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Comprehensive Review of Intelligent Modeling and Control of Smart Building

Diego Peredo, Wen Yu

Abstract— **In this paper, recent intelligent methods to modeling and control of smart buildings in the sense of continuous control theory, such as refrigeration, ventilation and air conditioning systems are reviewed. The models are subdivided into physics-based models, data-driven models, and gray-box models, with more emphasis given to data-driven models. A complete study of the control methods is made. These are divided into conventional control methods, intelligent control methods, and mixed control methods.**

I. Introduction

In worldwide, a large amount of energy is used to control the indoor temperature in commercial buildings. This is due to the complexity of generating controllers for heating, cooling, and air conditioning (HVAC) systems. HVAC systems usually have traditional controllers, such as an ON/OFF controller or a PID controller.

In this paper, a study is made of the different methods to model energy expenditure in HVAC systems, and also, the types of control for these systems. The control methods are briefly described, and there is a review of the works in which they are applied. The final section provides a conclusion on what has been researched in the literature regarding modeling and control of HVAC systems.

HVAC systems are of great importance in smart building, since they help improve living conditions in areas with a climate that is difficult to bear. This type of device has a large energy consumption, and methods are currently being sought to reduce it. One option to reduce the energy consumption of a building is to use smart controllers; To use these controllers, in some cases, it is necessary to have a model of the thermodynamics of the complete system, that is, a model of the HVAC system which will be contained within a building. There are various methods to model HVAC systems [1], we divide them into three groups shown in Table I.

Physics-based models are created using the laws of thermodynamics, and taking into account the physical characteristics of the system, this seeking the greatest amount of accuracy when modeling.

Resistance-capacitance models are those in which an equivalence is created between thermodynamic properties and electrical properties, converting thermal systems into electrical systems; In articles such as [2], [3], and [4] RC is used as the main method to model the thermodynamic characteristics of the building. In [4] an example is shown, in which a system made up of a wall, the external environment, and the internal environment is converted, and in which one passes from thermodynamic properties to an electrical circuit.

Diego Peredo and Wen Yu are with the Departamento de Control Automatico, CINVESTAV-IPN (National Polytechnic Institute), Av.IPN 2508, Mexico City, 07360, Mexico. yuw@ctrl.cinvestav.mx

Within the same article, a representation is generated in the state space, which has the following simple form

$$\begin{array}{l}\dot{T}(t) = \mathbf{A}T(t) + \mathbf{B}u(t)\\ y(t) = \mathbf{C}T(t) + \mathbf{D}u(t)\end{array}$$

where T is the state vector, u is the control variable, $\mathbf{A}$ is the state matrix, $\mathbf{B}$ is the control matrix, $\mathbf{C}$ is the output matrix, and $\mathbf{D}$ is the feedforward matrix. The most developed form of the above equation is the following

$$\begin{bmatrix}\dot{T}_w\\ \dot{T}_i\end{bmatrix} = \begin{bmatrix}-\frac{R_o-R_i}{R_o\cdot R_i\cdot C_w} & \frac{1}{\cdot R_i\cdot C_w}\\ \frac{1}{\cdot R_i\cdot C_i} & -\frac{1}{\cdot R_i\cdot C_w}\end{bmatrix}\begin{bmatrix}T_w\\ T_i\end{bmatrix} + \begin{bmatrix}\frac{1}{\cdot R_o\cdot C_w}\\ 0\end{bmatrix}$$

II. Computational intelligence based models

The methods with which both functions can be carried out were grouped as Smart models, these being regression functions and classification functions.

A. Fuzzy models

In [5] fuzzy logic is defined as a tool, whose function is to embed human knowledge into algorithms; This can simplify control and deal with uncertainties. Fuzzy logic is an extension of conventional logic; This logic contemplates different levels of truth in the answers. Conventional logic operates on absolute values. In [5] fuzzy logic is used to represent the thermal comfort of the occupants and thus, taking this into account, carry out corrections with respect to the reference point at which the HVAC system will maintain the temperature of a specific zone.

