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Dynamic optimization of chilled water pump operation to reduce HVAC energy consumption

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Corresponding Author:	Nasruddin N. University of Indonesia Depok, West Java Indonesia
First Author:	Timotius Kelvin Wijaya
Order of Authors:	Timotius Kelvin Wijaya
	Sholahudin Sholahudin
	Muhammad Idrus Alhamid
	Kiyoshi Saito
	N. Nasruddin
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Suggested Reviewers:	Bidyut Baran Saha Kyushu University: Kyushu Daigaku bidyutb@cm.kyushu-u.ac.jp He is an expert in Thermal System Design.
	Muhammad Aziz University of Tokyo: Tokyo Daigaku maziz@iis.u-tokyo.ac.jp He is an expert in Thermal Design.
	T.M. Indra Mahlia University of Technology Sydney TMIndra.Mahlia@uts.edu.au He is an expert in Energy Systems.
Opposed Reviewers:	

Depok, 7th April 2021

J. de Brito, PhD,
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Journal of Building Engineering

Dear Editor,

Please find enclosed our manuscript entitled "Dynamic optimization of chilled water pump operation to reduce HVAC energy consumption" which we request you to consider for publication in *Journal of Building Engineering*.

Energy demand in Indonesia has dramatically increased up to 50% in 2020 and the household sectors spent almost increased more than 40% of the final energy consumption from 2013-2018. Around 30–50% of total electricity consumption in buildings is related to air conditioning (AC) systems operation. Control developments over heating ventilating and air conditioning (HVAC) systems are mostly focused on compressor operation as it can be the heart of system and consume the largest portion of energy. However, the operation on chilled water pump also has large contribution for energy saving in large HVAC system.

Currently, the chilled water pump operations of HVAC system are mostly run by ON/OFF control with single speed. However, if optimal operation strategy is introduced, it also has significant contribution on building energy use reduction. This paper presents an optimal control strategy for chilled water pump operation by integrating Neural network and Genetic algorithm method for dynamic optimization of HVAC system. The performance of developed controller is analyzed by investigating the thermal comfort and energy consumption of building.

This manuscript has not been published elsewhere and is not under consideration by another journal. We have approved the manuscript and agree with submission to *Journal of Building Engineering*. There are no conflicts of interest to declare. We believe that the findings of this study are relevant to the scope of your journal and will be of interest to its readership.

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We suggest the following recommended reviewers:

1. Prof. Bidyut Baran Saha from Multiscale Science and Engineering for Energy and the Environment Thrust, National University Corporation Kyushu University (email: bidyutb@cm.kyushu-u.ac.jp)
2. Prof. M. Aziz from Department of Mechanical Engineering, The University of Tokyo (email:maziz@iis.u-tokyo.ac.jp)
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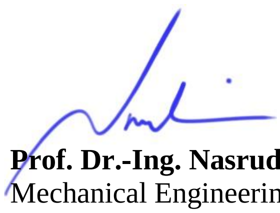

Prof. Dr.-Ing. Nasruddin
Mechanical Engineering Department
Universitas Indonesia
Kampus UI Depok 16424
West Java Indonesia
Phone No: +62-21-7270032
Fax No: +62-21-7270033
Email : nasruddin@eng.ui.ac.id

Dynamic optimization of chilled water pump operation to reduce HVAC energy consumption

Timotius Kelvin Wijaya[a], Sholahudin[b], M. Idrus Alhamid[a] , Kiyoshi Saito[c], N. Nasruddin[a,*]

[a]Department of Mechanical Engineering,
University of Indonesia, Depok 16424, Indonesia

[b]Waseda Research Institute for Science and Engineering,
Waseda University, 3-4-1 Shinjuku-ku, Tokyo 169-8555, Japan

[c]Department of Applied Mechanics and Aerospace Engineering,
Waseda University, Tokyo, 169-8555, Japan

