Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2811-3950

A Review of HVAC System Optimization and Its Effects on Saving Total Energy Utilization of a Building

Rajeanderan Revichandran[1], Jaffar Syed Mohamed Ali[1,*], Moumen Idres[1], A. K. M. Mohiuddin[2]

[1] Department of Mechanical Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Jalan Gombak, 53100, Selangor, Malaysia
[2] Director & Chief Scientific Officer, AQ Chowdhury Group, Dhaka, Bangladesh

ARTICLE INFO

Article history:
Received 14 August 2021
Received in revised form 15 January 2022
Accepted 20 January 2022
Available online 4 March 2022

Keywords:
HVAC optimization; Control Parameters; Common Energy Model; Prescient Energy Model; Thermal Comfort; Optimization Models; PMV Index; EnergyPlusTM

ABSTRACT

The paper illustrates the review on the optimizations studies of HVAC systems based on three main methods – HVAC operational variables optimization, optimization of control parameters in HVAC system and parameter optimization in building models. For the HVAC system's operational variables, the optimization process is based on the common and prescient energy utilization models. Thus, by comparing both, the non-common HVAC system models can get better output of energy reduction. Based on most of the studies, the occupancies thermal comfort requirements, are represented by the indoor air quality (IAQ) or the predicted mean vote (PMV) indexes. Comparing both requirements, the PMV index had a better overall energy reduction output of 47% and estimated annual energy reduction of 2,769 kg/year. Meanwhile, in optimization of HVAC's control parameters, its overall aim is to achieve a better response output of the HVAC system in order to prevent energy wastage. Among this different optimization's controller, the fuzzy logic tuning optimization has a better overall energy reduction. On the other hand, the parameter optimization in building model approach is performed before the construction of the structure itself, where multiple construction parameters are considerations in the design. In overall, when different tools for building parameter and model optimization are compared, the EXRETopt by using PMV comfort index approximately reduces 62% of the energy utilization.

1. Introduction

The HVAC system stands for heating, ventilating and air conditioning where an optimized HVAC system aims to provide efficient output of thermal control and occupancy comfort by using the principles of thermodynamics, fluid mechanics, and heat transfer. HVAC systems are widely used in all types of buildings all over the world and it is one of the highest utilizer of energy [1-4]. For HVAC systems, the coefficient of performance (COP) has been utilized as an index to evaluate, its total energy performance [5-7]. COP is defined as the ratio between the output of cooling/heating energy and input of electrical energy. Generally, lower energy consumption and higher efficiency of system

* *Corresponding author.*
E-mail address: jaffar@iium.edu.my

https://doi.org/10.37934/arfmts.93.1.6482

are outcomes of greater COP values, as shown in study by Oropeza-Perez [8]. In order to increase the COP value thus to achieve a lower energy utilization, the indoor set temperature can be increased to be closer to temperature of the outdoor such that comfortable environment is given by preventing wastage of electrical energy.

In this review paper, only studies that involves the thermal comfort of the occupancies are assessed as this type of comfort is linked to the effects of HVAC systems optimization in buildings. Indicators such as predicted mean vote (PMV) or indoor air quality (IAQ) can be utilized to evaluate the thermal comfort levels of occupants inside a building. PMV was introduced by Fanger [9], it has been commonly applied in many studies linked to optimization of thermal comfort level of HVAC systems and it is utilized in the ISO 7730 Standards [10-13]. PMV is an index that forecast the mean value of the votes of a large group of people on a 7-point thermal sensation scale ranging and the proposed PMV range is between -0.5 and +0.5. Inside a building the PMV value is identified based on the temperature of the air (T_{air}), mean radiant temperature (T_{mrt}), metabolism rate (M), velocity of air, humidity ratio (RH) and thermal insulation (I_{clo}). By controlling the combinations of this six parameters a satisfactory PMV value can be achieved. Nevertheless, the combination must not only able to provide a satisfactory PMV value, but also able to accomplish without utilizing too much of energy.

Moreover, the thermal comfort inside a building can also be measured through the indoor air quality (IAQ), which directly influences the thermal comfort output and overall health of the occupants [14]. Furthermore, IAQ widens the thermal comfort levels by concentrating on the air contamination level of a building. Many factors affect the IAQ value such as air temperature, humidity ratio, carbon dioxide (CO2) level, rate of airflow and static pressure. The IAQ value of a structure should obey the standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in ASHRAE Standard 62.1 [15]. However, output of a satisfactory IAQ value will result in extreme construction cost up and so most the building developers rarely take IAQ values into consideration in their design.

The HVAC system operation needs to be optimized, thus to minimize the buildings overall energy usage and establishing better thermal comfort level. This can be achieved by utilizing the single or multiple objective optimization. In the single-objective optimization, the optimization algorithm primarily targets on reducing the overall energy utilization but a fundamental thermal comfort level that must be met is enforced to prevent occupancy discomfort. Nevertheless, in the multi-objective optimization, the optimization algorithm seeks a balance between reduction of electrical energy utilization and maximizing occupancies thermal comfort level.

The objective of this review paper is to hand over a detailed review on various HVAC system optimization methods that are utilized to achieve a balance between the electrical utilization of the building and overall occupancies thermal comfort from basic classical techniques to the latest advanced techniques. Primarily three optimization approaches are discussed in this review paper. They are the main control of HVAC system's overall energy utilization models and the prescient models, controller variables and the buildings construction parameters [17-43]. In addition, the pros and cons and limitations of every approach are described and suitable recommendation are made throughout the review paper. The scope of the review paper consists of different methods as follows:

(i) The HVAC systems operational parameter optimization.
(ii) Controller optimization methods.
(iii) Building parameter and design optimization method.

2. Optimization Approaches in HVAC System

The primary aim of doing optimization process linked to HVAC systems is to reduce the overall energy utilization of the system while ensuring a pleasant living and working environment. The HVAC's operational variable optimizations are performed based on the system model in order to determine the acceptable parameter settings for low electrical energy utilization. Meanwhile, optimizations based on the control system model of HVAC systems performed thus to enhance the existing system response to prevent wastage of energy utilization. The objective of building design optimizations is to determine acceptable building parameters and models that will result in efficient utilization of overall energy for the HVAC system.

2.1 HVAC Operational Variables Optimization

To obtain quality indoor comfort without triggering HVAC systems to utilize high amount of electrical energy, appropriate operation variables settings can be obtaining by optimizing the parameters of the system. Most of the HVAC system designs represent the bonding between various operational variables and its output variables, such as utilization of energy, temperature set points and humidity ratio. The optimization of these operational parameters can be categorized based on the common energy consumption models or the non-common energy consumption models, as explained in the following sections [16-24,28-35].

2.1.1 Operational parameters optimization based on the common energy consumption models

Common energy consumption method is considering one of the easiest ways to optimize the operational parameters of an HVAC system. The model is based on operational parameters such as the overall temperature of air, air head pressure, overall airflow rate with the energy utilization of the system. The overall energy usage of an HVAC system (P_{system}) is defined as the total power usage from its components, such as the Heat exchanger (P_{HE}), ($P_{chiller}$), fan motor ($E_{fan\ \mathrm{motor}}$), pump (P_{pump}) and the cooling tower ($P_{cooling\ tower}$), as shown in Eq. (1) [16-19].

There are many operating parameters that affect the sum of energy used by these components and some are used as the optimization variables of the system. For example, P_{HE} is effected by the heat exchanger temperature and positioning, $P_{chiller}$ is affected by the HEX temperature and position, while $P_{fan\mathrm{motor}}$ is affected by the return and supply air rate. In several studies two operational parameters were considered in reducing the HVAC systems overall energy consumption such as in Lu *et al.,* [16] and Lu *et al.,* [17]. In the study by Lu *et al.,* [16], the supply chilled water temperature (T_{CHW}) and the airflow rate supplied in the system (m_{SA}) were utilize as the optimization variables, whereas in the study by Lu *et al.,* [17], the temperature of the supplied air and the fix air set point were used.

$$P_{system} = P_{HE} + P_{fanmotor} + P_{chiller} + P_{pump} + P_{cooling\ tower} \tag{1}$$

There are also studies that include multiple operational parameters to be optimized. For example, in study conducted by Kusiak *et al.,* [18], optimization parameters used were the temperature of cooling water (T_{CW}), the temperature of chilled water temperature from main chiller ($T_{CHW,\mathrm{main}}$), the temperature of chilled water from secondary chiller ($T_{CHW,sec}$) and the temperature of supplied air (T_{sa}). Figure 1 shows the schematic of the studies system.

