{totdays}\right) + C_4\left(\frac{\sum_{i=1}^{n} (1-TC_m) * Days_i}{totdays}\right) + \\ C_5\left(\frac{\sum_{i=1}^{n} (1-TC_g) * Days_i}{totdays}\right) C_6\left(\frac{\sum_{i=1}^{n} (1-TC_c) * Days_i}{totdays}\right) + C_7\left(\frac{\sum_{i=1}^{n} (1-TC_r) * Days_i}{totdays}\right) \end{array} \right)$$

Where HE_i, CE_i, LE_i are the average heating, cooling and artificial lighting energy demands during period *i*. A year is divided into five periods (n=5): early winter, spring, summer, autumn, and late winter. $Days_i$ is the number of days in period *i*. *totdays* corresponds to the total number of days in the year. *X* is the vector of the design variables. *TC*, the parameter used to assess the performance of a given room in terms of thermal comfort, is the ratio of the time for which the indoor air quality is acceptable (i.e. there are less than 20% of people dissatisfied in the room) out of the total time of occupancy for the room under consideration.
To have the desired optimization objective, the designer prescribes weights C_1 to C_7.

After defining the objectives, the next step is to determine the critical parameters taking into account the building envelope and its function. Six parameters were identified: the window sizes, the angles of the exterior louvers, and the lower and upper range of outside temperature set-points to activate the dampers. These selected parameters would give the following 10 design variables: 1) the width and the height of the windows for the south, east, and north façades (6 parameters); 2) the inclination of the louvers on the south and east façades (2 parameters); and 3) the outside temperature set points to activate (i.e. open or close) the dampers (lower and upper temperatures) (2 parameters).

The simulations were performed with the ESP-r energy simulation tool, (*http://esru.stratch.ac.uk*). The software tool uses finite-difference methods for thermal and airflow simulations. Thermal simulations can be run in conflation with mass flow simulations. The selected building has four rooms, each represented by a thermal zone and a mass flow node, plus one thermal zone representing the plenum, and another fictitious thermal zone representing a mixing box. The boundary conditions are set to "exterior" for exterior walls; "adiabatic" for the rear walls of the room; and "similar" for the floor and the upper surface of the ceiling zone. A mass flow network is constructed to represent the airflow between different interior zones and with the exterior environment. The simulations are run for a whole year which is in turn divided into 5 periods: early winter, spring, summer, autumn, and late winter. Three control files (for winter; spring and autumn; and summer) define different temperature set-points for weekday and weekend building occupancy times. Each simulation period is preceded by a 21 day pre-simulation. A whole-year simulation takes approximately 1.25 hours (CPU time).

RESULTS AND DISCUSSION

The original case is analyzed using the ESP-r energy tool, and the average energy and performance factor are determined. Figure 1 shows the annual heating and cooling energy consumption for the whole periods for the entire building; the average annual thermal comfort factor for the manager and reception rooms is shown in Fig. 2. Due to the large glazing surface area, the building has a large cooling load during the summer time (as shown in Fig. 1 for period 3) that makes it less comfortable for the occupants, as depicted in Fig. 2. Cooling is required when the outside temperature is greater than 6°C. The heating demand is also very significant during early and late winter (shown as period 1 and 5 on the same figure).

Before processing to the optimization, the design space is properly defined, taking into account the existing building office and the nominal values of the selected parameters. As far as the window dimensions are concerned, the glazing area could not be increased due to the geometry of the building. On the other hand, the area of the windows under consideration could be decreased providing that the total glazing area (exclusive of skylights) is not less than 10% of the floor area of the room in which it is located (Ontario Building Code and Supplementary Guidelines 1997).

The angle of the louvers is measured from the horizontal plane corresponding to the roof, with a 0° angle corresponding to the horizontal position. The angle can vary from 20° to 160°. Natural ventilation can be used with outside air temperatures ranging from 12°C to 28°C,whence the variation range for the lower temperature ,from 10°C to 15°C; and from 23°C to 28°C for the upper temperature.

The goal of the optimization is to achieve energy savings by reducing the heating and cooling demands while improving occupants' thermal comfort. The ANN was used to assess the performance of the building candidates in the optimization process. A back propagation ANN was used. It used 38 simulation results from the ESP-r runs to construct the response surface, using 30 for training and 8 for testing. The network has 10 input nodes corresponding to the selected 10 parameters; 21 hidden nodes obtained by trial and error to model the current problem; and 7 output nodes corresponding to the objective values given in Eqn. 1. The ESP-r simulations were carried out in Pentium III 733 MHz and required about 3 weeks. The ANN training took about 3 hours in Pentium IV, 2.2GHz. The average error on the validation test cases was found to be less than 5%, as seen in Fig. 3 a. Figure 3 b. shows the comparison between the prediction of the heating and cooling energy demands by the ANN with that of the building simulations, which shows a very good accuracy of prediction of the ANN.