*Corresponding author:
E-mail : nasruddin@eng.ui.ac.id
Tel/Fax : +6282122581717

Abstract

Energy consumption in building has been increasing significantly due to higher demand on cooling system. It consumes a large share of total building energy usage. A proper operation control strategy for this system promises the large energy saving. This paper proposes the optimization of chilled water pump to improve the cooling system operation in a building. The method is developed by combining the artificial neural network and genetic algorithm. This study aims to develop a control method that can determine the optimal mass flow rate of chilled water to absorb the heat on cooling system during the operation. The building energy performances are modeled using Energy Plus software, while the control strategy is developed in MATLAB. Input output data sharing between MATLAB and EnergyPlus is performed by BCVTB (Building Controls Virtual Test). The dynamic optimization of chilled water flow is carried out continuously during real time operation. The developed control performance has been tested under various operating condition including variable outdoor temperature, sudden change of load condition, and different indoor temperature set point. The results show that the optimization of chilled water flow rate operation on large cooling system could reduce the energy consumption of chilled water pump as 51.11%.

Keywords: Optimization, Building performance, Energy efficiency, Air conditioning

Nomenclature

A	Surface area where the heat transfer takes place (m^2)
C_p	Air specific heat (kJ/kg.K)
$C_{p,w}$	Water specific heat (kJ/kg.K)
C_T	Sensible heat capacity multiplier
h	Heat transfer coefficient ($W/m^2.K$)
I_{DNR}	Direct normal radiation ($W/\ m^2$)
I_{DHR}	Diffuse horizontal radiation ($W/\ m^2$)
$\dot{m}$	Mass flow rate of air (kg/s)
$\dot{m}_{\mathrm{inf}}$	Mass flow rate of air infiltration (kg/s)
$\dot{m}_{sys}$	Mass flow rate in the system (kg/s)
$\dot{m}_{\mathrm{CHW}}$	Mass flow rate of chilled water (kg/s)
N_{sl}	Number of surfaces load
$N_{surfaces}$	Number of surfaces
PLR	Chiller part load ratio (-) defines the comparison between cooling load and chiller available cooling capacity
$\dot{Q}$	Convective internal loads (kW)
RH	Relative humidity (%)
$T_{cw,ls}$	Set point temperature of cold water leaving (°C)
$T_{cond,e}$	Temperature of the incoming condenser liquid (°C)
$T_{cw,l}$	Remaining cold water temperature (°C)
T_{DB}	Outdoor dry bulb temperature (°C)
T_r	Room temperature (°C)
T_s	Temperature of surface (°C)
T_{sup}	Air supply temperature (°C)
y_p	Predicted data by ANN
y_s	Simulated data by EnergyPlus
y_m	Measured data from actual building

Greek letters

ΔT_w	Water temperature difference (°C)
ρ_{air}	Air density (kg/m^3)

Subscripts

i	independent variable (i = 1, 2, 3, …)

1. Introduction

The increased population and social growth cause a crucial factor on higher energy usage. As the global energy generations are still dominated by fossil fuels, the large energy consumption leads the global greenhouse gas (GHG) emission increases rapidly [1]. Energy demand in Indonesia has dramatically increased up to 50% in 2020 [2]. The household sectors spent almost increased more than 40% of the final energy consumption from 2013-2018 [3]. The other statistics reports estimate that around 30–50% of total electricity consumption in buildings is related to air conditioning (AC) systems operation [4]. Thus, the improvement of building energy efficiency through cooling systems is required to reduce the energy demand globally and save the environment.

Vapor compression technology has been widely used for cooling system in most building applications. The improvements of this technology have been carried out in previous works focusing on system components including heat exchangers [5, 6], compressor [7], and expansion valve [8]. However, the significant improvement of this system available on the market is not appeared yet during the last decade [9]. The proper control strategy for the system operation offers the significant energy reduction as the systems work in most of the time.

Control developments over heating ventilating and air conditioning (HVAC) systems are mostly focused on compressor operation as it can be the heart of system and consume the largest portion of energy [7]. However, the operation on chilled water pump also has large contribution for energy saving in large HVAC system. Currently, the pump operations of HVAC system are mostly run by ON/OFF control with single speed [10, 11]. With considering variable speed pump technology, the chilled water flow can be optimized for better energy saving. The effect of chilled water pump operation on HVAC system performance has been investigated in literature [12]. The results found that the minimization of unnecessary transitional status of chilled water pump could save electricity by 2.72%. It indicates that the optimal control for chilled water pump is beneficial for reducing energy consumption on HVAC systems. Nonetheless the study related to the optimization of chilled water pump operation is very limited [13–15].