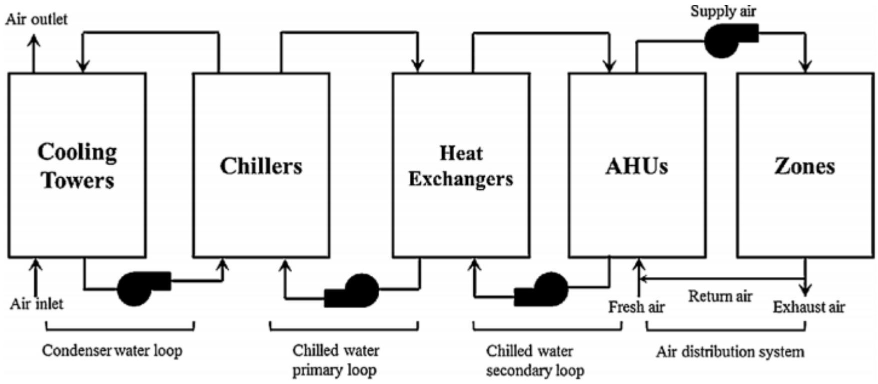

Fig. 1. Schematics of the AC system [18]

Whereas, from the study conducted by Wang *et al.,* [19], the parameters that been optimized included the temperature of two zones (T_{z1}, T_{z2}), the humidity ratios of different zone (RH_{z1}, RH_{z2}), the air-discharge temperature (T_a), the chilled water temperature (T_c), the ambient airflow rates (m_{OA}), the airflow rates and the duct system internal static pressure (P). To obtain optimized HVAC performances the optimized operational variables were then directed to the local domain loops such as the blower speed control loop. By reducing the energy consumption of the HVAC system, the optimized operational parameter values can be determined and can contribute towards energy saving. The energy reduction output from the optimization techniques in previous studies were stated to be up to 10%, 7.66%, 11.82% and 20% respectively when compared to the non-optimized at fixed setting operation method [16-19]. In multiple studies, the reduction of HVAC's energy usage is obtained by reducing the total exergy loss of the system [21,22]. In thermodynamics, 'essergy' is the energy that is available to be utilized. High essergy loss are signs of low efficiency HVAC system, while low essergy loss are signs of highly efficient system. Total essergy loss (EL_{sys}) is defined by Eq. (2), which is total energy loss from the water flow rate of cooling tower ($EL_{cooling\ tower}$), energy used by the subsystem's cooling tower ($E_{cooling\ tower}$), the energy used by chillers ($E_{chillers}$), the air handling units (E_{AHUs}) and the discharge essergy of the air handling units ($E_{AHUs,\ out}$). From Du *et al.,* [21] and Du *et al.,* [22] It is observed that by reducing the energy consumptions of the heat exchanger, pumps, cooling tower and chiller (as in Eq. (1)), total essergy loss can be reduced too.

$$EL_{system} = EL_{pump} + E_{pump} + EL_{HE} + E_{HE} + EL_{cooling\ tower} + E_{cooling\ tower} + E_{chiller} + E_{AHU} + E_{AHU,out} \tag{2}$$

In the optimization method given by Du *et al.,* [21], some of the optimized variables were the temperature of supply cooling water ($T_{C,out}$), the temperature of supply chilled water ($T_{CT\ ,out}$), and the ambient air flow rate (m_{OA}). Whereas, the study by Du *et al.,* [22] optimizes only the rate of cooling (Q_{rate}) s to minimize the energy loss. By identifying the optimized variables, the proposed methods by Du *et al.,* [21] and Du *et al.,* [22] were able to achieve energy reduction up to 12% and 9.2%, respectively, when compared to non-optimized methods. In the study by He *et al.,* [23], harmony search engine algorithm and particle swarm optimization have been utilized to concurrently reduce the HVAC energy consumption and room temperature gradient rate. The proposed method used similar common energy model and results in 15% of energy reduction which is significantly high because it incorporates the building thermal parameters. From study conducted by He *et al.,* [23], it can have been seen that in forming the energy utilization model of HVAC system for achievement of energy reduction, not only it can be achieved based on the HVAC system itself, it can also be accomplished based on the structure temperature variations and achieving a significant high energy saving. Porowski [82] studied the energy optimization of HVAC system from a holistic perspective by controlling the relative humidity of the operating environment. From the result the HVAC system structure optimization, annual primary energy saving can be achieved of 4.4%–6.5% at humidity control between 40% to 60%. Bhattacharya *et al.,* [86], studied the commercial building optimal configuration and size of the chillers plant thus to minimize the overall energy consumption by using Bayesian optimization (BO). The study is planned as a mixed-integer programming model and solved using BO that controls a high-reliability of commercial chiller plant operation to evaluate different candidate designs. Based the result the new purposed configuration manages to reduce total annual energy consumption by 33% and 56% in reduction of in peak power demand. Jia *et al.,* [87], studied the effects of dual-temperature chilled water plants for energy saving by using different control strategies. Two different optimal control strategies were introduced for the dual-temperature chiller which are named as strategy B and strategy C. By applying the both strategies the total energy saving was 10.1% for strategy B and 16.4% for strategy C respectively. The summary of studies on the operational parameter's optimization based on the common energy utilization model shown in Table 1.

Table 1
Summary of optimization studies based on the common energy utilization model

Optimized Parameters	Energy Reduced	Reference
• temperature of chill water (T_{CHW})	10.0%	Lu *et al.,* [16]
• set point of static air • temperature of supply air	7.0%	Kusiak *et al.,* [18]
• temperature of cooling water (T_{CW}) • water temperature from primary chiller ($T_{CW,prm}$) • water temperature from secondary chiller ($T_{CW,sec}$) • temperature of supplied air (T_{sa})	11.8%	Wang *et al.,* [19]
• zone temperature ($T_{z1}T_{z2}$) • humidity (RH_{z1} , RH_{z2}) • temperature of discharge air (T_a) • chill water temperature (T_c) • air flow rate (m_{oa}) • static pressure (P)	20.0%	Zheng and Zaheer-Uddin [20]
• temperature of cooling water ($T_{CH,OUT}$) • chill water temperature ($T_{CT,OUT}$) • air flow rate (m_{oa})	12.0%	Du *et al.,* [21]
• cooling rate (Q_{rate})	9.2%	Du *et al.,* [22]
• ramp rate	15.0%	He *et al.,* [23]
• Humidity (%)	4.4%-6.5%	Porowski [82]
• Chiller configuration	33%	Bhattacharya *et al.,* [86]
• Chill water temperature (T_C)	10.1%-16.4%	Jia *et al.,* [87]

2.1.2 Operational parameters optimization based on the non-common energy consumption models

The model of non-common control has been introduced thus to make the HVAC systems more energy-efficient while providing thermal comfort. Such models are simpler and not difficult to be implemented on real-time applications contrast to other models such as physical and dynamic models [24]. Unlike the common models, the non-common models of HVAC system are not confined only to energy based models, but also for additional system outputs such as carbon dioxide level, set temperature, humidity ratio and number of occupancies [24]. Due to these privileges, in recent years' prescient models have been utilized in multiple optimization studies on operation of HVAC systems

[25-28]. Based on the studies conducted by Kusiak *et al.,* [32,33], the prescient of the desired output (o) was made based on present and/or past values of the govern parameters (p) and the uncontrolled variables (v_1 to v_6) given in Eq. (3) is the interval of time (t) equivalent distance (d), x_1 is the air supplied static pressure and x_2 is the temperature of supplied air. Whereas, T_{v1} to T_{v6} refer to combine air temperature, chilled water temperature, ambient air temperature, air humidity, return and supply air fan motor rate, respectively. Meanwhile, in some studies constant parameters such as supply air temperature setting to be optimized, the supply air static pressure setting and the air and mean radiant temperature points of the layout which is influenced by the building thermal comfort and dynamics [24-35].

$$(t+d) = f(o(t), x_1(t), x_2(t), T_{v1}(t), T_{v1}(t-d), T_{v2}(t), T_{v2}(t-d), T_{v3}(t), T_{v4}(t), T_{v5}(t), T_{v6}(t) \tag{3}$$

In the study by Cigler *et al.,* [35] the researchers studied based on the single-objective optimization and used only the non-common energy model as the primary function to determine the optimized values of the two operational variables x_1 and x_2, and approximately manage to reduce the overall energy consumption of the designed system of the HVAC by about 17%. In the multiple-objective HVAC system optimization works, several non-common models were used as the primary functions for minimizing the overall energy consumption of the system without breaching the indoor air quality (IAQ). As indoor air quality affects the overall health, comfort and the human development, any energy preservation attempts must not influence the IAQ in a negative perspective [36]. In the study by Porowski [24], the carbon dioxide, air humidity ration and air temperature set point were used along the prescient energy consumption model as the primary functions to obtain the optimized variable setting for x_1 and x_2. Whereas, in One of the studies multi-objective optimization approaches involved joining all the objective outputs into a single function to be reduced by the optimizer such as that given in Eq. (4), where the outputs of the four objectives are z_1, z_2, z_3, and z_4 represent the total energy (in kJ), infraction of temperature (°F), infraction of humidity ratio (%) and infraction of Carbon dioxide concentration (ppm). The infractions of parameters are generally due to lack of knowledge to visualize the required HVAC system to fulfil the thermal dynamics requirements of the building structure. In a study by He *et al.,* [23], the thermal dynamics minimum and maximum values were used, along with the weight correlated with each of the objectives (w_1, w_2, w_3, and w_4) thus to streamline the issue formulation. The weights w_1, w_2, w_3, and w_4 are linked with z_1, z_2, z_3, and z_4 respectively. The values of the weight parameter of each objective was based on certain ranking or prejudice set by the user where they are summed to be one, $w_1 + w_2 + w_3 + w_4 = 1$. From the study by Porowski [24], it has been proved that by utilizing this method of study, about 12.4% of total energy utilization can be minimized without notably violating the IAQ limitations. The lower the IAQ violation becomes as the higher the weight value increases. By excluding the IAQ in the objectives it minimizes the amount of energy utilize but results in a serious violation of IAQ levels. It can also have been seen that by adding the IAQ violations as optimization objective, the model is able to comply the thermal comfort needs in the commercial building without creating the need of higher energy utilization.

