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# Performance analysis of space heating smart control models for energy and control effectiveness in five different climate zones

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ABSTRACT

This paper compares smart control models for heating supply air among five different climate conditions to discuss the effectiveness of machine learning tools in terms of control and energy efficiency.

A thermostat on/off control is typically used to maintain room temperature at a desired level. Advanced computing technologies have recently been introduced to complement the conventional on/off controls to improve control efficiency in heating systems. However, these methods, which were mostly utilized to control fuel amount or fan motor speed, lacked the capability to promptly respond to various outdoor temperature conditions as climate zones requiring refined control strategies to reduce environmental impacts.

This paper proposes intelligent controls of mass and temperature simultaneously for heating air supply. The Fuzzy Inference System (FIS) and Artificial Neural Network (ANN) algorithms are utilized to develop six control models, and the models are tested to evaluate both control and energy efficiency during the winter season in five climate zones (from climate zone 2 through 6; i.e., Houston, Dallas, Raleigh, Chicago, and Detroit, respectively). Results include the energy consumption, control errors, and control signals in comparison to the baseline on/off control, which confirms the fact that the ANN simultaneous controls of mass and temperature is more effective than the other controllers for control accuracy and energy savings by 71.3% and 0.3%, respectively. The effectiveness of the ANN controller can contribute to maintaining room temperature accompanying the reduction of energy consumption, which is directly related to improve human comfort and reduce environmental impacts in various climate zones.



## 1. Introduction

### 1.1. Control system

Various theoretical and practical approaches for Heating, Ventilating, and Air-Conditioning (HVAC) systems have been developed to provide energy to maintain comfortable indoor thermal conditions. A Proportional-Integral-Derivative (PID) algorithm has been typically used to improve HVAC system controls, thus providing an appropriate energy level to meet thermal demands. A conventional PID algorithm and its controllers are commonly utilized when testing HVAC controls in an attempt to optimize amount of fuel entering the boiler or the fan motor speed. Rapid development of computing and statistical technologies has recently facilitated research performance through comprehensive models and large databases.

Since 1980's, plant models were frequently considered as control targets to improve energy efficiency. Because the production cost and maintenance, coal fired boiler was commonly selected for mathematical and simulation model to test effective controlling fuel amount into plant models and to measure optimized turbine speed control [1–3]. To benchmark or control HVAC systems, switching parameters such as amount of gain, overshooting, and signal delay in multivariate regression model were conventionally utilized, and also, manipulating parameters through the more refined mathematical algorithms were used for improving PID tuning rules with advanced computing applications [4–8]. By using the refined tuning rules derived from computing simulation,

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**Nomenclature**

| | |
|---|---|
| $A$ | area ($m^2$) |
| $Cv$ | specific heat capacity at constant volume (J/kg·K) |
| $Cp$ | specific heat capacity at constant pressure (J/kg·K) |
| $D$ | depth of envelope components (m) |
| $E$ | error as difference between set-point and measured room temperature (°C) |
| $\Delta E$ | derivative of error |
| $h$ | convection heat transfer coefficient ($W/m^2 \cdot K$) |
| $h_{in}$ | specific enthalpy into room (J/kg) |
| $h_{out}$ | specific enthalpy out from room (J/kg) |
| $IAE$ | integral (Sum) of absolute error between set-point and measured room temperature (no unit) |
| $k$ | transmission coefficient (W/m·K) |
| $\dot{m}_{ht}$ | mass flow-rate from heater (kg/h) |
| $\dot{m}_{in}$ | mass flow-rate into room (kg/h) |
| $\dot{m}_{out}$ | mass flow-rate out from room (kg/h) |
| $m_{roomair}$ | mass of room air (kg) |
| $Q_{loss}$ | convection and transmission heat loss (J) |
| $Q_{gain}$ | convection and transmission heat gain (J) |
| $R$ | thermal resistance (m·K/W) |
| $R^2$ | fraction of variance |
| $RMSE$ | root mean square error |
| $t$ | time |
| $T_{ht}$ | air temperature entered into room (°C) |
| $T_{out}$ | outdoor temperature (°C) |
| $T_{room}$ | room temperature (°C) |
| $T_{set}$ | set-point temperature (°C) |
| $u$ | internal energy (J) |
| $W$ | work (J) |

