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Review Article

Review on the HVAC System Modeling Types and the Shortcomings of Their Application

Raad Z. Homod

Department of Mechanical Engineering, University of Basrah, Qarmat Ali Campus, Basrah 61004, Iraq

Correspondence should be addressed to Raad Z. Homod; raadahmood@yahoo.com

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The modeling of the heating, ventilation, and air conditioning (HVAC) system is a prominent topic because of its relationship with energy savings and environmental, economical, and technological issues. The modeling of the HVAC system is concerned with the indoor thermal sensation, which is related to the modeling of building, air handling unit (AHU) equipments, and indoor thermal processes. Until now, many HVAC system modeling approaches are made available, and the techniques have become quite mature. But there are some shortcomings in application and integration methods for the different types of the HVAC model. The application and integration processes will act to accumulate the defective characteristics for both AHU equipments and building models such as nonlinear, pure lag time, high thermal inertia, uncertain disturbance factors, large-scale systems, and constraints. This paper shows types of the HVAC model and the advantages and disadvantages for each application of them, and it finds out that the gray-box type is the best one to represent the indoor thermal comfort. But its application fails at the integration method where its response deviated to unreal behavior.

1. Introduction

The HVAC system modeling implies to the modeling of building, indoor, outdoor, and air handling unit (AHU) equipments. It is normally difficult for one HVAC system model to be completely comprehensive. Therefore, it is possible to divide the comprehensive model into submodels which may be appropriate in some instances. The key to any successful indoor thermal analysis or representation lies in the accuracy of the model of the indoor conditioned space within building and AHU equipments.

The simple hand-calculation methods were available to find out the cooling/heating load until the advent of computer simulation programs for the HVAC systems in the mid 1960s. The first simulation method attempted was to imitate physical conditions by treating the variable time as the independent [1]. Most of the earliest simulation methods were based on the white-box or mathematical (physical) models, which are preferred over other models such as the black-box and the gray-box models because they are easy to analyze even though they are more complex than others [2].

1.1. The Mathematical Model of the HVAC System. There are two types of the white-box or the mathematical model: the lumped and the distributed parameters. The main advantage of the lumped parameter model is that it is much easier to solve than the distributed model.

The mathematical models are very popular for the HVAC systems in representing the processing signal. The processes' signals are constructed based on physical and chemical laws of conservation, such as component, mass, momentum, and energy balance. These laws describe the linking between the input and the output which is transparently represented by a large number of mathematical equations. Furthermore, the mathematical model is a good tool to understand the behavior of the indoor condition by describing the important relationships between the input and the output of the HVAC system. In general, the modeling process of the HVAC systems leads to dynamic, nonlinear, and high-thermal inertia, pure lag time, uncertain disturbance factors, and very high-order models. The whole model can be described by several submodels to alleviate the complexity of the model [3].

These submodel processes are related to fluid flow and heat-and-mass transfers between interfacing submodels, which can be governed by mass, momentum, and energy conservation principles. These principles are usually expressed by differential equations, which may be implemented by time domain or S (frequency) domain, where the S domain can be represented by a transfer function or a state-space function. The limitations of the early building mathematical models are mainly due to the limitation in the computer hardware since the models needed an intensive computational process. But the situation is changing as computational tools capacity has improved by the evolution in software and hardware of computers. The recent mathematical models are being developed to solve the large set of equations that also incorporate submodels mathematical equations.

1.2. The Black-Box Model of the HVAC System. The concept of the black-box model is to fit the transfer function model to the input/output real model data to yield coefficient polynomials that can be factored to provide resonance frequencies and characterization of damping coefficients without knowledge of the internal working. Hence, it does not reflect any specific physical or mathematical structure of the existing behavior in the real model. The mathematical representations of this model include time series such as autoregressive moving average (ARMA), autoregressive model structure with exogenous inputs (ARX), recurrent neural network models, and recurrent fuzzy models. For real-time operation and control, the black-box models are simple enough. On the contrary, physical or mathematical modeling involves detailed analysis of the relationships between all parameters that affect the system. Due to the complex nature of the HVAC systems and the large number of the parameters involved, it is difficult to mathematically model the system [4]. Romero et al. [5] mentioned that the mathematical models require detailed facility information that is sometimes hardly found.

Therefore, the black box is the simplest solution, but at the same time it has to be regularly updated as operation conditions change. Thus, it cannot be used for prediction outside the range of the training data, and such models have poor performance in general.

1.3. The Gray-Box Model of the HVAC System. Some physical processes of the HVAC system are less transparently described where there is much physical insight available, but certain information is lacking. In this case, mathematical models could be combined with black-box models where the resulting model is called a gray-box or a hybrid model. Furthermore, the white-box model of the HVAC system needs modification to provide better performance; this can be accomplished by using a gray-box technique to mimic the output of the white-box analysis. This method is implemented by Leephakpreeda [6] when building a gray-box model based on the white-box model to predict indoor temperature. Some black-box models of the HVAC system are modified to become gray-box models to improve their performance as done by Zhao et al. [7] when they identified the nonlinear link model parameters by a neural network to represent heat exchanger. This means that the main function of a gray box is to improve the performance of the white- or the black-box model.