Using fuzzy logic, fuzzy models are obtained. The following model is called the Takagi and Sugeno fuzzy model.

$$\begin{array}{l}\hat{y}_{i,r}(x_i) = \psi_{i,r}^T\theta_r\\ \hat{y}_i = f^{TS}(x_i) = \sum_{r=1}^m \upsilon_{2i,r} y_{i,r}(x_i)\end{array}$$

Modeling type	Description of the division
Physical models	The laws of thermodynamics are taken into account equations with energy expenditure.
Data-driven models	Energy expenditure in a building is predicted data from sensors, users, or stored databases.
Gray box models	Physics-based models via data-based methods.

TABLE I

Three types of modeling techniques

where x_i is the vector of inputs of the fuzzy model; $\upsilon_{2i,r}$ is the degree of activation; $\hat{y}_{i,r}$ is the estimate of the output vector of the local model for each rule r and sample i; $\psi_{i,r}^T$ is the regression vector; θ_r is the regression vector parametera and m is the number of rules of the fuzzy model. In [6] an extension of this model, called the diffuse interval model, is used to predict future disturbances, and thus generate limits for the temperature predictions in rooms with HVAC systems. In [7] the fuzzy model of Takagi and Sugeno is used as the basis for generating a composite model of the energy need for HVAC systems in real time for the city of Basra. The main contribution of fuzzy logic to this model is the forecast of the outside temperature.

B. Neural networks model

In [8] artificial neural networks are described as a tool, which is used to learn the relationship between inputs and outputs, this to predict the performance of the system. The multilayer perceptron is a specific case of feedforward artificial neural networks; in this, the node inputs come only from links from the previous layer to the current one. The following model represents the correlation that exists between inputs $x(k)$ and outputs $y(k)$ in a multilayer perceptron

$$\begin{aligned} y(k) &= f_{Tr2}(w_2 y_o(k) + c_2) \\ y_o(k) &= f_{Tr1}(w_1 x(k) + c_1) \end{aligned} \tag{1}$$

where $y_o(k)$ is the output vector of the hidden layer; w_2 represents the weight matrix that connects the hidden layer to the output layer; w_1 represents the weight matrix that connects the output layer with the hidden layer; c_1 and c_2 are the limits; f_{Tr1} and f_{Tr2} represent the transfer functions of the hidden layer and the output layer, respectively. You can select as a transfer function a step function, or a sign function, and if you are looking for functions that are differentiable at all times, you can use logistic functions or hyperbolic tangents. In [9] a predictive model of energy expenditure in buildings is generated, using artificial neural networks. In [8] the model of (1)is used to model the annual energy consumption of an HVAC system; this equation is also used to model the percentage of dissatisfied people with respect to thermal comfort.

In [10], Elman neural networks are used to predict the energy consumption of buildings. In the same article, genetic algorithms are used to optimize the selection of the weights of the neural network. In [11] three intelligent algorithms are used to estimate the parameters of a thermodynamic model that predicts temperatures in HVAC systems. One of these three methods is genetic algorithms and, as in the previous article, it is only used as an optimization method for a prediction algorithm.

C. Genetic algorithms based model

In [12] genetic algorithms are described as a subset of approximation techniques, in computer science, to estimate a proper solution for optimization problems. In genetic algorithms, the process begins by taking a random population, which continues for generations; In each generation the total population is judged, it is chosen randomly from among the most competent elements, and these together with the modified elements form a new generation, thus restarting the cycle. This method is based on Darwin's theory of gradual evolution. In [13] it is explained that each generation, in the genetic algorithm, is made up of strings, also called artificial creatures. These strings are made up of information elements, in the simplest case they would be ones and zeros, representing the existence or lack of some signal. A set of strings, of the same phenomenon to be represented, is called a population and its size is the number of strings that exist in them. The figure 1 shows the basic elements of a genetic algorithm for population μ and string size ν; the information elements $q_{i,j}$ can have values 1 o 0.