Table 1 shows the values of the design parameters, as per the optimization, compared to the original values of the existing building. The glazing area decreases while the louver angles increase. This is sensible enough since decreasing the gazing area would enable to decrease both the heating load in winter and the cooling load in summer. Likewise, the louver angle proves to be the best compromise in terms of use of natural light and cooling load associated with direct sun beams. Figure 4 shows the comparison between the optimized and the original buildings' energy demand; the heating and cooling energy demands have thus been reduced by 12% and 4.8% respectively. The value of *TC* has increased by 1% to 4.0 % on average for the rooms, as seen in Fig. 4.

CONCLUSION

This work demonstrates the feasibility of optimizing an existing office building energy consumption using an optimization scheme that couples GA's and ANN's. The optimization objective is to minimize energy consumption while maximizing occupants' thermal comfort. The ANN database counts less than 40 simulations and predicts rather accurately the objective function. The implemented optimization methodology results in significant annual energy savings while maintaining and improving occupants' thermal comfort throughout the year. Further work needs to be done to apply the methodology to other buildings and for full-scale buildings cases.

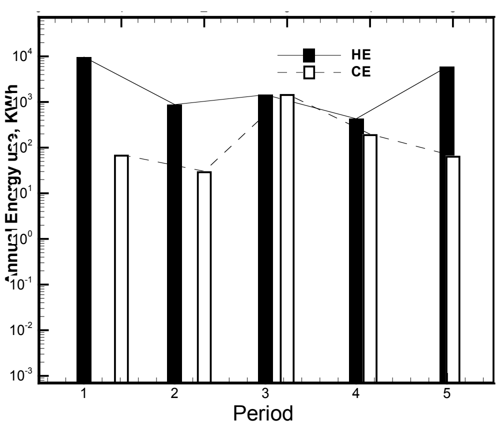


Figure 1. Average annual heating and cooling load

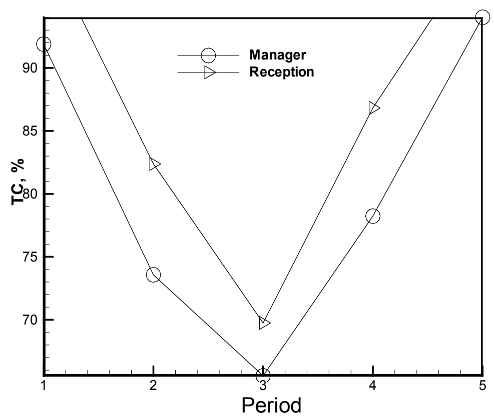
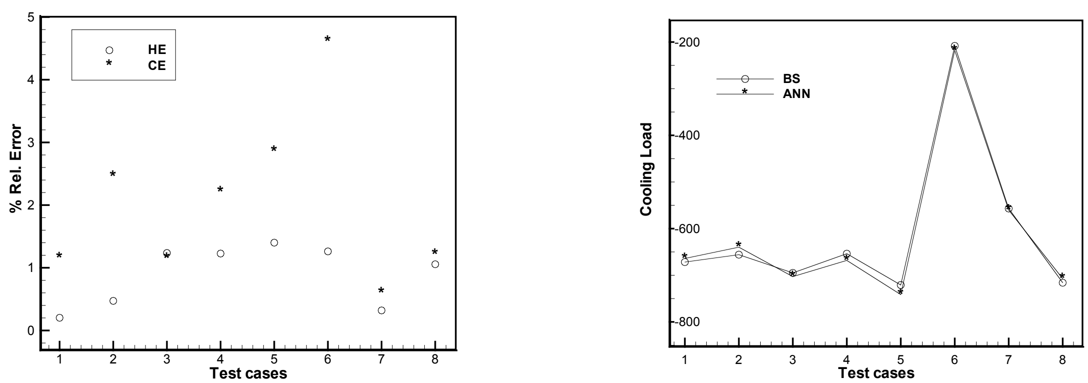
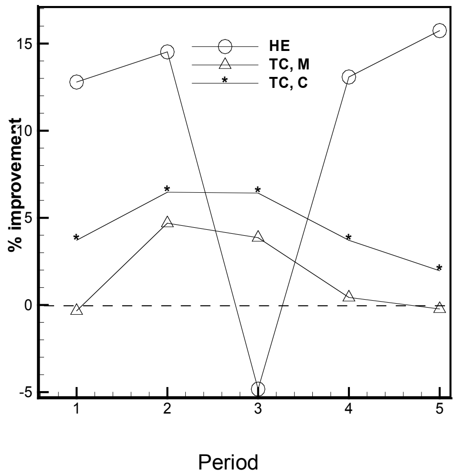


Figure 2. Average annual thermal comfort



a) b)

Figure 3. The ANN model validation.



Parameters	Original value	Optimal value
Window Dim, South (WxH) in m	2.8 x 1.9	2.4 x 1.7
Window Dim, North (WXH) in m	2.8 x 1.9	2.4 x 1.7
Window Dim, East (WXH) in m	2.8 x 1.9	2.4 x 1.7
Angle of louvers, South, in degree Angle of louvers, East in degree	90 90	139 135
Lower and upper bound for the outside temperature set point for the control of ventilation in °C	[13, 28]	[13, 26]

Figure 4. Heating energy saving improvement in. Table 1. Design parameter values TC for rooms Manager and Conference.

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