2. The Background of the HVAC Systems Modeling

The commercial and residential buildings are facing a new era of a growing demand for intelligent buildings worldwide. Intelligent buildings are referred to as energy and water saving, and they provide healthy environment. The first intelligent building was introduced in the late 1970s when buildings were equipped with IT equipments [8]. The developments of the improved building and AHU models are essential to meet the requirements of an intelligent building [9].

The HVAC system modeling evolution of research has been reflected on the representation of the indoor thermal behavior by development and enhancement of identification of buildings and AHU equipments. In general, research on indoor thermal comfort can be divided into two main categories: design-oriented research and research-oriented design as explained by Fallman [10]. This study followed the second category where it depends on the previous research outcomes to develop a design that enhances the indoor thermal comfort.

3. The Evolution of the HVAC System Modeling

Building and AHU modeling has been used for decades to help the HVAC system scientists design, construct, and operate the HVAC systems. The pioneering development in the building and the HVAC system equipments industry is the heat conduction equation model by Joseph Fourier published in 1822, which is the most cited model (see, e.g., [11–14]).

The earlier simulation work in building structure by Stephenson and Mitalas [15, 16] on the *response factor* method significantly improved the modeling of transient heat transfer through the slabs, the opaque fabric, and the heat transfer between internal surfaces and the room air. The heat balance approaches were introduced in the 1970s [17] to enable a more rigorous treatment of building loads. Rather than utilizing weighting factors to characterize the thermal response of the room air due to solar incident, internal gains, and heat transfer through the fabric, instead, the heat balance methodology solves heat balances for the room air and at the surfaces of fabric components.

Since its first prototype was developed over two decades ago, the building model simulation system has been in a constant state of evolution and renewal. Numerical discretization and simultaneous solution techniques were developed as a higher-resolution alternative to the response-factor methods [18]. Essentially, this approach extends the concept of the heat balance methodology to all relevant building and plant components. More complex and rigorous methods for modeling of the HVAC systems were introduced in the 1980s. Transient models and more fundamental approaches were developed [19] as alternatives to the traditional approach which performed mass and energy balances on preconfigured templates of common HVAC systems. The delivery of training and the production of learning materials [20] are also receiving increased attention. Additionally, many validation exercises have been conducted [21] and test procedures developed [22] to assess, improve, and demonstrate the integrity of simulation tools.

The literature presented two types of the HVAC system model: steady-state models, which are extensively presented such as in [23–28], and unsteady-state models presented by [29, 30]. Unsteady-state models can be further categorized into two extreme modeling approaches. The first approach, called *physical or mathematical models*, builds up models entirely based on universal laws, physical laws, and principles [31]. The second approach, called *empirical or black-box models*, constructs models entirely based on experiments or data [32–34].

4. The Mathematical Model

Mathematical models have been widely used in areas as diverse as engineering, economics, medicine, ecology, and agriculture for many kinds of different purposes to satisfy scientific curiosity, prediction, control, fault diagnosis and inadequacies, simulation, and operator training.

In the field of the HVAC system modeling, the most complicated model part is the building model. This is because components that need to be modeled for building are not limited to building construction, such as roof, walls, floor slab, windows, and external shading. Internal loads such as the activity within the space, the number of people, and the heat gain from lighting must also be modeled as well. The subdivision of the building model is an extensive scope of the HVAC models' field, and there are rarely studies that include the entirely scope of a building model. For example, Lü [35] studied the transmission of heat and moisture throughout the walls, roofs, and ceilings to estimate the indoor air temperature and humidity. He did not consider the transmission of heat and moisture throughout ventilation, filtration (doors and windows), and internal load. Furthermore, the moisture conservation equation used assumed the temperature to be the same in all of the phases. He constructed his model by applying the conservation of mass and energy theory based on the fundamental thermodynamic relations. For mass conservation law, he implemented this in moisture transmission by applying Darcy's law and Fick's law. For energy, he implemented Fourier's law. He used the distributed white-box model where partial differential equations are discretized in space by using finite element with time marching scheme and Crank-Nicolson scheme.

On the other hand, Ghiaus and Hazyuk [36] used the mathematical model to estimate the heating load in dynamic simulation by using steady-state heat balance for normalized outdoor conditions. They applied the superposition theorem for electrical circuits to obtain their model's parameters. And they assumed that the thermal model of the building is linear, thermal capacity of the wall and the indoor air is lumped and considered that the time series of disturbances (such as weather and internal loads) and occupational programs are known because they used model predictive control (MPC) which proposed an unconstrained optimal control algorithm to solve the load estimation problem. They obviously have imposed many assumptions to facilitate the calculations of heating load, which leads to lack of accuracy in the results. In addition, they used a single-input single-output- (SISO-) type model that does not consider the moisture transmission, an important element in deciding thermal comfort.

