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Simple automatic supervisory control system for office building based on energy-saving decoupling indoor comfort control

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ABSTRACT

This work proposes a simple automatic supervisory control system (ASCS) that is based on an energy-saving decoupling indoor comfort control (ESDICC) for regulating the indoor comforts of an office building. Three energy-saving indoor comfort control algorithms are modified to yield the ESDICC algorithms. The ESDICC-based ASCS is modeled using a Petri net (PN), whose graph is presented in detail and whose dynamics are thoroughly described. Results of two test cases demonstrate the simplicity of the operations of ESDICC-based ASCS and the energy-saving effect of the ESDICC algorithms.

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1. Introduction

To eliminate the global warming, energy consumption must be reduced. In recent years, several researchers have focused on saving the energy consumed by buildings [1–5]. However, *indoor comfort* is also important for office buildings, because it directly relates to the working efficiency, and so strongly influences corporate profit [6,7].

Comfort condition generally concerns *air quality* [8,9], *thermal* [10,11] and *visual comforts* [12,13]. One of the major issues related to air quality is CO_2 *concentration*, whose dynamics can be described by the following differential equation [8].

$$V\dot{C}_i(t) = F(t)(C_o - C_i(t)) + L_c \tag{1}$$

where, $F(t)$ represents the rate of incoming outdoor air; V denotes the volume of the room; C_i and C_o represent the indoor and outdoor CO_2 concentrations, respectively, and L_c represents the pollutant load. Conventionally, thermal comfort is quantified by an index called *PMV*, which can be calculated using a formula that was developed by Fanger [14]:

$$\mathrm{PMV} = \left(0.303e^{-0.036M} + 0.028\right)\left\{\begin{array}{l}(M-E) - 3.05\times10^{-3}\,[5733 - 6.99\,(M-E) - P_a]\\ -0.42\,[(M-E) - 58.15] - 1.7\times10^{-5}M\,(5867 - P_a) - 0.0014M\,(34 - T_a)\\ -3.96\times10^{-8}f_{cl}\left[(T_{cl}+273)^4 - (T_r+273)^4\right] - f_{cl}h_c\,(T_{cl} - T_a)\end{array}\right\} \tag{2}$$

where,

$$T_{cl} = 35.7 - 0.028\,(M-E) - I_{cl}\left\{3.96\times10^8 f_{cl}\left[(T_{cl}+273)^4 - (T_r+273)^4\right]\right\};$$

$$h_c = \left\{\begin{array}{ll}2.38(T_{cl}-T_a)^{0.25} & \text{for}\ \ 2.38(T_{cl}-T_a)^{0.25} \le 12.1\sqrt{V_{ar}}\\ 12.1\sqrt{V_{ar}} & \text{for}\ \ 2.38(T_{cl}-T_a)^{0.25} > 12.1\sqrt{V_{ar}}\end{array}\right\};$$

$$f_{cl} = \left\{\begin{array}{ll}1.00 + 1.29I_{cl} & \text{for}\ \ I_{cl} \le 0.078\,\mathrm{m^2\,^\circ C/W}\\ 1.05 + 0.645I_{cl} & \text{for}\ \ I_{cl} > 0.078\,\mathrm{m^2\,^\circ C/W}\end{array}\right\};$$

M denotes the metabolic rate [M](=[58.2 W/m^2]); E denotes the external work [W]; I_{cl} denotes the thermal resistance of clothing [clo](=[0.155 m^2 °C/W]); f_{cl} denotes the ratio of the surface area of a clothed person to that of a naked person; T_a denotes the air

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temperature [°C]; T_r denotes the mean radiant temperature [°C]; V_{ar} denotes the relative air velocity [m/s]; P_a denotes the partial water vapor pressure [Pa], which is directly related to the humidity; h_c denotes the convective heat transfer coefficient [w/m^2 °C], and T_{cl} denotes the surface temperature of clothing [°C]. Visual comfort is determined by the indoor *luminance* [12,13].

To regulate indoor comfort automatically, an *automatic supervisory control system* (ASCS) must be used. The ASCS monitors indoor comfort conditions using a wireless sensor network [15], such that when any of these conditions falls outside the *pre-set range* for comfort, the ASCS triggers the corresponding energy-saving *indoor comfort control algorithm* to calculate the *set values* and activate the controller of the controlled system to return the undesired conditions to desired conditions. Therefore, incorporating energy-saving indoor comfort control algorithms, a suitable ASCS can automatically maintain indoor comfort with effective energy utilization. However, most research into energy issues related to buildings focus on the analysis of energy consumption [1–3,5], energy-saving strategies [1,2,4] and indoor comfort control methods [8–13] and few considered the modeling of an ASCS.