$$Objective = w_1 z_1 - z_{1,min} z_{1,max} - z_{1,min} + w_2 z_2 - z_{2,min} z_{2,max} - z_{2,min} + w_3 z_3 - z_{3,min} z_{3,max} - z_{3,min} + w_4 z_4 - z_{4,min} z_{4,max} - z_{4,min} \tag{4}$$

Zeng *et al.,* [31] performed the HVAC optimization based on the different configuration and multiple operating zones of its operational parameters. Studied performed by Kusiak *et al.,* [32] were similar to that in the study by Porowski [24]. However, compare to Porowski [24] only three objective functions were used, instead of four, where the carbon dioxide concentration was excluded. The multi-objective optimization equation was also alike to Eq. (4). Studies showed approximately 13.4% energy minimization potential without considerable violation on the IAQ rules. Similarly, another study which is using a multi-objective equation has been completed by Risbeck *et al.,* [29] where only the prescient models of energy and temperature set points were used, and the energy utilization of the systems HVAC performance was minimized by 18.5%. From the output of these study, it can be observed that as multiple objectives were introduced in the optimization problem formulation equation, the potential of energy saving were minimized due to the needs of energy consumption with the rules of IAQ. In the studies by Kusiak and Xu [34] and Cigler *et al.,* [35], the comfort index, and PMV are defined by Eq. (5), has been utilized instead of the IAQ values. It can be seen how the mean radiant temperature (T_{mrt}), temperature of air (T_{air}), rate of metabolism (M), velocity of air (va), humidity ratio (RH) and insulation (I_{clo}) determine the PMV value. in the optimization study only, few parameters are used as variable parameters because not all six PMV parameters can be controlled. Variables such as attire types of the occupants, absolute humidity ratio and wind speed in a building simply cannot be manipulated but it is possible to be set to a certain normalized or average value depending to the types of building structure and nature of business. As an example, an office to be occupied with people wearing casual clothing while at another location which is a restaurant to be filled with people wearing thinner attires. In the studies by Kusiak and Xu [34] and Cigler *et al.,* [35], the focus of optimization in these studies was to reduce the infractions of PMV in the office building while minimizing its overall energy usage. In the studies by Reddy *et al.,* [37] and Golshan *et al.,* [38], operating variables that need to be optimized and regulated were the temperature of water supply (T_{sw}), the air temperature set point (T_{air}) and the mean radiant temperature (T_{mrt}). This method was able to minimize the HVAC system energy utilization by up to 10% while ensuring the occupants' thermal comfort. In the recent energy optimization based on the PMV model, researchers achieve high energy minimization up to 46%. Similarly, Dong *et al.,* [79] performed a comprehensive evaluation and optimization of rural space heating modes in cold areas based on PMV-PPD method. From the evaluation a reasonable design thermal index of 35.18 W/m^2 is obtained, thus the highest obtain comprehensive rate was 89.64%, and the estimated energy and carbon dioxide emission reduction are 2,769 kg/year and 4,014 kg/year respectively.

$$PMV = (0.303.\exp(-0.036.M) + 0.028).L \tag{5}$$

The optimization of HVAC systems by using only common energy models has the potential to minimize a significant amount of overall energy utilized, however more models need to be incorporate as the objective functions for a better performing system which has higher overall efficiency of operation. Due to this, such fundamental method is still being used until present time and improvised time to time to more advanced versions thus to save more overall energy consumption of the required system. In the optimizing of HVAC system usage of IAQ and PMV enables low energy utilization while sustaining the level of thermal comfort of the occupancies in a building. While non-common models are mostly utilized in multi-objective optimization studies of the HVAC system operation. If the models need to be very accurate, this method needs recognition of the model via system recognition method, which may take a crucial amount of time [29-32]. Johnson *et al.,* [76] studied the impact of the scale of the hot water demand on a grid-integrated hybrid energy system's overall performance by using photovoltaic (PV) model. TRNYS software was used to perform this numerical evaluation by using high and low emissivity collector's absorber plate. By using PV module's, the electrical efficiency is improved by about 13.9% as the volume of hot water increased. In overall, the low emissivity collector produces more energy than of the high emissivity collector, and this numerical evaluation difference becomes more noticeable as the demand for thermal energy expands. Tükel *et al.,* [80] studied on climatic zones for building thermal regulations at turkey based on thermoeconomic analysis. In this study Turkey was reclassified into 5 zones based on fuzzy c-means clustering method regarding 27 different optimum insulation thickness ($X_{OIT,H\&C}$) attributes calculated for each city. the optimum insulation thickness by considering both heating and cooling are defined by Eq. (6). Where HDD stands for heating degree day, fuel price (C_f), Present worth factor (PWF), thermal conductivity (k), number of cities (η), Lower heating value for fuel (LHV), Cooling degree day (CDD), electricity price (C_e), Coefficient of performance (COP) and insulation material cost (C_i).

$$X_{OIT,H\&C} = \left(\frac{86400.HDD.C_f.PWF.k}{\eta.LHV.C_i} + \frac{0.024.CDD.C_e.PWF.k}{COP.C_i}\right)^{0.5} - k.R_{tw} \quad (6)$$

The results showed that compared to the current national thermal zones, based only on HDD values, 16 out of 80 provinces shift to a new category, all of which correspond to a higher zone indicating the requirement of a thicker insulation layer.

2.2 Optimization of Control Parameters in HVAC System

Golshan *et al.,* [38] and Haniff *et al.,* [39] studied to improve the dynamic performance of the system, thus to ensure better system performance, it is viral that the overall control method of the HVAC system to be effective .Apart the overall time taken for the temperature of supply air to achieve the desired set point, the speed of the air been supply is also a crucial parameter in its overall dynamic performance since having higher air flow rate of the temperature being cooled will cause large amount of electrical energy wastage [41-42]. The overshoot of the supplied air can be minimized by upgrading the error tracking method of the system response as mentioned by NSW government [43] and Aswani *et al.,* [44], where improvised optimization methods have been utilized in reducing the tracking error of temperature of chilled water supply, the return water temperature of condenser and the temperature of supplied air. Studies done by NSW Government [43] and Aswani *et al.,* [44] able to minimize the percentage of tracking errors by more than 24% and the overall energy utilization of the HVAC system has been minimized by 11%. Nonetheless, the main issue was occurrence of the high tracking error when the set point of one of the supplied air temperatures been changed to a new value. Figure 3 shows that there is an error between the temperature of supply air and the value of temperature every time the temperature changed to a new set point. Asad *et al.,* [45], utilized Genetic algorithm (GA) to optimize the fuzzy control rules and other members of the functions by controlling the value of set temperature with the aim of reducing the overall energy utilization while delivering PMV values within the pleasant range. This approach was able to minimize the energy consumptions up to 18% for both cooling and heating cycle respectively when matched to the system performance of a commonly used control tool EnergyPlus. In the study by Asad *et al.,* [45], another study that is linked to fuzzy logic control optimization for a HVAC system was described. In this study, Gauss Newton method was used so that the fuzzy controller was able to be self-tuned for nonlinear regression models with including of the PMV model, thus to avoid problem related to comfort of occupants while minimizing the overall energy utilization. At least 32% of the electricity usage has been reduced in this method. Similar to Asad *et al.,* [45] in another study conducted by Kampelis *et al.,* [78], GA-based approach was developed to investigate demand response (DR) implementation for a near-zero-energy industrial building. From the analysis overall cost of energy reductions in the range between 9.9% and 25%. Overall based on many review studies it can have been that the most widely used approach method for HVAC systems optimization is the Proportional–Integrate–Derivative (PID) controller [47-54]. To obtain a more effective control of HVAC system the PID controller has been executed with fuzzy rules for tuning of the controller variables (k_p, k_i and k_d) [50,51]. Optimal tuning of the two parameters has improved the control of the common parameters such as the temperature set point values and humidity ratio of system. Figure 2 shows the optimization output of the PID controller for a room temperature set point [47]. By optimizing the PID controller parameters It can be seen that, energy wastage has been minimized and the duration taken for the room to achieve set temperature have been shortened, hence making the energy efficiency of system better. Based on study conducted by Homod *et al.,* [48] the optimized PID controller was able to minimize the overall energy utilization of the HVAC system approximately up to 20%.