For the air-handling unit (AHU) mathematical model, Wang et al. [37–40] built models of heat exchanger for air-handling unit based on the conservation of energy and applied thermal balance equation on control volume for heat exchanger. This model is characterized as a SISO model since it does not take into account the effect of the mixing air chamber and assumed that the temperature of air supplied to the conditioned space is equal to the surface temperature of heat exchanger. Furthermore, they neglected the humidity of the moisture air supplied to the conditioned space because they do not want to include the effectiveness of humidity variation on thermal comfort. Therefore, they supposed that the type of cooling coil is of a dry type and that there is no indoor latent load.

5. The Black-Box Model

The physical model involves detailed study of the relationships between all parameters that affect the hygrothermal (the variation of humidity and temperature) system. Due to the complex nature of hygrothermal systems and the large number of parameters involved, physical modeling has become more complicated in application. Usage of the black-box model is sometimes preferred because it is straightforward to construct and there is no need to have knowledge of the system's internal structure.

Mustafaraj et al. [4] identified the humidity and thermal behavior models of an office in a modern commercial building by using different methods of the black-box model such as Box-Jenkins (BJ), autoregressive with external inputs (ARX), autoregressive moving average exogenous (ARMAX) structure, and output error (OE) models. They adopted linear parametric models to predict room temperature and relative humidity for different time scales. The linear model is adopted to obtain a simple and low number of model parameters, but this caused downbeat on the accuracy, especially in the representation of the heat storage or flywheel effect on the instantaneous load. In this group of models, they found out that the BJ model is suitable for the winter season where the ARMAX and ARX models give good results for the summer and autumn seasons and that the OE model is appropriate for the summer season. This means that there is no specific model that can represent indoor temperature and humidity for all four seasons. Furthermore, Mustafaraj et al. [41] created the neural network-based nonlinear autoregressive model with external inputs (NNARX) model, which is suitable to predict indoor office temperature and relative humidity for the summer season. The learning of NNARX model is done off-line because this type of model is well known for having a sluggish learning process. On top of this, they used the optimal brain surgeon (OBS) strategy which made the learning much slower, so it is not suitable to apply the online learning process [42].

Yiu and Wang [43] created a generic SISO and MIMO black-box model for AHU. The ARX and ARMAX structures are used, where their parameters are identified by using the recursive extended least squares (RELS) method. In general, the selection of model structure, between SISO and MIMO as well as between ARX and ARMAX, is a compromise between model simplicity and accuracy. The accuracy of the anticipated model outputs is in contrary with the simplicity and the time period of the updating weight. Furthermore, the more the accurate the ARMAX structure is, the more complex it becomes, which will also yield more residual white noise.

Barbosa and Mendes [44] integrated the works of a group of researchers in order to obtain a comprehensive model, for the chiller model is quoted from CA [45] by applying empirical equations based on regression functions. The cooling tower model used is based on Merkel's theory for the mass and sensitive heat transfer between the air and water in a counter flow cooling tower. The pump and fan models are quoted from Brandemuehl et al. [46] where power for variable flow is calculated from a regression of part-load power consumption as a function of part-load flow with the assumption that motor efficiency is constant. For the cooling and dehumidification coil model, there are three possible conditions for the coil: completely dry, partially wet, or completely wet. The model for all three conditions is quoted from Elmahdy and Biggs [47] based on coil outside surface temperature and air dew-point temperature. The room building model for heat and moisture transfer is based on the Philip and DeVries theory, which solves the partial differential governing equations for room control volume within the porous building element, which is quoted from Mendes et al. [48], where it is assumed that the water vapor behaves like a perfect gas and the vapor exchanged between the wall and the air is in a linear function of the differences between the temperature and moisture content.

6. The Gray-Box Model

The Gray-box model, sometimes called the semiphysical or hybrid model, is created by a combination of *physical and empirical models*, which is to compensate for their deficiencies as individual approaches.

In some gray-box modeling, the model structures are derived mathematically from physical or thermodynamic principles, while their parameters are determined from catalog, commissioning, or operating data. This is what Braun et al. [49] and Wang et al. [50] did when they developed an effective model through introducing the idea of air saturation specific heat. Catalog data at an operating condition are used to obtain the number of transfer units, which is then employed to obtain the performance at other operating conditions.

Based on the same concept of Braun et al., Wang et al. [51] built their gray-box model for predicting the performance of chilled water cooling coils in a static state. The mathematical part they built was based on the heat transfer mechanism and the energy balance principle. A model with no more than three characteristic parameters that represent the lumped geometric terms was developed. Procedures for determining the unknown parameters using commissioning or catalog information by linear or nonlinear least squares methods are used. Using this method, the model captures the inherent nonlinear characters of the AHU. Both Braun's and Wang's models have high levels of uncertainties because they evaluated models parameters depending on catalog and operation data where most of these data are estimated from ideal operation conditions. Some data are measured from the real operation, but these parameters values will eventually change due to the aging of the HVAC system.