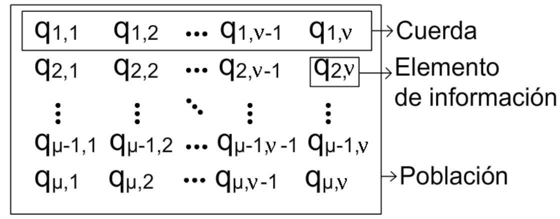

Fig. 1. Basic representation of the parts of a genetic algorithm.

A simple genetic algorithm is composed of the following operators

- Reproduction
- Recombination
- Mutation

Strings with more fitness will be more likely to reproduce, in [13] they represent this with a roulette, in which it is divided between the strings taking into account their percentage of total fitness. These reproduced items are randomly grouped and matched. These random pairs undergo recombination. In this recombination, first an integer is randomly selected, which we will call χ, which is between the number 1 and the number $n-1$, where n is the length of the string. Recombination is carried out by exchanging, in the string pair, the elements to the right of $\chi + 1$. In Figure 2 the recombination is exemplified, where the strings Q_{r1} and Q_{r2} are generated, when exchanging elements of the pair Q_1 and Q_2.

D. Gray box models

In gray box models, a combination of physics-based models and data-based models is carried out. In these models, analytical models based on physics are used as a basis, and the parameters of these models are estimated using intelligent data-based methods.

In [14] a thermal gray box model is used to investigate the demand response potential of residential air conditioning

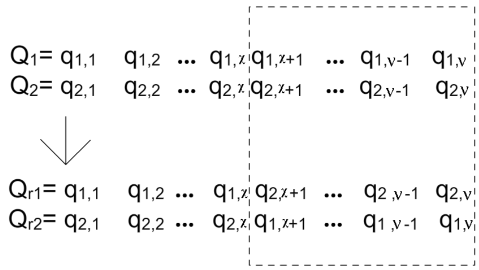

Fig. 2. Recombination of the string pair Q_1 and Q_2.

systems on smart grids. In [15] Bayesian neural networks are used to obtain the parameters of a RC model of a house. The objective of this work is to show that a gray model of the thermodynamics of a house can be obtained, as long as you have enough information. In [16] the aim is to generate a temperature and humidity controller in massive historical buildings.

Another work where genetic algorithms and RC models are used is in [17]. This article seeks to generate an RC model for the analysis of the thermal dynamics of buildings, this by simplifying the structure of the model.

The simplification of the model is carried out as follows

1) First, a complex model training is performed using genetic algorithms. This training is necessary to obtain a first approximation of the parameters. Next, a nonlinear least squares method, called the Levenberg-Marquardt algorithm, is used to fine-tune the approximation of the parameters. From the tuning, the estimated parameters, the estimated standard error, and an estimated objective function are obtained. The latter must not exceed a certain value, to maintain its good structure.
2) In the second step, the parameters whose standard error exceeds a defined threshold in each round are removed. Any element of the model that depends on these parameters is eliminated. Few parameters are removed per round.
3) Steps two and three are repeated until there are no unidentifiable parameters, or the objective function exceeds the aforementioned value.

So far the mentioned methods generate their own algorithm to estimate the system parameters, this gives the user more control over the estimation method, but generates an extra workload. One option is to use existing tools, as is the case in [18].

E. Remarks

For the physics based modeling methods, the following advantages can be mentioned,

- These models usually have great accuracy.
- There are simulators that facilitate the modeling task.
- They do not depend on databases, so they can be generated as long as the physical characteristics of the medium to be modeled are known.

and the following disadvantages

- It is necessary to have specialized knowledge in thermodynamics to generate them.
- Due to their great complexity, most of these models have non-linearities.

For data-driven methods, the following advantages are observed

- No specialized knowledge of thermodynamics is required to generate the model.
- There are a wide variety of methods for modeling.
- It is relatively easy to adapt these models, so that they work in buildings other than the building for which they were generated.

and the following disadvantages

- These methods rely on databases, which are not always kept by building owners.
- The model parameters do not represent system characteristics and are therefore difficult to interpret.