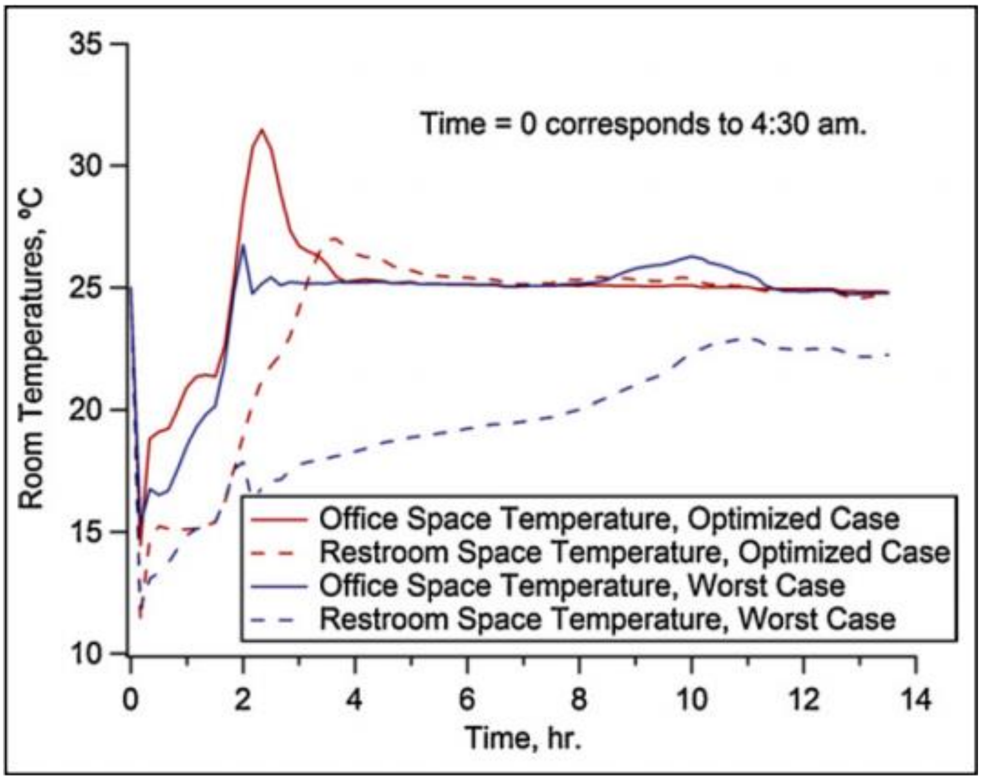

Fig. 2. Response output of room temperature for optimized PID parameters [46]

In a study by Homod [55], an adaptive network control was strategies to obtain an efficient control of the HVAC model by tracking the set values of air-temperature been supplied. For usage of various environmental conditions simultaneous perturbation stochastic approximation (SPSA) algorithm was used as the optimizer to modify the network controller weights. From the results by Homod [55], it has been seen that the network control strategy was able to perform well with the change of the temperature of supplied air values without much delay in operating duration compared to the fixed variables of the PID controller. Similarly, in another study on optimizing network controller strategy, the back-propagation (BP) and particle swarm optimization (PSO) algorithms were implemented to tune the network controller weights for better control of the temperature [56]. Guo *et al.,* [57], implemented performance function of mean squared error to tune the network weights of the HVAC heat medium prescient model in optimizing the energy utilization and thermal comfort of occupants. The HVAC system response is very important to be controlled because poor control of response will cause discomfort to occupants within the working environment and results in wastage of electricity. The usage of accurate mathematical models in HVAC system is necessary for better implementation of controllers. This method has been valid to be very effective in minimizing a reasonable amount of electricity consumption. Different types of multiple optimization algorithms to determining the optimal controller parameter set points has proven to enhance the control of HVAC system thus to achieve better overall performance. Compared to all previous review conducted of PID controllers in the previous studies, Turhan *et al.,* [83] developed a new thermal comfort driven control (PTC-DC) algorithm to improve HVAC control systems with no need of retrofitting HVAC system components [47-55]. The results showed that the developed PTC-DC control algorithm Vs. PID controller satisfied the neutral thermal comfort by 92% and 6% of total measurement days. Moreover, the PTC-DC has better energy reduction of 13.2% compared to PID controllers.

2.3 Parameter Optimization in Building

Many methods of direct optimization have proven on effective control of the HVAC system, however other than directly optimizing the operational variables and network controllers, HVAC system energy utilization in commercial buildings can be minimized by proper planning before even buying the system and during designing phase of the building itself before been constructed [58-61]. Constructing a low-energy building structure not only needs the efficiency of HVAC system to be evaluated, but also the multiple combinations of designs and thermal properties of the elements involved such as the roof thickness, window thickness, wall type, wall thickness, width of the window, and thickness of insulation material used. These are some of the variables that define the overall energy demand, energy utilization and the maintenance cost of the buildings. By improving the thermal quality of a buildings overall energy demands can be minimized [62]. From study conducted by Wetter [63] shows that commercial buildings with better thermal parameter designs are able to save up to USD170 billion annually. Recent times for designing green building, simulation-based optimization approaches have been introduced. In the previous studies, the optimization process which concerns such as building materials and building designs are taken into consideration as factors for evaluating overall energy utilization [64-70]. In a study by Wei and Junmin [58], a simulation tool called SEDICAE was introduced which has advance features for evaluating energy consumption. SEDICAE is an advance system for designing of energy-efficient structures, which reduces the maintenance costs and improves the overall energy rating of a building by defining what types of construction materials and parameters of HVAC system should be used [67]. The construction materials of a structure are decided based on the thermal properties of the materials itself such as the solar factor and air-tightness. The HVAC system is decided based on the types of demand from the needed cooling or heating rate. Example of case study performed by Wei and Junmin [58], the Tabu search algorithm was used to optimally enhanced or re-designed the initial building model proposal based on the required energy rating. By using Tabu search, it was able to re-design a structure with 30 years' life span cost as low as EUR6000. In the study by Wei and Junmin [58], an optimized building model has also been identified by using the simulation tool. Exergy Analysis Model for Retrofit Optimization (EXRETOpt), determined by Gou *et al.,* [68] to reduce the building annual energy usage, thermal comfort of occupants and building annual exergy consumption. The optimized building model parameters include the types of HVAC system in the building, thermal insulation and dimension of roof, wall and foundation, repairing percentage of cracks and joints, window glazing level, set points of cooling or heating, and types of lighting system used. Figure 3 shows the impact of insulation types and thickness to the energy use and exergy reduction. From Figure 3, It can be observed that as thickness of insulation increases, the overall energy utilized will also hike up but the exergy reduction will reduce. Concurrently, Figure 4 describes the effect of change in HVAC system layout to thermal comfort level of occupancies, overall energy usage and exergy destruction. In the study by Attaran *et al.,* [56], it shows that as the HVAC layout uses minimum energy with low exergy wasting, the building will be intolerable at usage of longer period of time. The method used by Attaran *et al.,* [56] it was able to optimize the building parameters and types of HVAC configuration and attained enhancement of 63% in annual overall energy usage, approximately 58% of exergy wastage and up to 30% occupancy thermal comfort.

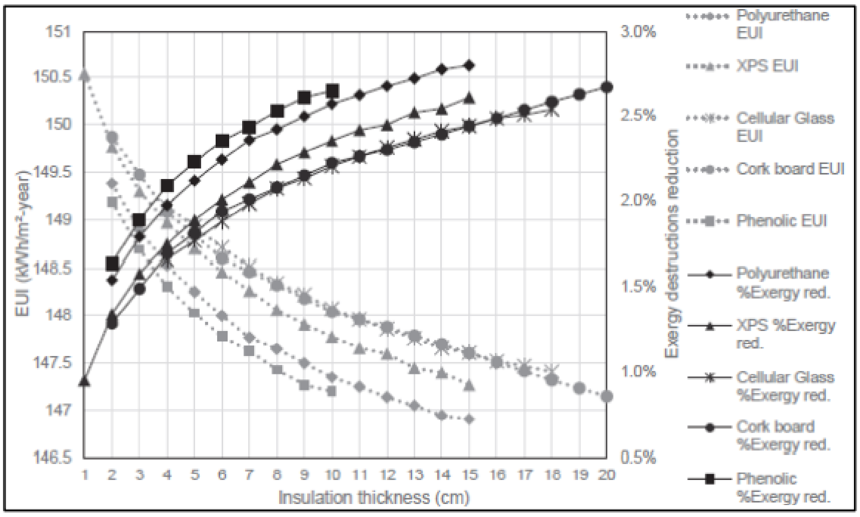

Fig. 3. Effects of insulation type and thickness on energy utilization [55]