Meanwhile, Ghiaus et al. [52] used a gray-box model to identify the AHU by imposing in the mathematical part that air temperature difference occurs in cooling coils and that the humidity ratio difference occurs in the humidifier only, meaning that the cooling coil is of dry type and that there is no change in the air temperature through the humidifier. This is to separate the transfer functions for each element in order to overcome the coupling between the temperature and humidity, where the parameters of the discrete form of these models are then experimentally identified. It is obvious that the assumptions made by the authors are too unrealistic and cannot be achieved except in some rare cases. This led to avoidable inaccuracy in the model's output data.

7. The Shortcomings in the Previous Works

From the reading through the literature on the topics of this research's objectives which are summarized in the previous sections, some shortcomings that prevent the possibility to be implemented in the simulation environment are faced. Thus, it can be concluded that the most important discouraging gaps to implement the analysis simulation properly and accurately for each objective are listed as follows.

There are a lot of deficiencies for each of the models studied that need to be addressed. These deficiencies resulted from various simplifying assumptions to reduce the complexity of thermal interactions, unmeasured disturbances, uncertainty in thermal properties of structural elements, and other parameters, which makes it quite a challenge to obtain reliable analytical models.

The most prominent shortcoming in this area of studies is the fact that there is no model that includes both building and AHU with all of the details. The other shortcoming is that the existing building models do not represent the lag time cooling load and solar gains incident on the surfaces of wall, roof, and window. In addition, the AHU model represented only the cooling coil without precooling coil and neglected the effectiveness of air mixing chamber. Furthermore, there are some studies where the models are simplified, eliminating many of the important features such as the humidity transmission, the change of air temperature through humidifier.

Besides, most of the literature on previous works presented the SISO type-model which is easy to manipulate using linear controller [53]. And the most important of all is that a lot of studies assume that the cooling coil is dry, which is contrary to the reality.

8. The Alternative Methods

In addition to the shortcomings due to the inaccurate application of the HVAC system modeling, there are difficulties in the characterstics of the HVAC systems which do not allow its modeling to deploy efficiently; these characteristics are listed as follows.

(1) For the building and AHU model, consider the following.

   (a) It is difficult to represent solar gain incident on the building envelops.
   (b) Large number of variables is required to describe the HVAC system model.

(2) For the indoor thermal comfort model, consider the following.

   (a) It is difficult to represent indoor thermal comfort model as white-box to analyze.
   (b) The indoor thermal comfort is identified as an implicit nonlinear model, and this is difficult to implement in the real time.

To address the aforementioned shortcomings and the difficulties in the existing model, the following building and AHU model procedures are suggested for this study.

(1) Use a physical-empirical hybrid modeling to describe the HVAC with its various thermal inertia parts.
(2) Systematize the HVAC system into five subsystems to reduce the complexity of the modeling process.
(3) Use the empirical methods for thermal load's calculations which are friendly with variable air volume (VAV) to enhance energy savings.
(4) Use precooling coil to control indoor humidity, and such method results in reducing energy waste as presented by Homod et al. [54].

The alternative method for this issue is proposing a hybrid model combing building structure with the equipments of the HVAC system in one model as adopted by Homod et al. [55, 56]. The hybrid identification is built with physical and empirical functions of thermal inertia quantity. The empirical residential load factor (RLF), which is modeled by the residential heat balance (RHB), is required to calculate a building cooling/heating load. The model parameters can be calculated differently from room to room and are appropriate for the variable air volume (VAV) factor [57]. In this work, a precooling coil is added to humidify the incoming air, which controls the humidity more efficiently inside conditioned space.

The modifications of the HVAC system modeling recommended for the alternative method are based on the reorganizing of the subsystem models. The model for the HVAC system is divided into two parts: building and AHU model and indoor thermal comfort model. The building and AHU model adapted is based on hybridization between two methods: physical and empirical methods, and it depends on the thermal inertia quantity. Physical laws are used to build a submodel for subsystems that have low thermal inertia, while the empirical method is used to build a submodel for subsystems with high thermal inertia. The empirical method used is the residential load factor (RLF). Furthermore, a precooling coil is added to the AHU to humidify the incoming air, which controls the humidity more efficiently inside conditioned space. The indoor thermal comfort model is to evaluate indoor comfort situations using predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD) indicators. These indicators are identified by a Takagi-Sugeno (TS) fuzzy model and tuned by the Gauss-Newton method for nonlinear regression (GNMNR) algorithm. This type of model is regarded as a white-box model, which is useful for analytical processes such as prediction and extrapolation [58]. The variation behavior of PPD versus PMV is imperative for the HVAC system to control indoor desired conditions as adopted by many researchers [59–64].