Generally, the activities in a building can be described as a *discrete event system* (DES) [16]. The various models of a DES include *finite state automata, Petri net* (PN), *Markov chain* and *queuing network models*, among others [16]. Of these models, PN is the easiest one to understand [16]. Similar to other models that are used to describe DES, the PN model suffers from growing exponentially with the number of states. Therefore, the simplicity of the PN model is closely related to the control strategy that is used to control the three aspects of indoor comfort. Clearly, a *decoupling control* strategy for the indoor comfort can help in implementing a simple PN model. However, straightforward decoupling may neglect the need for the indoor comfort controls to help save energy. Accordingly, the *purpose* of this work is to develop energy-saving decoupling indoor comfort control (ESDICC) algorithms and propose an easily implementable PN model for an ESDICC-based ASCS and to demonstrate the simplicity of its operations and the energy saving effect of the ESDICC algorithms in case studies.

The paper is organized as follows. Section 2 presents the ESDICC algorithms. Section 3, presents the PN model of the proposed ESDICC-based ASCS. Section 4 applies the proposed ESDICC-based ASCS and the ESDICC algorithms to case studies to demonstrate the simplicity of the operations of ESDICC-based ASCS and the energy saving effect of the ESDICC algorithms. Section 5 draws conclusions.

2. Energy-saving decoupling indoor comfort control (ESDICC) algorithms

2.1. Control means of three indoor comforts

From Eqs. (1) and (2), we can see that the air quality (*i.e.* CO_2 concentration) and the thermal comfort (*i.e.* PMV) are controlled using the air conditioning system; the control variable for the former is $F(t)$ [8,9], and the control variables for the latter are T_a, P_a and V_{ar} [10,11]. The visual comfort is controlled using the *venetian blind* and the *lighting* [12,13]. *PMV control* and CO_2 concentration control will be used hereafter in place of thermal comfort control and air quality control, respectively.

2.2. Relationships among three indoor comforts

From the control means of the three indoor comforts, controlling PMV does not affect CO_2 concentration or indoor luminance. Additionally, the controls of the CO_2 concentration and the indoor luminance do not affect each other. Accordingly, the CO_2 concentration and the indoor luminance can be controlled independently within their normal ranges. Now, the remaining problem concerning the decoupling of the three indoor comfort controls is whether control of the CO_2 concentration and the indoor luminance affect PMV. From the work of [17] and Eqs. (1) and (2), the value of PMV is affected by control of the indoor luminance and the CO_2 concentration. The former brings the radiated heat of the sun to enter the office and affects T_a, and the latter brings the outdoor air whose humidity and temperature affect both T_a and P_a. However, the effect of the above factors on the value of PMV is eliminated by the control of PMV, because the air conditioning system is *automatically* controlled to keep the environmental conditions at the calculated set values of T_a, P_a and V_{ar} obtained using the PMV control algorithm [11]. Form the above discussions, even though the value of PMV is affected by control of the indoor luminance and the CO_2 concentration, the three indoor-comfort controls can be decoupled from the control viewpoint, but the price paid for eliminating the aforementioned influence of radiated heat and incoming outdoor air on the value of PMV is the additional energy consumed by the air conditioning system in maintaining the set T_a and P_a. Based on this idea, the strategy of the ESDICC algorithm should be reducing the additional energy that is consumed in controlling PMV owing to the incoming outdoor air and the radiated heat as much as possible while performing the decoupling energy-saving indoor comfort controls.

2.3. Development of ESDICC algorithms

Based on previous discussions, the energy saving effect of the ESDICC depends on simultaneously performing the following two tasks. The first task is to control each individual indoor comfort condition based on the least energy consumption criterion. The second task is to reduce the additional energy that is consumed in controlling PMV owing to the incoming outdoor air and the radiated heat of the sun induced from controlling CO_2 concentration and indoor luminance, respectively. Performing these two tasks simultaneously involves the indoor comfort control algorithms [9,11,13]. In the following, these algorithms are summarized and then their necessary modifications to yield the ESDICC algorithms are presented.

2.3.1. Summary of indoor comfort control algorithms

2.3.1.1. CO_2 concentration control algorithm. The CO_2 concentration control algorithm that was proposed by Lin and Chen [9] has two stages – the initial and the regular stages. The normal range of CO_2 concentration is [600 ppm, 800 ppm]. The initial stage control is applied only at the beginning of a working day, and its purpose is to lower the indoor CO_2 concentration C_i to 800 ppm in *minimum time* if it exceeds 800 ppm. Therefore, in the initial stage, the air conditioning system will set the rate of incoming outdoor air $F(t)$ to F_{max}, which is the highest possible $F(t)$, for an optimal period of time that is obtained from the first-stage control algorithm. When C_i touches 800 ppm, the algorithm enters the regular stage, in which C_i is maintained within the *pre-set range* [C_{min}, 800 ppm], where 600 ppm < C_{min} < 800 ppm. Let C_{ii} represent either 800 ppm or C_{min}. The mechanism of the regular stage is that whenever C_i reaches 800 ppm or C_{min}, the air conditioning system sets $F(t)$ to the optimal F^*_{reg} for an optimal period t^*_f, which is determined from solving the following optimization problem to bring

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