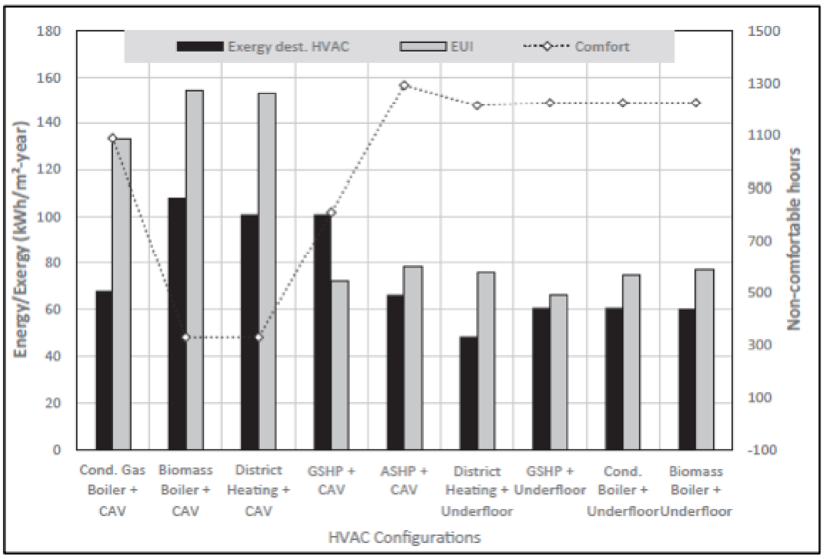

Fig. 4. Impact of reduction and comfort of HVAC's energy use [55]

An energy efficient building model was designed by Ruiz *et al.,* [60] without giving up the predictive percentage of dissatisfaction (PPD) of the occupancies by using the genetic algorithm (GA) optimization algorithm. The PPD was assessed by using EnergyPlusTM simulation program that evaluates the structure thermal comfort level and overall annual energy utilization. There are more than 70 design parameters which are considered in this optimization study that involves the HVAC schedule details, window and wall design and floor design of the structure with specific control of input values. In a study by Kerdan *et al.,* [61], a much more simplified study of building design optimization for low HVAC system energy utilization using EnergyPlusTM been introduced, which only optimizes the windows' width and the exterior shading device. Hooke-Jeeves search algorithm was utilized to evaluate the objective functions of the optimization problem. Approximate around 14% of energy utilization minimization of the heating/cooling and lighting achieved by Kerdan *et al.,* [61]. Gärtner *et al.,* [71] performed a study of building design optimization for low HVAC system energy utilization using thermal building simulation software (TRNSYS) been introduced, which the optimization performed based on control zoning strategy. The results show that radiant ceilings and thermally-active building systems are promising solutions for flexible office spaces in the location of Stuttgart, whereas mechanical ventilation systems require a more complex control strategy to ensure thermal comfort [71]. Similarly, in a study by Johnson *et al.,* [76], TRNSYS software was used to evaluate the impact of the hot water demand on a grid-integrated hybrid energy system's overall performance. From the evaluation through TRNSY low emissivity collector recorder the highest temperature. From the software outcome it could be observed that the cooling response shows a faster cooling rate as the load size increases. In overall the software outcomes shows that, the low emissivity collector is recommended for the building applications. Meanwhile, an energy efficient building model was designed by Bünning *et al.,* [72] based on Model-predictive control (MPC) optimization approaches, which this method used data from the control system to determine the analytically optimal set points, and then write back the optimal set points into the control system to minimize system energy utilization or costs. Across the evaluation at sites, HVAC savings following the implementation of the optimization system were mixed, ranging from 0–9% [72]. In addition, from the method utilized by Bünning *et al.,* [72] it can be seen that analysis of site operational data showed that occupant comfort was neither positively nor negatively impacted. Similar in the study by Bünning *et al.,* [72], Lu *et al.,* [84] exploited Bayesian optimization (BO) by using model predictive control (MPC) tuning application for (HVAC) plant optimization. In this study a reference model was constructed to evaluated the closed-loop performance of a low-complexity MPC controller at where BO is let to learn the functions of the controller thus to find the optimum controlling parameters. From the result the studied method manages to reduce the computational time by 28%.

Ismail and Jamil [73] performed a Computational Fluid Dynamics (CFD) modelling of a badminton hall by studying the effects of exhaust fans and its arrangement on the room wall temperature and air velocity. Across the study 5 different models were introduced through the CFD, where the modelling has been drawn using GAMBIT pre-processor. From the CFD simulation the lowest wall temperature recorded was 26.52 °C at velocity of 0.083ms$^{-1.}$ From the method utilized by Ismail and Jamil [73], it can be seen that exhaust fan arrangements and the number of exhaust fans have a huge potential to reduce the wall temperature that contributes towards occupant comfort in the building. Meanwhile, to achieve optimum efficiency an air ducting system in a HAVC system was designed by Misaran *et al.,* [74] based on different wye tee duct configurations. Misaran *et al.,* [74] look into multiple wye tee duct configurations by altering different protrusion height at the top of the wyee-tee duct thus to study its effects on resistance coefficient. Figure 5 shows the resistance coefficient values at different protrusion height. From the simulation in it shows that vane protrusion height H=0.05 m gave the best efficiency improvement of 22.29%. Similar to study done by Ruiz *et al.,* [60], Kampelis *et al.,* [78] validated a building energy model with aid of genetic algorithm. The aim of the study was to optimize the trade-off between the minimum daily cost of energy and thermal comfort. From the result the overall cost of energy reductions in the range between 9.9% and 25%, whereas the reduction in HVAC energy consumption varied between 10.4% and 25%.

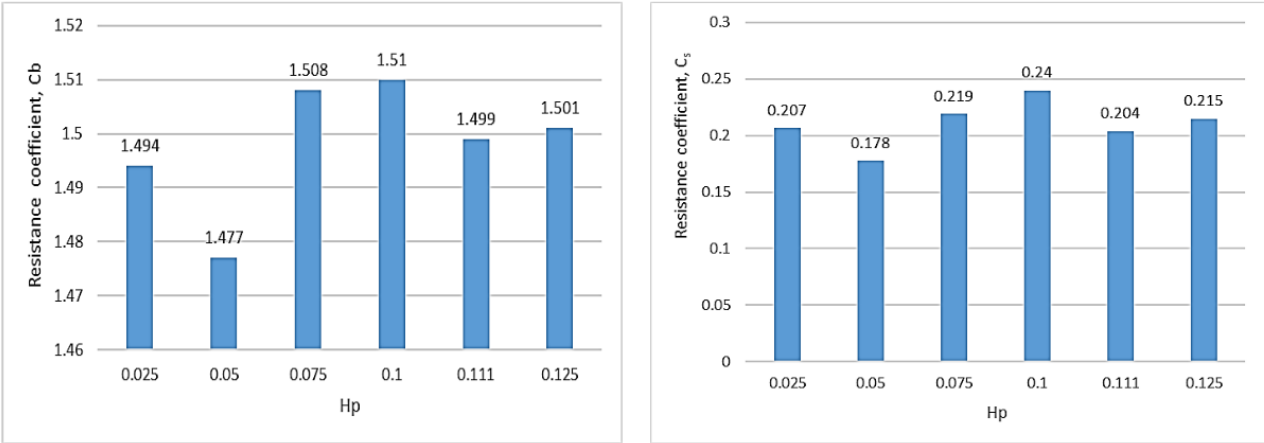

Fig. 5. Height of protrusion vs Resistance coefficient [74]

Ismail *et al.,* [75] investigated building materials effects on the rate of indoors thermal comfort on existing high rise offices in Kuala Lumpur by using Kestrel weather tracker to measure the office interior involving level of wind chill, humidity and temperature. In the study by Ismail *et al.,* [75], readings were recorded during hot weather at temperature ranging from 30°C and above from noon till evening because during this period heat gain was to be known at the highest peak. From the results it clearly shows the temperature difference based on material selection and the design of facade outer layers plays an important role that effects the indoor environment that will affect the overall thermal comfort of the occupancies.

Azmi *et al.,* [77] conducted study on Phase Change Performance (PCM) in bricks for energy-efficient building application. In the study only organic PCM has been tested where the change in performance latent heat storage (LHS) is monitored. From the results design of the brick and selection of PCM is crucial in optimizing the LHS performance. PCM filled bricks have been proven to be able to provide heat modulation in energy-efficient buildings. Komatsu and Kimura [81] studied the Energy fault detection for small buildings based on peer comparison of estimated operating status by using building energy management system (BEMS). The parameters are defined as common operating status for the business type using the results of operating time estimation from multiple structures. If each estimated operating status is judged to be significantly larger than the average level for the building type, the system identifies it as an energy fault. From the result based on conducted case studies using an open BEMS dataset propose that the framework can detect failures in energy conservation caused by incorrect HVAC management. Similar to Azmi *et al.,* [77], Pandey *et al.,* [85] developed a co-simulation framework between the most popular BES tool which is EnergyPlus and CFD tool (Ansys Fluent) to model the PCM integrated built environment and compare its accuracy. From the result the proposed co-simulation has better likelihood accuracy than the BES tool for active use of PCM and passive use of PCM under forced convection. Similar to Bünning *et al.,* [72] and Lu *et al.,* [84], Bhattacharya *et al.,* [86], developed an optimal configuration and size of the chillers plant thus to minimize the overall energy consumption by using Bayesian optimization (BO). The simulation is based on BO to efficiently explore the design space and jointly optimize both the system and control-design parameters of a commercial building chiller plant. Based the result the new purposed configuration manages to reduce total annual energy consumption by 33% and 56% in reduction of in peak power demand.