The space physical behavior for the building and AHU model for the two main output components is given by combining thermal model equation with moisture model equation deriving the whole subsystem state-space equation of conditioned space as presented by Ghiaus and Hazyuk [36]. Then, eliminating the states vector x, we follow a similar method in the precooling coil by taking the Laplace transformation on both sides of the state-space equation to get the following:

$$\begin{bmatrix} T_r(s) \\ \omega_r(s) \end{bmatrix} = \begin{bmatrix} G_{1,19} & G_{1,20} & G_{1,21} & G_{1,22} & G_{1,23} & G_{1,24} & G_{1,25} & G_{1,26} & G_{1,27} \\ G_{2,19} & G_{2,20} & G_{2,21} & G_{2,22} & G_{2,23} & G_{2,24} & G_{2,25} & G_{2,26} & G_{2,27} \end{bmatrix} = \begin{bmatrix} T_{\mathrm{wl}_{\mathrm{in}}}(s) \\ T_{g_{\mathrm{in}}}(s) \\ T_{\mathrm{slb}_{\mathrm{in}}}(s) \\ T_o(s) \\ T_s(s) \\ f_4 \\ \omega_s(s) \\ \omega_o(s) \\ Q_{\mathrm{ig},l} \end{bmatrix}, \tag{1}$$

where $G_{1,19}(s)\ G_{1,20}(s), \ldots, G_{1,27}(s)$ and $G_{2,19}(s)\ G_{2,20}(s), \ldots, G_{2,27}(s)$ are the input-output transfer factors that are presented in the Appendix.

The combined model block diagram for building and AHU model and indoor thermal comfort model represents a good overall picture of the relationships among transfer function variables of a subsystem model. It is possible to arrange the final subsystem's transfer functions in a way to reflect reality where the output of the first subsystem is the input to the next subsystem and so on. This is illustrated by Figure 1. Note here that it is difficult to arrange and derive the overall mathematical model that represents the system's general equation by only looking at these equations. Therefore, we sought the help of graphics.

9. Conclusion

This paper has reviewed the previous works related to the HVAC systems modeling to guide the researcher to develop the best and rational solutions for the problem statements of the current HVAC system modeling. Through the literature review for different types of modeling for the HVAC system, a lot of advantages, disadvantages, and shortcomings of the current models have been discovered. The review of the models' literatures are aimed at figuring out which type of model is the most suitable to represent the behavior of the real HVAC system. By displaying the advantages and disadvantages of each of the three model types, it became evident that the gray-box model has many features which discriminate it from the other models by closely representing the real behavior of a HVAC system. The hybrid or the gray-box method is employing energy and mass conservation law to obtain the overall system model, where this model is built with physical and empirical functions of thermal inertia quantity. The building and HVAC system structures are including both types of high and low thermal inertia, and this study recommended the hybridization between the two modeling approaches, physical and empirical, to arrive at an accurate model of the overall system. However, to do that for such a system with various thermal inertia subsystems, care must be given to the heat storage capacity of the subsystem and its relation to the difference in the temperature (input and output temperatures of control volume) and the difference in the humidity ratio. If heat storage is a function of these two properties only, then we can apply physical laws directly. The integration between the building and the HVAC system equipments model usually found in the previous studies incorporated two subsystems: heat exchanger for heating or cooling of supply air to the building and a conditioned space, which included the building structure and indoor and outdoor heating/cooling loads. This integration method leads to the trimming of some influencing subsystems in order to reduce a multiple subsystem into two subsystems, and this leads to inaccurate representation of the real model. To represent identical real model, the trimmed subsystems must be incorporated inside the model. So, a real model consists of an enormous number of variables and parameters that complicate it since it is difficult to deal with these variables and parameters. To reduce the complexity of the HVAC model, some studies divided it into parts and adopted a hybrid method that uses both physical and empirical modeling schemes to arrive at a model that can accurately represent a building and AHU model with its various thermal inertia subsystems. An important finding of this study is that one of the major unpredicted disturbances to the system is the variation of solar radiation, which is very hard to model correctly. For these reasons, the empirical analyses that were employed on those parts of the system are recommended to follow.

Highlights

(i) The advantages, disadvantages, and shortcomings of the HVAC systems modeling application are shown.

(ii) The entire literature modeling aspects that related to indoor thermal sensation are summarized.

(iii) It is found out that the gray-box model is the best one to represent the indoor thermal comfort.

(iv) An alternative method to combing building structure with AHU for the gray-box model is show.

Appendix

Parameters, Factors, and Origin of (1) (Source: Homod et al. [55])

The definitions of system parameters and variables are given as follows.