statistical and mathematical predictive control approaches in building heating system were developed to effectively respond to demand changes as Model Predictive Control (MPC) [9,10]. In large-scaled buildings and district level, heating control models were developed in terms of reduction of gas emission and improvement of energy conservation, and also, adaptive control designs of network based model were tested for optimized heating supply control to improve energy storage, or reduce heat loss in distribution pipe lines [11–13]. To reduce heat dissipation and loss in distribution network, lowering district heating water temperature were being tested in northern Europe and North America because several advantages to reduce fossil fuel use and avoid heat loss, and to promote the use of renewable energy resources and technologies [14,15].

Since early 2000's, these control models were developed from the advanced control systems such as Fuzzy Inference System (FIS) and Artificial Neuro-Fuzzy Inference System (ANFIS). At early years of FIS, wide matrix for fuzzy rule was tested to define effectiveness for large scaled model. To effectively deal with large data sets, fuzzy membership rules were developed to define sub-range of continuous variables and linguistic variables for space heating system using multi-layered genetic algorithms and fluid dynamics [16–18]. For the decision making problems about output signal, FIS membership functions were developed by multi-criteria genetic algorithm using valve position, fan speed, and thermal comfort, and also compared to the conventional PID rule [19–21]. By using the concept of Integral of Absolute Error (IAE), the energy performance of FIS controller in typical energy supply network were compared, and combining FIS and PID for boiler model was proposed through the simplified simulation model to define interaction between FIS and PID tuning algorithms [22–24]. In addition to the boiler control models, some other devices control strategies based on lab-scaled experimental models were developed to optimize electricity use for fan motor and damper angle with simulation models combining PID and FIS and advanced data mining algorithms [25–27]. FIS was utilized to improve energy performance in various parts of HVAC system. By using genetic algorithms, some parts of air handling unit and power system were tested to find optimal process to meet various requirements of central operation and three different thermal zones associated with weather conditions from existing and forecast weather data [28–30].

Adding to the mechanical and statistical applications, the concept of Predicted Mean Vote (PMV) was adopted to improve passive design strategies and linguistic fuzzy sets for subjective human comfort [31]. To develop this approach about human sensation and thermal comfort regulation, some studies used various thermal conditions such as architectural design components, ventilation, relative humidity, air velocity, and users' activity level [32,33]. To develop genetic algorithm related to human comfort, multiple objective functions and multi-layered fuzzy membership matrix were used, and the energy performance was compared by using EnergyPlus and co-simulation programs [34]. Building envelopes and fenestration systems for lighting and ventilation were developed in mainly heating dominated climates, and conventional psychrometrics was adopted into simulation process to define thermal comfort associated with occupant's quality [35,36].

In many studies, control approaches were diversely tested to improve energy efficiency in plant, system, and zone scales. With the rapid development of computing and statistical tools, researchers were able to simulate complex thermal models and compare the performance of conventional and developed control systems. Among the tools, the FIS and ANN were preferred to deal with complicated tasks that could not be solved by typical rule based control systems.

### 1.2. Problem statement

To provide appropriate control signals, PID control schemes associated with advanced statistical methods were typically utilized in practice. However, these tools, which were mostly used to control fuel amount or fan motor speed, had lack of the capability of prompt response to the thermal demand of zones in terms of human comfort. Also, most damper control models were utilized to define time response to supply heating air for demands. And supply air control issues are mainly dealing with mass to infuse into thermal zones, mostly not incorporating supply air temperature as a control parameter. These approaches were not very much effective to use sensitive control corresponding to various outdoor temperature conditions.

In this paper, six smart controllers using FIS and ANN to optimize heating air supply are proposed and tested in the conditions of five different climates. In section 2, the structures of HVAC model and equations used are described. And definitions of FIS and ANN fitting models used are explained. Finally, results and conclusions are discussed in sections 4 and 5.