3. Conclusions

This review paper provides an assessment on optimization studies linked to buildings' HVAC systems to determine an overall energy saving operation while enhancing occupants' thermal comfort. The optimization studies considered three different sections; namely HVAC operational parameters optimization, HVAC control system optimization and building design optimization. The HVAC system, operational variable optimization is performed to obtain the optimum operational parameter settings that are able to minimize the overall energy utilization while ensuring the comfort of the building's occupancy. In this section, the common energy consumption model and the prescient HVAC system models were the two proposed ways to minimize the energy utilization.

The use of the non-common HVAC system configurations was able to deliver better energy utilization reduction compared to the common method. Moreover, the PMV approach has been pin point to have a better output than that of the IAQ with approximate of 47% reduction in the energy utilization and estimated annual energy reduction of 2,769 kg/year. Next, the controller optimization is established for the reason of improving the overall response rate of the HVAC system outputs in order to prevent nonessential energy waste, while building model optimization involves in identifying a practical energy building designs in terms of the type of HVAC system in the building, construction parameters, building location and thermal design used. Moreover, from the review among the different controller optimizations approaches discussed in multiple papers, the fuzzy logic tuning optimization gives the best performance outcome in minimizing overall energy utilization. In conclusion, the hybrid blend of a prescient HVAC system approach with a fuzzy logic controller would provide the best optimization outcome with the current available technology.

The paper shows that the optimization effort of minimizing overall energy utilization of HVAC system not only can be achieved on the operation of the HVAC system itself, but also dependent on the building outline and the structure's thermal dynamics. Operational variables and controller optimization methods are effective and can be executed on current buildings but it needs the building's thermal properties and HVAC system dynamic model, which can be complex to be redesign. Nonetheless, the building design optimization method is more direct and can be included during the early stages of the building design but cannot be implemented if buildings have been constructed without incurring high renovation costs. It is also significantly to notice that the common methods of optimizing HVAC operation are been utilized in many works with advance development in order to increase the effectiveness of energy saving.

The operational variables and controller optimization approaches can provide approximately 30% of reduction on electricity consumption while conserving thermal comfort of occupancies compared to normal non-optimized HVAC operations. Meanwhile, the building design variables optimization method alone can accommodate approximately up to 62% of the electricity consumption minimization compared to structures that are not designed for efficient energy utilization.

In conclusions, various optimization approaches have been utilized in achieving optimal HVAC energy utilization and thermal comfort levels occupancies in buildings. Pre planning of building design parameters and constrains before the building construction itself will have a significant impact on the usage of overall HVAC electricity, and when it is collaborated with optimization methods for the HVAC system used in the structure via its operational variables and overall control system which can be accomplished based on the building thermal dynamics and properties for further saving of electrical energy.

References

[1] Haniff, Mohamad Fadzli, Hazlina Selamat, Rubiyah Yusof, Salinda Buyamin, and Fatimah Sham Ismail. "Review of HVAC scheduling techniques for buildings towards energy-efficient and cost-effective operations." *Renewable and Sustainable Energy Reviews* 27 (2013): 94-103. https://doi.org/10.1016/j.rser.2013.06.041

[2] Rahman, Md Mustafizur, M. G. Rasul, and Mohammad Masud Kamal Khan. "Energy conservation measures in an institutional building in sub-tropical climate in Australia." *Applied Energy* 87, no. 10 (2010): 2994-3004. https://doi.org/10.1016/j.apenergy.2010.04.005

[3] Kusiak, Andrew, Guanglin Xu, and Zijun Zhang. "Minimization of energy consumption in HVAC systems with data-driven models and an interior-point method." *Energy Conversion and Management* 85 (2014): 146-153. https://doi.org/10.1016/j.enconman.2014.05.053

[4] Lam, Joseph C., Kevin KW Wan, and Liu Yang. "Sensitivity analysis and energy conservation measures implications." *Energy Conversion and Management* 49, no. 11 (2008): 3170-3177. https://doi.org/10.1016/j.enconman.2008.05.022

[5] Zapater, Marina, Patricia Arroba, José Luis Ayala Rodrigo, Katzalin Olcoz Herrero, and José Manuel Moya Fernandez. "Energy-Aware policies in ubiquitous computing facilities." *Cloud Computing with E-science Applications* 2015 (2015): 267-284. https://doi.org/10.1201/b18021-13

[6] Alves, Octávio, Eliseu Monteiro, Paulo Brito, and Pedro Romano. "Measurement and classification of energy efficiency in HVAC systems." *Energy and Buildings* 130 (2016): 408-419. https://doi.org/10.1016/j.enbuild.2016.08.070

[7] Alibabaei, Nima, Alan S. Fung, Kaamran Raahemifar, and Arash Moghimi. "Effects of intelligent strategy planning models on residential HVAC system energy demand and cost during the heating and cooling seasons." *Applied Energy* 185 (2017): 29-43. https://doi.org/10.1016/j.apenergy.2016.10.062

[8] Oropeza-Perez, Ivan. "Comparative economic assessment of the energy performance of air-conditioning within the Mexican residential sector." *Energy Reports* 2 (2016): 147-154. https://doi.org/10.1016/j.egyr.2016.06.002

[9] Fanger, P. O. *Thermal comfort: analysis and applications in environmental engineering*. McGraw-Hill, New York, 1972.

[10] Bradshaw, Vaughn. *The building environment: Active and passive control systems*. John Wiley & Sons, 2010.

[11] Ismail, Ahmad Rasdan, Shashi Kumar SA Karagaratnan, Rozli Zulkifli, Baba Md Deros, and Mohd Nizam Abdul Rahman. "A review on thermal comfort assessment in Malaysian industries." *Jurnal Teknologi* 59, no. 2 (2012): 7-11. https://doi.org/10.11113/jt.v59.1597

[12] Kamaruzzaman, Khadijah, and A. S. B. M. Tazilan. "Thermal comfort assessment of a classroom in tropical climate conditions." *Recent Advances in Energy, Environment and Development* (2013): 88-91.

[13] Azizpour, F., S. Moghimi, S. Mat, C. Lim, and K. Sopian. "Objective and subjective assessment of thermal comfort in hot-humid region." In *Proceedings of 5th WSEAS international conferences on Recent Researches in Chemistry, Biology, Environment and Culture*, Montreux, Switzerland, pp. 207-210. 2011.

[14] ASHRAE. *Indoor Air Quality Guide*. American Society of Heating, Refrigerating, and Air- Conditioning Engineers, Inc. (2009).

[15] ASHRAE. *Ventilation for Acceptable Indoor Air Quality*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (2009).

[16] Lu, Lu, Wenjian Cai, Lihua Xie, Shujiang Li, and Yeng Chai Soh. "HVAC system optimization-in-building section." *Energy and Buildings* 37, no. 1 (2005): 11-22. https://doi.org/10.1016/j.enbuild.2003.12.007

[17] Lu, Siliang, C. E. Hameen, and Azizan Aziz. "Dynamic hvac operations with real-time vision-based occupant recognition system." In *2018 ASHRAE Winter Conference*, Chicago. 2018.

[18] Kusiak, Andrew, Mingyang Li, and Fan Tang. "Modeling and optimization of HVAC energy consumption." *Applied Energy* 87, no. 10 (2010): 3092-3102. https://doi.org/10.1016/j.apenergy.2010.04.008

[19] Wang, Junqi, Gongsheng Huang, Yongjun Sun, and Xiaoping Liu. "Event-driven optimization of complex HVAC systems." *Energy and Buildings* 133 (2016): 79-87. https://doi.org/10.1016/j.enbuild.2016.09.049

[20] Zheng, G. R., and M. Zaheer-Uddin. "Optimization of thermal processes in a variable air volume HVAC system." *Energy* 21, no. 5 (1996): 407-420. https://doi.org/10.1016/0360-5442(96)00114-4

[21] Du, Zhimin, Xinqiao Jin, and Bo Fan. "Evaluation of operation and control in HVAC (heating, ventilation and air conditioning) system using exergy analysis method." *Energy* 89 (2015): 372-381. https://doi.org/10.1016/j.energy.2015.05.119

[22] Du, Zhimin, Xinqiao Jin, Xing Fang, and Bo Fan. "A dual-benchmark based energy analysis method to evaluate control strategies for building HVAC systems." *Applied Energy* 183 (2016): 700-714. https://doi.org/10.1016/j.apenergy.2016.09.019