M_{He} is the mass of heat exchanger (kg), cp_{He} is the specific heat of heat exchanger and (J/kg·°C), $\dot{m}_{w,t}$ is the mass flow rate of chilled water at time t (kg/sec.), $T_{h,t}$, $T_{\mathrm{os},t}$, $T_{o,t}$ are the temperatures of heat exchanger, outside supply air, and outside air, respectively, at time t (°C), T_{wo} and T_{win} are the water out/in heat exchanger temperature (°C), $\dot{m}_{o,t}$ is the mass flow rate of outside air at time t (kg/sec.), M_{ahe} is the mass of air in heat exchanger (kg), $T_{\mathrm{os},t}$ and $\omega_{\mathrm{os},t}$ are the temperature and humidity ratio of outside air supplied, respectively, M_m is the mass of air in control volume of mixing air chamber (kg), cp_a is the specific heat of moist air (J/kg·°C), $T_{m,t}$, $T_{\mathrm{os},t}$, and $T_{r,t}$ are the mixing, outside supply, and return temperature, respectively, at time t (°C), $\dot{m}_{\mathrm{os},t}$, $\dot{m}_{r,t}$, and $\dot{m}_{m,t}$ are the mass flow rate of ventilation, return, and mixing air at time t (kg/sec.), $M_m cp_a$ is the heat capacitance of air for mixing air chamber (J/°C), M_{mHe} is the mass of main heat exchanger (kg), cp_{He} is the specific heat of heat exchanger J/(kg·°C), $\dot{m}_{\mathrm{mw},t}$ is the mass flow rate of main cooling coil chilled water at time t kg/(sec.), $T_{h,t}$, $T_{s,t}$, and $T_{m,t}$ are the heat exchanger, supply air, and mixing air temperature, respectively, at time t (°C), T_{wo}, and T_{win} are the water out/in heat exchanger temperature (°C), $(T_{\mathrm{wo}} - T_{\mathrm{win}}) = \Delta t_{\mathrm{mw}}$ is the cooling design temperature difference (°C), $M_{\mathrm{wl}} cp_{\mathrm{wl}}$ is the heat capacitance of walls, ceilings, roofs, and doors (J/K), $\sum_i \dot{Q}_{opq_{\mathrm{in}}}$ and $\sum_i \dot{Q}_{opq_{\mathrm{out}}}$ are the heat gains and losses through walls, ceilings, roofs, and doors, U is the construction U-factor W/(m^2·K), Δt is the cooling design temperature difference, °C, DR is the cooling daily range (K), OF_t, OF_b, and OF_r are the opaque-surface cooling factors, the k parameters are k_1 which is the function of thermal resistant and outside temperature, k_2 which is the function of thermal resistant and solar radiation incident on the surfaces (°C), and k_3 which is the function of thermal resistant and convection heat transfer, $\mathrm{CF}_{\mathrm{fen}_j}$ is given by equation, $\dot{Q}_{\mathrm{fen}}$ is the fenestration cooling load (W), A_{fen} is the fenestration