The main advantage of the gray box models is their great precision, which is pointed out in most of the reviewed articles. Another important aspect is the ease of obtaining the parameters of the model, compared to models based solely on physics; Furthermore, these parameters are easy to interpret, as they form part of the base model based on physics.

III. Control of Smart Building

A. Conventional control

When it comes to HVAC systems, there are simple controllers that fulfill the main objective, which is to control the temperature to a desired reference. Said controllers would be the ON/OFF control, and the proportional integral derivative (PID) control. In the ON/OFF control, the input of a signal is simply allowed or denied, it is the simplest control. The PID controller is one of the most widely used controllers in the industry, and it is already well known.

Conventional control methods are those, as their name indicates, that follow the conventional methodologies of control systems; these methods require a model of the dynamic system to generate a controller. Different conventional control methods are applied in HVAC systems, a list of these is presented in Table II.

Model predictive control (MPC), as its name indicates, allows to generate predictions of the possible future behavior of dynamic systems, through the use of controllers in known models of said system. In [23] the sequence of operation of the MPC is explained. In [24] three approaches to the MPC are presented, these are described in the Table II

In [25] the internet of things is used to generate an architecture that allows applying MPC to smart buildings. The MPC is generated using, as a model for the HVAC system, a linear dynamic system. In [26] MPC is used to control the energy expenditure of a building, but this case takes into account the humidity and latent heat of the air. The resistance-capacitance method is used to represent the temperature dynamics of a zone.

Model predictive control	
Approaches	**Description**
Linear invariant in time	In this, to represent the thermodynamics of the system, a linear mathematical model invariant in time is used. The linear model that is commonly used is that of resistance capacitance, which we already discussed in the modeling section.
Non linear	Due to the non-linearities, which arise when carrying out more detailed analyzes of the phenomenon, the non-linear MPC arises. In this, as its name implies, a non-linear model is used, it needs a relatively large parameter space.
Guided by simulation	For this case, simulators of the physical properties of buildings are used, such as EnergyPlus and TRNSYS, which we already discussed in the modeling section.

TABLE II

DIFFERENT APPROACHES TO MODEL PREDICTIVE CONTROL.

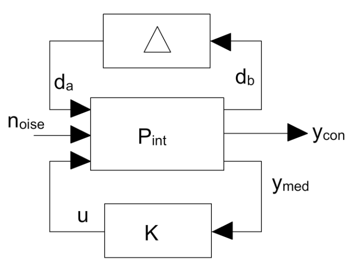

Fig. 3. Scheme of the structure of the fractional linear transformation.

In [35] robust control is used to control air handling units with variable air volumes. In [36] a comparison is made between minimum order and full order observers, in the robust control of air handling units, which in turn is in the presence of uncertainty.

B. Intelligent control

Smart control is a type of control which can be generated in a system without the need to know its dynamic model. This type of control is very useful when working with buildings, due to how difficult it is to generate a dynamic model due to the complexity of the energy transfer in them.

1) Genetic algorithm method: In [37] genetic algorithms are defined as a stochastic method for solving optimization problems with or without limitations, which are based on natural selection. The fitness function evaluates the strings of the genetic algorithm, so the control is carried out on it. Genetic algorithms are commonly used as methods to solve optimization problems in fuzzy logic controllers. At [8] multi-purpose genetic algorithms are used in conjunction with artificial neural networks to optimize the performance of two chillers in a commercial building. In [38], genetic algorithms are used to implement direct response strategies to the change in electricity rates, for a building found in Italy. In [39] genetic algorithms are used to control the CO_2 level, and reduce energy consumption in HVAC systems. In [40] genetic algorithms are used to control a variable air volume of an HVAC unit, the selected control variables are the temperature of the supplemented air and the static pressure of the air duct; Using this strategy, it was possible to reduce electricity consumption to 5.72%, compared to normal operating conditions.

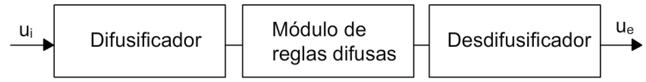

Fig. 4. Schematic of a fuzzy controller.