[23] He, Xiaofei, Zijun Zhang, and Andrew Kusiak. "Performance optimization of HVAC systems with computational intelligence algorithms." *Energy and Buildings* 81 (2014): 371-380. https://doi.org/10.1016/j.enbuild.2014.06.021
[24] Porowski, Mieczysław. "The optimization method of HVAC system from a holistic perspective according to energy criterion." *Energy Conversion and Management* 181 (2019): 621-644. https://doi.org/10.1016/j.enconman.2018.11.069
[25] Wei, Xiupeng, Andrew Kusiak, Mingyang Li, Fan Tang, and Yaohui Zeng. "Multi-objective optimization of the HVAC (heating, ventilation, and air conditioning) system performance." *Energy* 83 (2015): 294-306. https://doi.org/10.1016/j.energy.2015.02.024
[26] Fiorentini, Massimo, Josh Wall, Zhenjun Ma, Julio H. Braslavsky, and Paul Cooper. "Hybrid model predictive control of a residential HVAC system with on-site thermal energy generation and storage." *Applied Energy* 187 (2017): 465-479. https://doi.org/10.1016/j.apenergy.2016.11.041
[27] Ruano, Antonio, S. Pesteh, S. Silva, H. Duarte, G. Mestre, P. M. Ferreira, H. Khosravani, and R. Horta. "PVM-based intelligent predictive control of HVAC systems." *IFAC-PapersOnLine* 49, no. 5 (2016): 371-376. https://doi.org/10.1016/j.ifacol.2016.07.141
[28] Dobbs, Justin R., and Brandon M. Hencey. "Model predictive HVAC control with online occupancy model." *Energy and Buildings* 82 (2014): 675-684. https://doi.org/10.1016/j.enbuild.2014.07.051
[29] Risbeck, Michael J., Christos T. Maravelias, and James B. Rawlings. "Real-time mixed-integer optimization for improved economic performance in HVAC systems." In *Computer Aided Chemical Engineering*, vol. 44, pp. 33-42. Elsevier, 2018. https://doi.org/10.1016/B978-0-444-64241-7.50004-5
[30] He, Xiaofei, Zijun Zhang, and Andrew Kusiak. "Performance optimization of HVAC systems with computational intelligence algorithms." *Energy and Buildings* 81 (2014): 371-380. https://doi.org/10.1016/j.enbuild.2014.06.021
[31] Zeng, Yaohui, Zijun Zhang, and Andrew Kusiak. "Predictive modeling and optimization of a multi-zone HVAC system with data mining and firefly algorithms." *Energy* 86 (2015): 393-402. https://doi.org/10.1016/j.energy.2015.04.045
[32] Kusiak, Andrew, Fan Tang, and Guanglin Xu. "Multi-objective optimization of HVAC system with an evolutionary computation algorithm." *Energy* 36, no. 5 (2011): 2440-2449. https://doi.org/10.1016/j.energy.2011.01.030
[33] Kusiak, Andrew, Guanglin Xu, and Fan Tang. "Optimization of an HVAC system with a strength multi-objective particle-swarm algorithm." *Energy* 36, no. 10 (2011): 5935-5943. https://doi.org/10.1016/j.energy.2011.08.024
[34] Kusiak, Andrew, and Guanglin Xu. "Modeling and optimization of HVAC systems using a dynamic neural network." *Energy* 42, no. 1 (2012): 241-250. https://doi.org/10.1016/j.energy.2012.03.063
[35] Cigler, Jiří, Samuel Privara, Zdeněk Váňa, Eva Žáčeková, and Lukáš Ferkl. "On predicted mean vote optimization in building climate control." In *2012 20th Mediterranean Conference on Control & Automation (MED)*, pp. 1518-1523. IEEE, 2012. https://doi.org/10.1109/MED.2012.6265854
[36] Cigler, Jiří, Samuel Privara, Zdeněk Váňa, Dana Komarkova, and Michael Šebek. "Optimization of predicted mean vote thermal comfort index within model predictive control framework." In *2012 IEEE 51st IEEE Conference on Decision and Control (CDC)*, pp. 3056-3061. IEEE, 2012. https://doi.org/10.1109/CDC.2012.6427051
[37] Reddy, T. Agami, S. Katipamula, J. K. Kissock, and D. E. Claridge. "The functional basis of steady-state tliermal energy use in air-side hvac equipment." *Journal of Solar Energy Engineering, Transactions of the ASME* 117, no. 1 (1995): 31-39. https://doi.org/10.1115/1.2847720
[38] Golshan, Milad, Hester Thoen, and Wim Zeiler. "Dutch sustainable schools towards energy positive." *Journal of Building Engineering* 19 (2018): 161-171. https://doi.org/10.1016/j.jobe.2018.05.002
[39] Haniff, Mohamad Fadzli, Hazlina Selamat, Nuraqilla Khamis, and Ahmad Jais Alimin. "Optimized scheduling for an air-conditioning system based on indoor thermal comfort using the multi-objective improved global particle swarm optimization." *Energy Efficiency* 12, no. 5 (2019): 1183-1201. https://doi.org/10.1007/s12053-018-9734-5
[40] Mei, Jun, Xiaohua Xia, and Mengjie Song. "An autonomous hierarchical control for improving indoor comfort and energy efficiency of a direct expansion air conditioning system." *Applied Energy* 221 (2018): 450-463. https://doi.org/10.1016/j.apenergy.2018.03.162
[41] Lee, Jing-Nang, Tsung-Min Lin, and Chien-Chih Chen. "Modeling validation and control analysis for controlled temperature and humidity of air conditioning system." *The Scientific World Journal* 2014 (2014). https://doi.org/10.1155/2014/903032
[42] Tashtoush, Bourhan, Mohammed Molhim, and Mohammed Al-Rousan. "Dynamic model of an HVAC system for control analysis." *Energy* 30, no. 10 (2005): 1729-1745. https://doi.org/10.1016/j.energy.2004.10.004
[43] NSW Government. *I Am Your Optimisation Guide: Heating, Ventilation and Air-Conditioning System*. Office of Environment and Heritage, 2015.
[44] Aswani, Anil, Neal Master, Jay Taneja, David Culler, and Claire Tomlin. "Reducing transient and steady state electricity consumption in HVAC using learning-based model-predictive control." *Proceedings of the IEEE* 100, no. 1 (2011): 240-253. https://doi.org/10.1109/JPROC.2011.2161242

[45] Asad, Hussain Syed, Richard Kwok Kit Yuen, and Gongsheng Huang. "Multiplexed real-time optimization of HVAC systems with enhanced control stability." *Applied Energy* 187 (2017): 640-651. https://doi.org/10.1016/j.apenergy.2016.11.081
[46] Asad, Hussain Syed, Richard Kwok Kit Yuen, and Gongsheng Huang. "Degree of freedom based set-point reset scheme for HVAC real-time optimization." *Energy and Buildings* 128 (2016): 349-359. https://doi.org/10.1016/j.enbuild.2016.07.013
[47] Hussain, Sajid, Hossam A. Gabbar, Daniel Bondarenko, Farayi Musharavati, and Shaligram Pokharel. "Comfort-based fuzzy control optimization for energy conservation in HVAC systems." *Control Engineering Practice* 32 (2014): 172-182. https://doi.org/10.1016/j.conengprac.2014.08.007
[48] Homod, Raad Z., Khairul Salleh Mohamed Sahari, Haider AF Almurib, and Farrukh Hafiz Nagi. "Gradient auto-tuned Takagi-Sugeno Fuzzy Forward control of a HVAC system using predicted mean vote index." *Energy and Buildings* 49 (2012): 254-267. https://doi.org/10.1016/j.enbuild.2012.02.013
[49] Attaran, Seyed Mohammad, Rubiyah Yusof, and Hazlina Selamat. "A novel optimization algorithm based on epsilon constraint-RBF neural network for tuning PID controller in decoupled HVAC system." *Applied Thermal Engineering* 99 (2016): 613-624. https://doi.org/10.1016/j.applthermaleng.2016.01.025
[50] Wemhoff, A. P. "Calibration of HVAC equipment PID coefficients for energy conservation." *Energy and Buildings* 45 (2012): 60-66. https://doi.org/10.1016/j.enbuild.2011.10.021
[51] Reynoso-Meza, Gilberto, Xavier Blasco, Javier Sanchis, and Miguel Martínez. "Controller tuning using evolutionary multi-objective optimisation: current trends and applications." *Control Engineering Practice* 28 (2014): 58-73. https://doi.org/10.1016/j.conengprac.2014.03.003
[52] Zajic, I., T. Larkowski, K. J. Burnham, and D. Hill. "Control analysis and tuning of an industrial temperature control system." *IFAC Proceedings Volumes* 45, no. 3 (2012): 679-684. https://doi.org/10.3182/20120328-3-IT-3014.00115
[53] Soyguder, Servet, Mehmet Karakose, and Hasan Alli. "Design and simulation of self-tuning PID-type fuzzy adaptive control for an expert HVAC system." *Expert Systems with Applications* 36, no. 3 (2009): 4566-4573. https://doi.org/10.1016/j.eswa.2008.05.031
[54] Moradi, Hamed, Hassan Setayesh, and Aria Alasty. "PID-Fuzzy control of air handling units in the presence of uncertainty." *International Journal of Thermal Sciences* 109 (2016): 123-135. https://doi.org/10.1016/j.ijthermalsci.2016.05.024
[55] Homod, Raad Z. "Analysis and optimization of HVAC control systems based on energy and performance considerations for smart buildings." *Renewable Energy* 126 (2018): 49-64. https://doi.org/10.1016/j.renene.2018.03.022
[56] Attaran, Seyed Mohammad, Rubiyah Yusof, and Hazlina Selamat. "A novel optimization algorithm based on epsilon constraint-RBF neural network for tuning PID controller in decoupled HVAC system." *Applied Thermal Engineering* 99 (2016): 613-624. https://doi.org/10.1016/j.applthermaleng.2016.01.025
[57] Guo, Chengyi, Qing Song, and Wenjian Cai. "A neural network assisted cascade control system for air handling unit." *IEEE Transactions on Industrial Electronics* 54, no. 1 (2007): 620-628. https://doi.org/10.1109/TIE.2006.888809
[58] Wei, Liu, and Zhou Junmin. "Particle swarm optimization PID neural network control method in the main steam temperature control system." In *2012 International Conference on Computer Science and Electronics Engineering*, vol. 2, pp. 137-140. IEEE, 2012. https://doi.org/10.1109/ICCSEE.2012.289
[59] Katić, Katarina, Rongling Li, Jacob Verhaart, and Wim Zeiler. "Neural network based predictive control of personalized heating systems." *Energy and Buildings* 174 (2018): 199-213. https://doi.org/10.1016/j.enbuild.2018.06.033
[60] Ruiz, P. Aparicio, FJ Sánchez De La Flor, JL Molina Felix, J. Salmerón Lissén, and J. Guadix Martín. "Applying the HVAC systems in an integrated optimization method for residential building's design. A case study in Spain." *Energy and Buildings* 119 (2016): 74-84. https://doi.org/10.1016/j.enbuild.2016.03.023
[61] Kerdan, Ivan Garcia, Rokia Raslan, and Paul Ruyssevelt. "An exergy-based multi-objective optimisation model for energy retrofit strategies in non-domestic buildings." *Energy* 117 (2016): 506-522. https://doi.org/10.1016/j.energy.2016.06.041
[62] Wright, Jonathan, and Ali Alajmi. "Efficient Genetic Algorithm sets for optimizing constrained building design problem." *International Journal of Sustainable Built Environment* 5, no. 1 (2016): 123-131. https://doi.org/10.1016/j.ijsbe.2016.04.001
[63] Wetter, Michael. "Design optimization with GenOpt." *Building Energy Simulation User News* 21 (2000): 19-28.
[64] Lai, Kun, Wen Wang, and Harry Giles. "Performance analysis of an energy efficient building prototype by using TRNSYS." *International High Performance Buildings Conference* (2014).
[65] Arcangeli, Greg. *Advanced tools for building simulation: Energy and airflow*. Texas, US (2008).