Yu et al. [13] have optimized the condensing temperature and variable chilled water flow to increase the coefficient of performance (COP) of air cooled centrifugal chillers. The results show that the annual electricity consumption reduction by 16.3– 21.0% could be achieved after implementing the optimization method. Ma et al. [14] developed optimal control strategies for variable speed pumps with different system configurations in complex building air conditioning systems to enhance their energy efficiencies. The pump operation is adjusted based on the differential pressure set-point optimizer that control pressure difference between the main chilled water supply and return pipelines. The results show that the pump energy consumption could be saved as 12– 32% by applying the optimization method. Gao et al. [15] proposed an energy efficient control strategy for secondary chilled water pump systems operation. The strategy employs the flow–limiting technique that ensures water flow of secondary loop not exceed that of the primary loop while still maintaining highest possible delivery of cooling capacity to terminals. The strategy includes a differential pressure set–point optimizer to determine the optimal set–point using proportional-integral derivative (PID) controller. The energy saving in the secondary chilled water pumps can be over 70% and 50% at starting and normal operating conditions, respectively.

The developed controls in previous works [14, 15] have successfully improved building energy efficiency using PID controller. However, a simple PID design with fixed control parameters is not sufficient to cover the wide range of operating conditions [16]. Moreover, the dynamic disturbances related to solar radiation, outdoor temperature, and occupant behavior such as sudden change in cooling load is not addressed yet. All these disturbances may frequently happen during building operation. Therefore, the optimal control that can capture all disturbances behavior is necessary to propose for HVAC system operation.

In optimal control development, system performance identification is an important task to characterize the relationship between controllable parameters, disturbances, and control objective. This effort can be conducted using first principle of fluid mechanics, heat transfer and thermodynamics theory. Unfortunately, it requires a lot of detail input parameters that may be difficult to obtain from actual system. Alternatively, artificial neural network (ANN) can be proposed as the solution for system characterization as it relies on few input and output parameters [17]. The accurate prediction results can be achieved by ANN model when the sufficient training data are available [17]. This method has been widely used in building application to predict heating loads of an apartment building [18]; hot water temperature of absorption chiller [19]; absorption chiller performance [20]; and thermal comfort and HVAC system performance simultaneously [21].

To address the aforementioned issues, this paper presents an optimal control strategy for chilled water pump operation that covers wide range of operating condition. The main motivation of this research is to improve the efficiency of chiller system operation installed in MAC building by properly controlling the chilled water pump operation, which is not implemented yet currently. The controller is developed by combining ANN method and genetic algorithms to optimize the chilled water pump operation with considering the disturbance from solar radiation, outdoor temperature, and occupant behavior. The proposed method can be applied to improve the efficiency of HVAC system performance.

2. Methodology

2.1 Research flow chart

The research presented in this paper consists of three main steps including building and HVAC system modeling, validation of simulation results, and optimal control development. The building energy performance is modeled using EnergyPlus software. This software is a flexible and reliable simulation program [22] that capable of customizing numerous simulation time step, HVAC system configurations, and output results. The reliability of building model is validated using actual data obtained from existing building. Then the optimal control is developed by integrating ANN and GA using MATLAB. The input and output data transfer between EnergyPlus and MATLAB can be linked by interface program of Building Controls Virtual Test Bed (BCVTB). It is a program developed based on Ptolemy II software environment that can connect the functions of one program to other programs for expanding the calculation task [23]. This technique gives the possibility to establish co-simulation between MATLAB and EnergyPlus for control development on complex HVAC system. The detail of research flowchart can be seen in Fig. 1

2.2 Building model

A campus building of Makara Art Center (MAC) located in University of Indonesia is selected as the object of present study. The actual and simulation model of building configuration are shown in Fig. 2. The building has area of 2400 m^2, ceiling (floor to floor height of 2-storey building) of 4- 5 m, and window to wall ratio (WWR) of 40% approximately. Moreover, the building is composed of 9 zones and mostly used as a virtual office building. The specification of building material and construction are provided in Table 2.