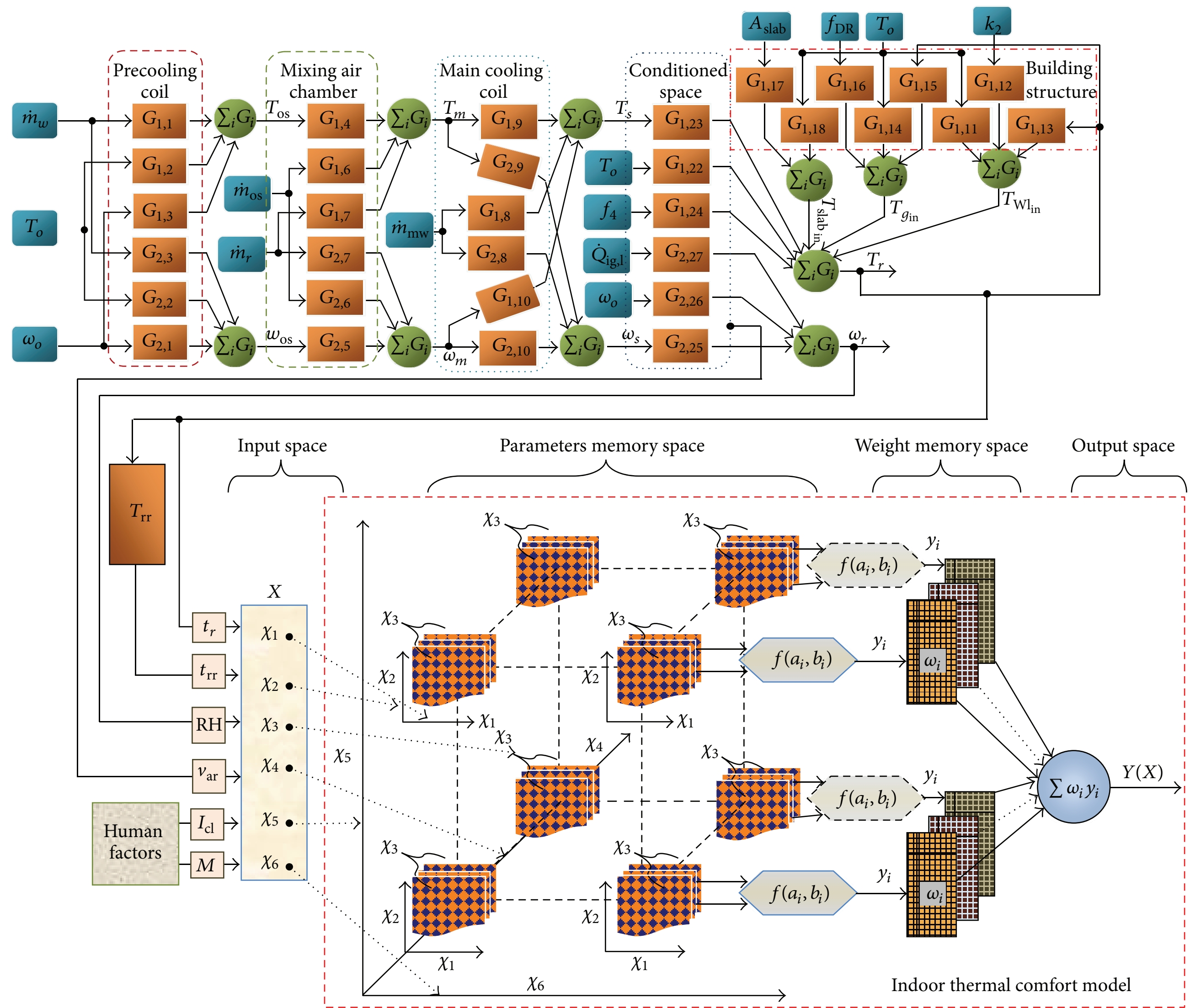

FIGURE 1: Subsystems model block diagram.

area (including frame) (m^2), CF_{fen} is the surface cooling factor (W/m^2), u_{NFRC} is the fenestration NFRC heating U-factor, W/(m^2·K), NFRC is the National Fenestration Rating Council, Δt is the cooling design temperature difference (K), DR is the cooling daily range (K), SHGC is the fenestration rated or estimated NFRC solar heat gain coefficient, IAC is the interior shading attenuation coefficient, FF_s is the fenestration solar load factor, PXI is a peak exterior irradiance (W/m^2), E_t, E_d, and ED are peak total, diffuse, and direct irradiance, respectively (W/m^2), T_X is a transmission of exterior attachment (insect screen or shade screen), F_{shd} is a fraction of fenestration shaded by permanent overhangs, fins, or environmental obstacles, L = site latitude, °N, ψ = exposure (surface azimuth), ° from south (−180 to +180), SLF is the shade line factor, D_{oh} is the depth of overhang (from plane of fenestration) (m), X_{oh} is the vertical distance from top of fenestration to overhang (m), and h is the height of fenestration (m), IAC is the interior attenuation coefficient of fenestration with partially closed shade, F_{cl} is the shade fraction closed (0 to 1), IAC_{cl} is the interior attenuation coefficient of fully closed configuration, $\sum_i \dot{Q}_{slab_{in}}$ and $\sum_i \dot{Q}_{slab_{out}}$ are the heat gain and loss through slab floors, respectively (W), $M_{wl}cp_{wl}$ is the heat capacitance of slab (J/K), $\dot{Q}_{slab_{out}}$ is the heat loss through slab floors (W), f_t is the heat loss coefficient per meter of perimeter W/(m·K), P is the perimeter or exposed edge of floor (m), $T_{slab_{in}}$ is the inside slab floor temperature or indoor temperature (°C), T_o is the outdoor temperature (°C), A_{slab} is the area of slab (m^2), Cf_{slab} is the slab cooling factor (W/m^2), h_{srf} is the effective surface conductance, including resistance of slab covering material (R_{cvr}), C_{slab} is the heat capacitance of slab floors (J/k), C_s is the air sensible heat factor (w/(L·S·K)), A_L is the building effective leakage area, cm^2, IDF is the infiltration driving force (L/(s·cm^2)), C_{af} is the heat capacitance of indoor air and furniture, $\dot{m}_{inf}$ is the infiltration air mass flow rate (kg/s), f_{fen} is the direct radiation (W), ω_s and ω_o are the humidity ratios of outdoor and supply air, respectively, and $\dot{Q}_{\mathrm{ig},l}$ is the latent cooling load from internal gains, where $G_{1,19} = k_{\mathrm{wl}}/f_2(\tau_6 S + 1)$, $G_{1,20} = 1/f_2 R_g(\tau_6 S + 1)$, $G_{1,21} = k_{\mathrm{slb}}/f_2(\tau_6 S + 1)$, $G_{1,22} = f_3/f_2(\tau_6 S + 1)$, $G_{1,23} = \dot{m}_m \mathrm{cp}_a/f_2(\tau_6 S + 1)$, $G_{1,24} = 1/f_2(\tau_6 S + 1)$, $G_{1,25} = 0$, $G_{1,26} = 0$, $G_{1,27} = 0$, $G_{2,19} = 0$, $G_{2,20} = 0$, $G_{2,21} = 0$, $G_{2,23} = 0$, $G_{2,24} = 0$, $G_{2,25} = \dot{m}_s/\dot{m}_r(\tau_r S + 1)$, $G_{2,26} = \dot{m}_{\mathrm{inf}}/\dot{m}_r(\tau_r S + 1)$, $G_{2,27} = 1/h_{\mathrm{fg}}\dot{m}_r(\tau_r S + 1)$, $k_{\mathrm{wl}} = \sum_j A_{w_j} h_{i_j}$, $k_{\mathrm{slb}} = \sum_j A_{\mathrm{slb}_j} h_{i_j}$, and $f_3 = C_s \times A_L \times \mathrm{IDF}$ (W/k); C_s is the air sensible heat factor (w/(L·S·K)), A_L is the building effective leakage area cm^2, IDF is the infiltration driving force (L/(s·cm^2)), $f_2 = \sum_j A_{w_j} h_{i_j} + 1/R_g + \sum_j A_{\mathrm{slb}_j} h_{i_j} + C_s \times A_L \times \mathrm{IDF} + \dot{m}_m \mathrm{cp}_a$, (W/k), $\tau_6 = C_{\mathrm{af}}/f_2$, (sec.), C_{af} is the heat capacitance of indoor air and furniture, $\dot{m}_{\mathrm{inf}}$ is the infiltration air mass flow rate, (kg/s), $f_4 = f_{\mathrm{fen}} + 136 + 2.2A_{\mathrm{cf}} + 22N_{\mathrm{oc}}$ (W), and $f_{\mathrm{fen}} = \sum_j A_{\mathrm{fen}_j} \mathrm{PXI}_j \times \mathrm{SHGC}_j \times \mathrm{IAC}_j \times \mathrm{FF}_{sj}$ is the direct radiation (W). ω_s, ω_o is the humidity ratio of outdoor and supply air respectively, and $\dot{Q}_{\mathrm{ig},l}$ is the latent cooling load from internal gains.