[66] Shi, Xing, Zhichao Tian, Wenqiang Chen, Binghui Si, and Xing Jin. "A review on building energy efficient design optimization rom the perspective of architects." *Renewable and Sustainable Energy Reviews* 65 (2016): 872-884. https://doi.org/10.1016/j.rser.2016.07.050
[67] Yigit, Sadik, and Beliz Ozorhon. "A simulation-based optimization method for designing energy efficient buildings." *Energy and Buildings* 178 (2018): 216-227. https://doi.org/10.1016/j.enbuild.2018.08.045
[68] Gou, Shaoqing, Vahid M. Nik, Jean-Louis Scartezzini, Qun Zhao, and Zhengrong Li. "Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand." *Energy and Buildings* 169 (2018): 484-506. https://doi.org/10.1016/j.enbuild.2017.09.095
[69] Ruiz, Pablo Aparicio, José Guadix Martín, José Manuel Salmerón Lissén, and Francisco José Sánchez de la Flor. "An integrated optimisation method for residential building design: A case study in Spain." *Energy and Buildings* 80 (2014): 158-168. https://doi.org/10.1016/j.enbuild.2014.05.020
[70] Kerdan, Iván García, Rokia Raslan, Paul Ruyssevelt, and David Morillón Gálvez. "An exergoeconomic-based parametric study to examine the effects of active and passive energy retrofit strategies for buildings." *Energy and Buildings* 133 (2016): 155-171. https://doi.org/10.1016/j.enbuild.2016.09.029
[71] Gärtner, Jasmin Anika, Francesco Massa Gray, and Thomas Auer. "Assessment of the impact of HVAC system configuration and control zoning on thermal comfort and energy efficiency in flexible office spaces." *Energy and Buildings* 212 (2020): 109785. https://doi.org/10.1016/j.enbuild.2020.109785
[72] Bünning, Felix, Benjamin Huber, Philipp Heer, Ahmed Aboudonia, and John Lygeros. "Experimental demonstration of data predictive control for energy optimization and thermal comfort in buildings." *Energy and Buildings* 211 (2020): 109792. https://doi.org/10.1016/j.enbuild.2020.109792
[73] Ismail, Mohd Azmi, and Mohd Sabri Che Jamil. "CFD HVAC Study of Modular Badminton Hall." *CFD Letters* 12, no. 7 (2020): 90-99. https://doi.org/10.37934/cfdl.12.7.9099
[74] Misaran, Mohd Suffian, Cheng Fang Sing, and Mohd Adzrie. "Study of wyee-tee duck design at various protrusion and guide vane location using CFD." *CFD Letters* 11, no. 11 (2019): 39-47.
[75] Ismail, Alice Sabrina, Hazrina Haja Bava Mohidin, Aminatunzuhariah Megat Abdullah, and Mohd Nazim Ahyaruddina. "The Effectiveness of Envelope Design in High Rise Office Building using Exterior Wall Cladding as Green Technology Solutions in Malaysia's Urban Context." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 16, no. 1 (2019): 1-9.
[76] Johnson, Zwalnan Selfa, Abakar Yousif Abdalla, Shanmugam Anandan, Chan Andy Tak-Yee, and Su Yuehong. "A Numerical Evaluation of the Effect of Building Thermal Load on the Overall Performance Characteristic of a Grid-Coupled PV/T Energy System." *Journal of Advanced Research in Numerical Heat Transfer* 4, no. 1 (2021): 32-43.
[77] Azmi, Mohd Irwan Mohd, Nor Azwadi Che Sidik, Yutaka Asako, Wan Mohd Arif Aziz Japar, Nura Muaz Muhammad, and Nadlene Razali. "Numerical Studies on PCM Phase Change Performance in Bricks for Energy-Efficient Building Application-A Review." *Journal of Advanced Research in Numerical Heat Transfer* 1, no. 1 (2020): 13-21.
[78] Kampelis, Nikolaos, Nikolaos Sifakis, Dionysia Kolokotsa, Konstantinos Gobakis, Konstantinos Kalaitzakis, Daniela Isidori, and Cristina Cristalli. "HVAC Optimization genetic algorithm for industrial near-zero-energy building demand response." *Energies* 12, no. 11 (2019): 2177. https://doi.org/10.3390/en12112177
[79] Dong, Zhang, Qu Boyi, Liu Pengfei, and An Zhoujian. "Comprehensive Evaluation and Optimization of Rural Space Heating Modes in Cold Areas Based on PMV-PPD." *Energy and Buildings* (2021): 111120. https://doi.org/10.1016/j.enbuild.2021.111120
[80] Tükel, Mert, Ekrem Tunçbilek, Anna Komerska, Gülşen Aydın Keskin, and Müslüm Arıcı. "Reclassification of climatic zones for building thermal regulations based on thermoeconomic analysis: A case study of Turkey." *Energy and Buildings* 246 (2021): 111121. https://doi.org/10.1016/j.enbuild.2021.111121
[81] Komatsu, Hidenori, and Osamu Kimura. "Energy fault detection for small buildings based on peer comparison of estimated operating status." *Energy and Buildings* 246 (2021): 111110. https://doi.org/10.1016/j.enbuild.2021.111110
[82] Porowski, Mieczysław. "Energy optimization of HVAC system from a holistic perspective: Operating theater application." *Energy Conversion and Management* 182 (2019): 461-496. https://doi.org/10.1016/j.enconman.2018.12.003
[83] Turhan, Cihan, Silvio Simani, and Gulden Gokcen Akkurt. "Development of a personalized thermal comfort driven controller for HVAC systems." *Energy* 237 (2021): 121568. https://doi.org/10.1016/j.energy.2021.121568
[84] Lu, Qiugang, Leonardo D. González, Ranjeet Kumar, and Victor M. Zavala. "Bayesian optimization with reference models: A case study in MPC for HVAC central plants." *Computers & Chemical Engineering* 154 (2021): 107491. https://doi.org/10.1016/j.compchemeng.2021.107491
[85] Pandey, Brijesh, Rangan Banerjee, and Atul Sharma. "Coupled EnergyPlus and CFD analysis of PCM for thermal management of buildings." *Energy and Buildings* 231 (2021): 110598. https://doi.org/10.1016/j.enbuild.2020.110598

[86] Bhattacharya, Arnab, Soumya Vasisht, Veronica Adetola, Sen Huang, Himanshu Sharma, and Draguna L. Vrabie. "Control co-design of commercial building chiller plant using Bayesian optimization." *Energy and Buildings* 246 (2021): 111077. https://doi.org/10.1016/j.enbuild.2021.111077
[87] Jia, Lizhi, Junjie Liu, and Shen Wei. "Optimal chiller loading in dual-temperature chilled water plants for energy saving." *Energy and Buildings* 252 (2021): 111425. https://doi.org/10.1016/j.enbuild.2021.111425