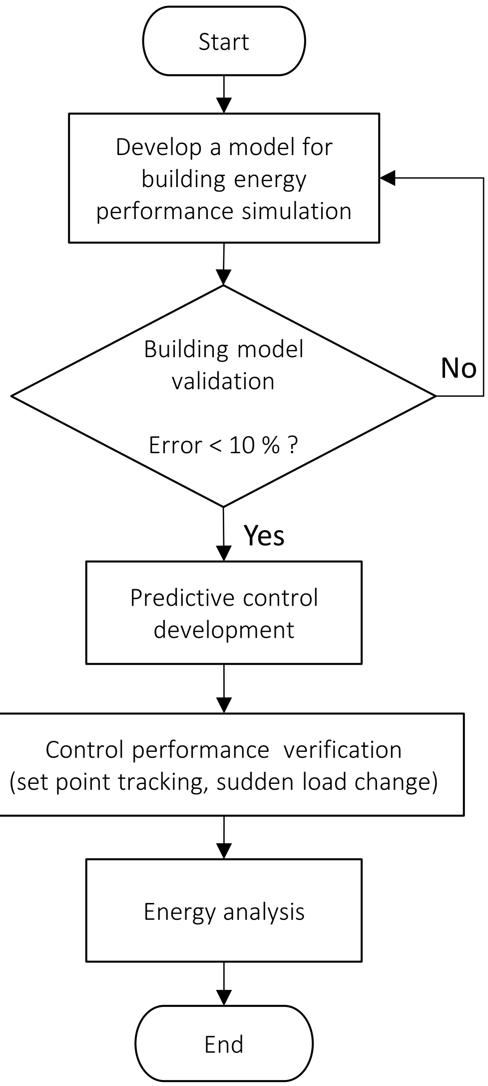

Fig. 1 Research flowchart

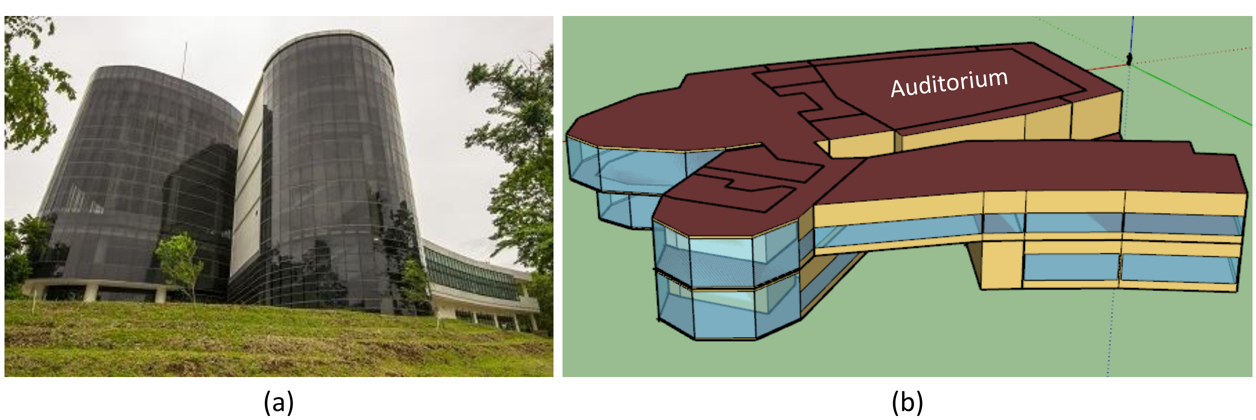

Fig. 2 (a) Actual MAC building; (b) Simulation building model

Table 1 Material characteristics of buildings for simulation

Construction	Materials	Conductivity [W/m.K]	Thermal resistance [m^2.K /W]
Interior ceiling	100 mm lightweight concrete	0.53	
	Ceiling air space resistance		0.18
	Acoustic tiles	0.06	
Interior Wall	19 mm gypsum board	0.16	
	Wall air space resistance		0.15
Interior Floor	Acoustic tiles	0.06	
	Air space resistance		0.18
	100 mm lightweight concrete	0.53	
	Carpet pad		0.1
Interior Partition	25 mm wood	0.15	
Interior Window	Clear 3 mm	0.9	
Exterior Window	Theoretical Glass	0.0133	
Interior Door	25 mm wood	0.15	
Roof	Roof Membrane	0.16	
	Roof Insulation	0.049	
	Metal Decking	45.006	
Exterior Wall	1 inch Stucco	0.69	
	8 inch concrete HW	0.17	
	Wall insulation	0.08	
	½ inch gypsum	0.16	

2.3 Overview of HVAC systems

The building features two different cooling systems, namely a large chiller and split duct system. The chiller is operated to maintain the temperature and humidity in auditorium only (see Fig. 2b). Meanwhile, the split duct systems serve nine other zones. Specification of chiller is presented in Table 2.

Table 2 Specification of HVAC system

HVAC and plant	Input design
Condenser type	Air cooled
Rated cooling capacity	196 kW
Chiller rated cop	4
Primary chilled water pump rated head	179352 Pa
Design pump power consumption	2468 W
Average water mass flow rate	9.66 g/s
Chilled water design set point	6.67°C
Condenser water design set point	29.4°C
Supply fan delta pressure	75 Pa
Supply fan total efficiency	75%
Supply fan motor efficiency	90%
Outdoor air flow rate per person	0.0094 m3/s