2) Fuzzy control: In [41] it is explained that the fuzzy logic control method consists of the following three elements:

- Fuzzifier
- Fuzzy rules module
- Defuzzifier

These fuzzy rules reveal the relationship between the linguistic variables and the fuzzy control outputs. The defuzzifier converts fuzzy control outputs into real control signals. Figure 4 shows the structure of the fuzzy controller, where u_i is the input of the controller, and u_o is the output of the controller. In [5] a demand response program is applied in an HVAC system in cooling mode, the control in said system is carried out with a fuzzy method. The main objective of the aforementioned study is to generate a controller that optimally adjusts the HVAC system set point; that is to say, seek to save energy, improve user comfort and reduce the energy cost of the HVAC system. In [42] a fuzzy logic control is used in an HVAC system, using the BCVTB simulator program as a mediator to achieve a team simulation between EnergyPlus and TRNSYS.

3) Neural network control: In neural networks the control is carried out by means of the backpropagation algorithm, also called the generalized delta rule. This algorithm seeks to minimize the cost function; This cost function is where the output of the system is compared to the reference we want to reach. In [43] a variation of the backpropagation method is used, which is called the Levenberg-Marquardt backpropagation method, to forecast the energy expenditure of the building and thus build predictive control strategies. In [44] artificial neural networks are used to generate a control algorithm; This optimizes the air discharge in the air handling unit of a variable air volume in various buildings.

C. Mixed methods

Mixed control is the combination of smart control and conventional control. An example of this type of control is in [45], where adaptive control and artificial neural networks are used to control a variable air volume, heating, ventilation, air conditioning and cooling system $(VAV - HVAC\&R)$ in buildings.

In [46] and [47], adaptive control and fuzzy logic are used to automatically tune a PID controller which controls an HVAC unit. In [48] adaptive control and fuzzy logic are used to generate control for HVAC systems in a smart grid environment. Said controller makes its own decisions, but in turn has the ability to adapt to new references supplied by the user. In [49], adaptive control, fuzzy logic, particle swarm optimization, and gray models are applied for multi-agent control of smart buildings.

In [50] a new approach to building design is proposed, which seeks to optimally reduce cost, and also integrate predictive control by multiobjective model to the HVAC system. The main goal of this article is to save money when thermally designing a building. For the optimal design of the building, a single-target genetic algorithm is used. The building's HVAC system MPC was designed using a model generated by EnergyPlus, and the control operations are performed in Matlab.

In [7] two controllers are used in an integrated way, for the control of HVAC systems for cases where a quick response is needed. The first controller they use is a Mandani-type fuzzy PI PD control (FPIPDM), this was chosen for its high reaction speed. The fuzzy control PI PD is composed of the sum of the fuzzy controls PI and PD, and these in turn were obtained by making PI and PD controllers fuzzy.

In [51] a fast convergence genetic algorithm is used to tune a PID controller applied to an HVAC system. The aforementioned genetic algorithm is called Big Bang-Big Crunch ($BB - BC$), and it is implemented, in conjunction with the PID, using a field programmable logic gate array (FPGA), in set with a simulation of the plant using Matlab's Simulink.

D. Remarks

In conventional control there are several advantages, such as PID control, this is the most popular control, and has a number of applications in HVAC systems. A disadvantage of PID control is its dependence on a mathematical model of the system; In addition, when applied to HVAC systems, the control can generate instabilities when it is used for a long time.

Nonlinear control has several advantages, such as the guarantee of closed-loop stability, in the case of Lyaponov control; Another advantage is the possibility of applying linear methods, as is the case of control by feedback linearization. Nonlinear control also has several disadvantages, such as finding a Lyapunov function that meets all the requirements of the method; or the sensitivity to non-mediated external disturbances, as is the case of feedback linearization. Using model predictive control can reduce fluctuations when reaching a set point.

Also with this method it is possible to predict future disturbances, and in turn generate control actions to deal with them. A disadvantage of this type of control technique is the need to identify a system model which is highly accurate.