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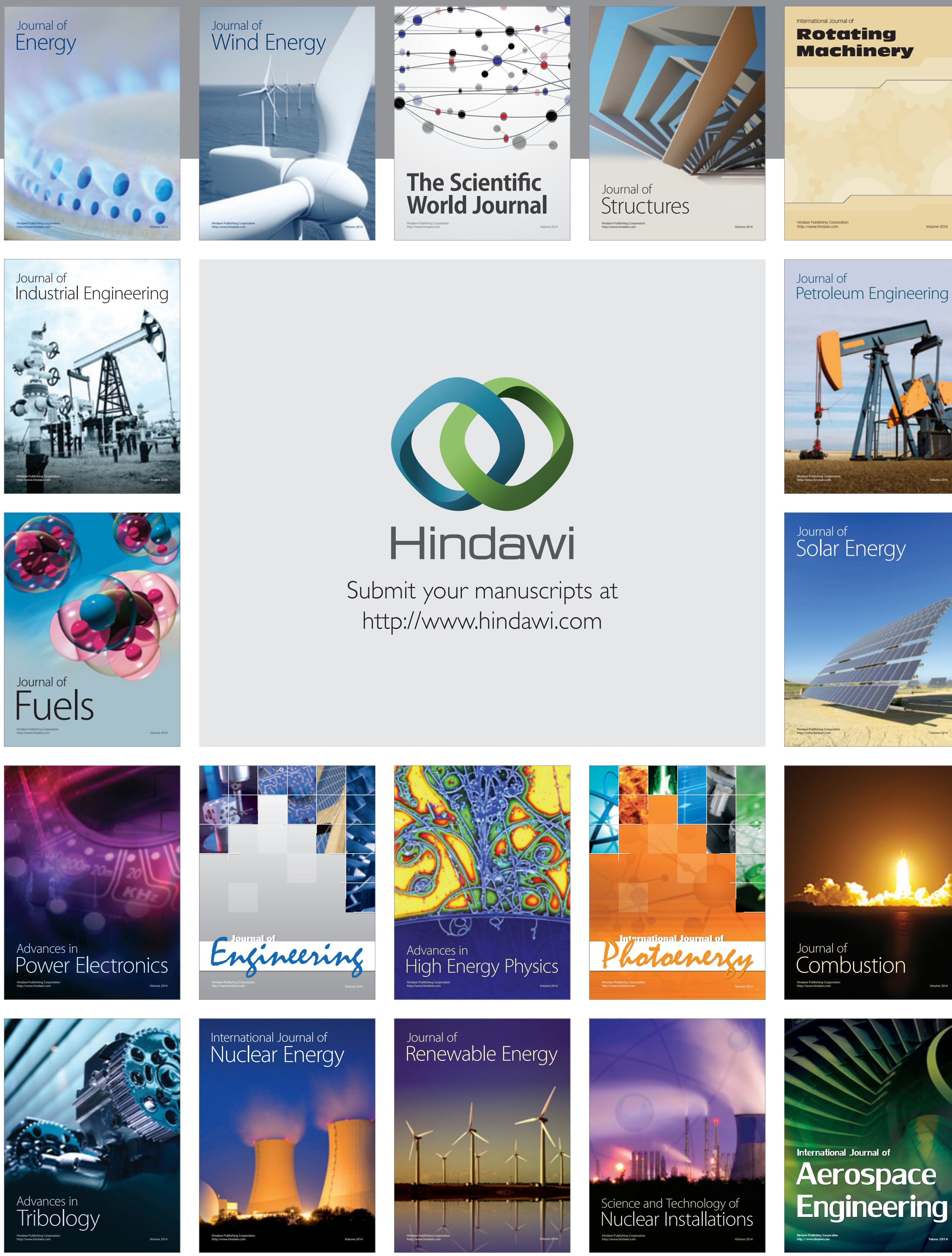
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