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Research paper

# Comparative performance analysis of the artificial-intelligence-based thermal control algorithms for the double-skin building

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## HIGHLIGHTS

- Integrated control algorithms were developed for the heating system and surface openings.
- AI theories were applied to the control algorithms.
- ANN, FL, and ANFIS were the applied AI theories.
- Comparative performance tests were conducted using computer simulation.
- AI algorithms presented superior temperature environment.

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## ABSTRACT

This study aimed at developing artificial-intelligence-(AI)-theory-based optimal control algorithms for improving the indoor temperature conditions and heating energy efficiency of the double-skin buildings. For this, one conventional rule-based and four AI-based algorithms were developed, including artificial neural network (ANN), fuzzy logic (FL), and adaptive neuro fuzzy inference systems (ANFIS), for operating the surface openings of the double skin and the heating system. A numerical computer simulation method incorporating the matrix laboratory (MATLAB) and the transient systems simulation (TRNSYS) software was used for the comparative performance tests. The analysis results revealed that advanced thermal-environment comfort and stability can be provided by the AI-based algorithms. In particular, the FL and ANFIS algorithms were superior to the ANN algorithm in terms of providing better thermal conditions. The ANN-based algorithm, however, proved its potential to be the most energy-efficient and stable strategy among the four AI-based algorithms. It can be concluded that the optimal algorithm can be differently determined according to the major focus of the strategy. If comfortable thermal condition is the principal interest, then the FL or ANFIS algorithm could be the proper solution, and if energy saving for space heating and system operation stability is the main concerns, then the ANN-based algorithm may be applicable.



## 1. Introduction

The artificial-intelligence-(AI)-based control strategy has been increasingly proposed for creating advanced building environmental quality. As AI theories are applied in the control process, the building indoor environmental quality is controlled in predictive and adaptive ways for improved environment and energy efficiency. Artificial neural network (ANN), fuzzy, and adaptive neuro fuzzy inference system (ANFIS) are the representative theories that are successfully employed for advanced building controls [1–3].

Employing the input, hidden, and output neurons in the respective layers and the connectivity and transfer functions between them, ANN can produce the optimal output for advanced building controls. Its prediction results were proven to be more accurate than those of mathematical models like the proportional-integral-derivative (PID) controllers, or of regression models. In addition, the adaptability via a self-tuning process supports the stability of the model without external expert intervention for the retuning model parameters [4,5].

ANN models were developed for predicting the optimal stop and start moments of the heating and cooling systems. Employing these

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**Nomenclature**

| | |
|---|---|
| $TEMP_{IN}$ | Indoor air temperature, °C |
| $\Delta TEMP_{IN}$ | Indoor air temperature change from the preceding control cycle, °C |
| $TEMP_{CAV}$ | Cavity air temperature, °C |
| $TEMP_{OUT}$ | Outdoor air temperature, °C |
| $TEMP_{PR}$ | Indoor temperature predicted by the ANN model, °C |
| $INPUT_{ACT}$ | Actual input value |
| $INPUT_{MIN}$ | Minimum input value |
| $INPUT_{MAX}$ | Maximum input value |
| U | Heating system operating ratio, unitless |
| $U_{NEW}$ | U of the current cycle, unitless |
| $U_{OLD}$ | U of the previous cycle, unitless |
| $U_{TRN}$ | U for the new training dataset, unitless |
| E | Difference between the current air temperature and the set point temperature, °C |
| ΔE | Change in E from the previous cycle, °C |
| $T_H$ | Set point temperature for the heating system, °C |
| $T_{NEW}$ | Temperature in the current control cycle, °C |
| $n_i$ | Number of input neurons |
| $n_h$ | Number of hidden neurons |
| $n_o$ | Number of output neurons |
| $n_d$ | Number of datasets |

calculated values, the ANN-based models created a more comfortable and energy-efficient indoor thermal environment [6–8]. The applicability of the ANN model was presented for the hydronic heating systems of solar buildings with significant energy savings [9,10]. In addition, the ANN-based control methods effectively controlled the HVAC systems and the radiant water heating systems that have a significant time lag [11–14].