Adaptive control, in the context of HVAC systems, is easy to apply, in addition to generating good stability and responding well to changes in system dynamics; The biggest disadvantage of this model is the need for an appropriate model, which requires a specialized design when applied.

The main advantages of robust control are its ability to cancel unknown interferences, and to deal with the uncertainty regarding the exact knowledge of the model parameters; Its main disadvantage is that this technique does not support drastic changes, such as change in climatic conditions. The mixed control generates a better accuracy, being compared with the individual use of the techniques used together in the mixed control.

IV. Conclusions

This paper presents state-of-art of modeling the energy expenditure of HVAC systems in smart buildings, and methods to control these models. The HVAC system models were divided into physics-based models, data-driven models, and gray box models. From this review, a subdivision was obtained for the data-based models, in which they are grouped taking into account whether their objective is to carry out regressions, classifications, or either of the two. The control techniques were subdivided into conventional methods, intelligent methods, and mixed methods.

References

[1] F. J.-S. A. Afram, "Review of modeling methods for hvac systems," *Applied Thermal Engineering*, 2014.

[2] Y. Li, J. Castiglione, R. Astroza, and Y. Chen, "Real-time thermal dynamic analysis of a house using rc models and joint state-parameter estimation," *Building and Environment*, 2020.

[3] B. H. Ronghu Chi, Yunkai Lv, "Distributed iterative learning temperature control for multi-zone hvac system," *Journal of the Franklin Institute*, 2019.

[4] D. S. Filip Belic, Zeljko Hocenski, "Algorithm for defining structure of thermal model of building based on rc analogy," *23rd International Conference on System Theory, Control and Computing (ICSTCC)*, 2019.

[5] A. Talebi and A. Hatami, "Online fuzzy control of hvac systems considering demand response and users' comfort," *Energy Sources, Part B: Economics, Planning, and Policy*, 2020.

[6] O. Cartagena, D. Muñoz-Carpintero, and D. Sáez, "A robust predictive control strategy for building hvac systems based on interval fuzzy models," *Institute of Electrical and Electronics Engineers*, 2018.

[7] R. Z. Homod, H. Togun, H. J. Abd, and K. S. Sahari, "A novel hybrid modelling structure fabricated by using takagi-sugeno fuzzy to forecast hvac systems energy demand in real-time for basra city," *Sustainable Cities and Society*, 2020.

[8] Nasruddin, Sholahudin, P. Satrio, T. M. I. Mahlia, N. Giannetti, and K. Saito, "Optimization of hvac system energy consumption in a building using artificial neural network and multi-objective genetic algorithm," *Sustainable Energy Technologies and Assessments*, 2019.

[9] S. Ferlito, M. Atrigna, G. Graditi, S. De Vito, M. Salvato, A. Buonanno, and G. Di Francia, "Predictive models for building's energy consumption: An artificial neural network (ann) approach," in *2015 XVIII AISEM Annual Conference*, 2015, pp. 1–4.

[10] L. Ruiz, R. Rueda, M. Cuellar, and M. Pegalajar, "Energy consumption forecasting based on elman neural networks with evolutive optimization," *Expert Systems With Applications*, 2017.

[11] K. Yan, C. Diduch, and M. E. Kaye, "An improved temperature prediction technique for hvac units using intelligent algorithms," *Institute of Electrical and Electronics Engineers*, 2019.

[12] F. Ecer, S. Ardabili, S. S. Band, and A. Mosavi, "Training multilayer perceptron with genetic algorithms and particle swarm optimization for modeling stock price index prediction," *Entropy*, 2020.

[13] D. E. Goldberg, *Genetic Algorithms in Search, Optimization & Machine Learning*. Addison-Wesley, 1989.

[14] M. Hu, F. Xiao, and L. Wang, "Investigation of demand response potentials of residential air conditioners in smart grids using grey-box room thermal model," *Applied Energy*, 2017.

[15] M. M. Hossain, T. Zhang, and O. Ardakanian, "Identifying grey-box thermal models with bayesian neural networks," *Energy & Buildings*, 2021.
[16] M. Wessberg, T. Vyhlídal, and T. Broström, *A model-based method to control temperature and humidity in intermittently heated massive historic buildings*. Building and Environment, 2019.
[17] Z. Wang, Y. Chen, and Y. Li, "Development of rc model for thermal dynamic analysis of buildings through model structure simplification," *Energy & Buildings*, 2019.
[18] M. Fiorentini, J. Wall, Z. Ma, J. H. Braslavsky, and P. Cooper, "Hybrid model predictive control of a residential hvac system with on-site thermal energy generation and storage," *Applied Energy*, 2017.
[19] E. Semsar, M. Yazdanpanah, and C. Lucas, "Nonlinear control and disturbance decoupling of an hvac system via feedback linearization and back-stepping," in *Proceedings of 2003 IEEE Conference on Control Applications, 2003. CCA 2003.*, vol. 1, 2003, pp. 646–650 vol.1.
[20] E. Semsar-Kazerooni, M. J. Yazdanpanah, and C. Lucas, "Nonlinear control and disturbance decoupling of hvac systems using feedback linearization and backstepping with load estimation," *IEEE Transactions on Control Systems Technology*, vol. 16, no. 5, pp. 918–929, 2008.
[21] G. Wang, W. Cai, Y. Zhang, K. Zhao, and X. Xu, "Lyapunov optimization based online energy flow control for multi-energy community microgrids," *Institute of Electrical and Electronics Engineers*, 2019.
[22] M. Elnour and N. Meskin, "Multi-zone hvac control system design using feedback linearization," in *2017 5th International Conference on Control, Instrumentation, and Automation (ICCIA)*, 2019.
[23] G. Serale, M. Fiorentini, A. Capozzoli, D. Bernardini, and A. Bemporad, "Model predictive control (mpc) for enhancing building and hvac system energy efficiency: Problem formulation, applications and opportunities," *Energies*, 2018.
[24] M. Aftab, C. Chen, C.-K. Chau, and T. Rahwan, "Automatic hvac control with real-time occupancy recognition and simulation-guided model predictive control in low-cost embedded system," *Energy & Buildings*, 2017.
[25] R. Carli, G. Cavone, S. B. Othman, and M. Dotoli, "Iot based architecture for model predictive control of hvac systems in smart buildings," *Sensors*, 2020.
[26] N. S. Raman, K. Devaprasad, B. Chen, H. A. Ingley, and P. Barooah, "Model predictive control for energy-efficient hvac operation with humidity and latent heat considerations," *Applied Energy*, 2020.
[27] Z. Huaguang and L. Cai, "Decentralized nonlinear adaptive control of an hvac system," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 32, no. 4, pp. 493–498, 2002.
[28] G. Lymperopoulos and P. Ioannou, "Distributed adaptive control of multi-zone hvac systems," in *2019 27th Mediterranean Conference on Control and Automation (MED)*, 2019, pp. 553–558.
[29] A. Beghi and L. Cecchinato, "Modelling and adaptive control of small capacity chillers for hvac applications," *Applied Thermal Engineering*, vol. 31, no. 6, pp. 1125–1134, 2011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1359431110005235
[30] G. Lymperopoulos and P. Ioannou, "Building temperature regulation in a multi-zone hvac system using distributed adaptive control," *Energy & Buildings*, 2020.
[31] V. H. Haji, A. Fekih, and C. A. Monje, "H-infinity robust control design for a combined cycle power plant," *Institute of Electrical and Electronics Engineers*, 2019.
[32] K. Zhou, *ESSENTIALS OF ROBUST CONTROL*. Prentice Hall, 1999.
[33] H. Setayesh, H. Moradi, and A. Alasti, "Nonlinear robust control of air handling units to improve the indoor air quality & CO_2 concentration: A comparison between H_∞ & decoupled sliding mode controls," *Applied Thermal Engineering*, 2019.
[34] H. Moradi, F. Bakhtiari-Nejad, and M. Saffar-Avval, "Multivariable robust control of an air-handling unit: A comparison between pole-placement and h-infinity controllers," *Energy Conversion and Management*, vol. 55, pp. 136–148, 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0196890411003098