Using the degree of truth or falsity of phenomena, fuzzy logic (FL) has been successfully applied in building environment controls based on their benefit of not requiring precise and noise-free input data for proposing the control signals [15].

A fuzzy model that employed two inputs — (i) the difference between the current temperature and the set point temperature (E); and (ii) the difference between the current E and the previous E (ΔE) — created a better output for operating HVAC systems compared to the proportional–integral (PI) or PID controllers [16]. In addition, a fuzzy-based PMV control strategy provided more comfortable PMV conditions as well as temperature and humidity conditions in a highly energy-efficient manner [17–19]. More recently, a radiant heating system in a residential building was successfully controlled by FL incorporated with the ANN model [20]. Moreover, FL was applied to condition the whole-building environment, such as the thermal, lighting, and air quality [21,22].

In order to overcome the difficulty of FL for finding optimized rules and membership functions, ANFIS can be applied to building environmental controls. ANFIS, a neuro-fuzzy theory, adopts FL and ANN in an incorporative manner for developing a globally applicable control method. As with FL, ANFIS employs a series of inputs and membership functions to produce an output. In addition, the membership functions are iteratively updated to produce a more accurate output using output errors, which is similarly conducted in the ANN model. This iterative tuning process supports the ANFIS model to optimally respond to the given systems and buildings [1,2].

In the previous study, the ANN and ANFIS models were comparatively tested for controlling evaporative condensers. In this study, the ANFIS models showed slightly superior results in terms of predicting condenser performance [23]. In other studies, the ANFIS model successfully operated the damper gap rate and fan speed in the HVAC system for faster, simpler, and more efficient temperature and humidity control [24,25]. In addition, in the comparative tests of ANN, FL, and ANFIS, the ANFIS-based model controlled the indoor temperature more comfortably and stably [3].

For the creation of a comfortable and energy-efficient indoor thermal environment for double-skin buildings, an AI-based control strategy was proposed in the previous studies [26–30]. The openings of the internal and external surfaces of the double skin and the heating system were operated in an integrative manner based on the prediction results from two ANN models. One model predicted the optimal opening strategy for keeping the indoor space comfortable, and the other model calculated the accurate operating ratio of the heating system. Compared to the conventional rule-based control method, the thermally comfortable period was remarkably increased with temperature stability when the ANN models were used for controlling the thermal condition of the double-skin building. On the other hand, energy efficiency for heating was not clearly demonstrated, resulting in a similar or lower efficiency.

Based on the findings of the previous studies, this study aimed at investigating the diverse AI-theories-based optimal control strategies for improving the thermal conditions and heating energy saving effect of double-skin buildings. Besides the ANN models proposed in the previous studies, FL and ANFIS were applied in the control algorithms, and their performances were comparatively analyzed. The comparison results would clearly show the optimal control strategy in terms of indoor thermal conditions and heating energy efficiency.

## 2. Development of the control algorithms

Algorithms for the integrative control of the heating system and the surface openings were developed. In the previous studies [29,30], the ANN-based surface control algorithm proved its superiority for the advanced thermal environment; thus, the ANN model was applied for surface opening control in the new algorithms in this study. On the other hand, FL and ANFIS models were applied for the control of the heating system. In particular, two ANFIS models with two input variables and one input variable, respectively, were developed and tested. Thus, performance analysis was conducted for five control algorithms, as summarized in Table 1. The algorithms were developed using the matrix laboratory (MATLAB) software and its relevant toolboxes, such as the neural network toolbox and the fuzzy logic toolbox [31].

### *2.1. Rules for the heating system and ANN for surface openings (1st algorithm)*

The first algorithm, which employs a specific rule for operating the heating system and the ANN model for operating openings, is shown in Fig. 1. In a specific rule for deciding the heating system operation, the current operating condition, current temperature

**Table 1**
Five control algorithms with different theories.

| | Applied theories | |
|---|---|---|
| | For heating system | For surface openings |
| 1st algorithm | Rule | ANN |
| 2nd algorithm | ANN | ANN |
| 3rd algorithm | FL | ANN |
| 4th algorithm | ANFIS with 2 inputs | ANN |
| 5th algorithm | ANFIS with 1 input | ANN |