[35] S. Cheng, Y. Chen, C. H. K. Chan, T. Lee, H. L. Chan, J. Qin, Q. Zhou, A. Cheung, and K. Yu, "A robust control strategy for vav ahu systems and its application," in *Advances in Intelligent and Soft Computing*, vol. 133. Springer, 2011.
[36] H. Setayesh, H. Moradi, and A. Alasty, "A comparison between the minimum-order and full-order observers in robust control of the air handling units in the presence of uncertainty," *Energy and Buildings*, vol. 91, pp. 115–130, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778815000225
[37] D. Ivanova, N. Valov, and M. Deyanov, "Application of the genetic algorithm for cascade control of a hvac system," in *International Conference on Circuits, Systems, Communications and Computers*, 2019.
[38] N. K. abd Nikolaos Sifakis, D. Kolokotsa, K. Gobakis, K. Kalaitzakis, D. Isidori, and C. Cristalli, "Hvac optimization genetic algorithm for industrial near-zero-energy building demand response," *Energies*, 2019.
[39] V. Congradac and F. Kulic, "Hvac system optimization with co2 concentration control using genetic algorithms," *Energy and Buildings*, vol. 41, no. 5, pp. 571–577, 2009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778808002685
[40] N.-C. Seong, J.-H. Kim, and W. Choi, "Optimal control strategy for variable air volume air-conditioning systems using genetic algorithms," *Sustainability*, 2019.
[41] H. Yan, Y. Xia, X. Xu, and S. Deng, "Inherent operational characteristics aided fuzzy logic controller for a variable speed direct expansion air conditioning system for simultaneous indoor air temperature and humidity control," *Energy & Buildings*, 2017.
[42] C. Anastasiadi and A. I. Dounis, "Co-simulation of fuzzy control in buildings and the hvac system using bcvtb," *Advances in Building Energy Research*, 2017.
[43] Z. Ye and M. K. Kim, "Predicting electricity consumption in a building using an optimized back-propagation and levenberg–marquardt back-propagation neural network: Case study of a shopping mall in china," *Sustainable Cities and Society*, 2018.
[44] J. M. Lee, S. H. Hong, B. M. Seo, and K. H. Lee, "Application of artificial neural networks for optimized ahu discharge air temperature set-point and minimized cooling energy in vav system," *Applied Thermal Engineering*, 2019.
[45] M. Ning and M. Zaheeruddin, "Neural network model based adaptive control of a vav- hvac&r system," *International Journal of Air-Conditioning and Refrigeration*, 2018.
[46] S. Soyguder and H. Alli, "Fuzzy adaptive control for the actuators position control and modeling of an expert system," *Expert Systems with Applications*, vol. 37, no. 3, pp. 2072–2080, 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957417409006228
[47] S. Soyguder, M. Karakose, and H. Alli, "Design and simulation of self-tuning pid-type fuzzy adaptive control for an expert hvac system," *Expert Systems with Applications*, vol. 36, no. 3, Part 1, pp. 4566–4573, 2009. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0957417408002200
[48] A. Keshtkar and S. Arzanpour, "An adaptive fuzzy logic system for residential energy management in smart grid environments," *Applied Energy*, vol. 186, pp. 68–81, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261916316130
[49] Z. Wang, R. Yang, L. Wang, R. C. Green, and A. I. Dounis, "A fuzzy adaptive comfort temperature model with grey predictor for multi-agent control system of smart building," in *2011 IEEE Congress of Evolutionary Computation (CEC)*, 2011, pp. 728–735.
[50] F. Ascione, N. Bianco, C. D. Stasio, G. M. Mauro, and G. P. Vanoli, "A new comprehensive approach for cost-optimal building design integrated with the multi-objective model predictive control of hvac systems," *Sustainable Cities and Society*, 2017.
[51] A. Almabrok, M. Psarakis, and A. Dounis, "Fast tuning of the pid controller in an hvac system using the big bang–big crunch algorithm and fpga technology," *Algorithms*, 2018.