Both chiller and split duct systems are modeled in building simulation. During the operation, the chiller system follows part load ratio (PLR) based model. This model simulates the thermal performance of chiller and the power consumption of compressor. The chiller model uses user-provided performance information at the reference condition, that relies three performance curves (curve objects) for cooling capacity and efficiency, to determine chiller operation under off-reference conditions [24, 25].

The three performance curves are as follows:

- Temperature Curve Cooling Capacity Function ($ChillerCapFTemp$)
- Input Energy to Output Function Temperature Curve Ratio ($ChillerEIRFTemp$)
- Input Energy to Cooling Ratio Output Function of Part Load Ratio Curve ($ChillerEIRPLR$)

The Function of Temperature Curve Cooling Capacity with the chiller reciprocating model is written as follows [24]:

$$
\begin{aligned}
&ChillerCapFTemp \\
&\quad = 0{,}507883 + 0{,}145228\left(T_{cw,ls}\right) - 0{,}00625644\left(T_{cw,ls}\right)^2 \\
&\quad - 0{,}0011178\left(T_{cond,e}\right) - 0{,}0001296\left(T_{cond,e}\right)^2 \\
&\quad \pm 0{,}00028188\left(T_{cw,ls}\right)\left(T_{cond,e}\right)
\end{aligned} \tag{1}
$$

Energy Input to Output Function Temperature Curve Ratio with the chiller reciprocating model can be described as [24]:

$$
\begin{aligned}
&ChillerEIRFTemp \\
&\quad = 1{,}03076 - 0{,}103536\left(T_{cw,l}\right) + 0{,}00710208\left(T_{cw,l}\right)^2 \\
&\quad + 0{,}0093186\left(T_{cond,e}\right) + 0{,}00031752\left(T_{cond,e}\right)^2 \\
&\quad \pm 0{,}00104328\left(T_{cw,l}\right)\left(T_{cond,e}\right)
\end{aligned} \tag{2}
$$

Energy Input for Output Function Cooling Ratio of Part Load Ratio Curve with chiller reciprocating model is determined as follows [24]:

$$ChillerEIRPLR = 0{,}088065 + 1{,}137742(PLR) + 0{,}225806(PLR)^2 \tag{3}$$

The change of room temperature is affected by cooling load and cooling capacity provided by system as described in the following equation:

$$
\begin{aligned}
\rho_{air} C_p C_T \frac{dT_r}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_r) + \sum_{i=1}^{N_{rooms}} \dot{m}_i C_p (T_{ri} - T_r) \\
+ \dot{m}_{\inf} C_p (T_{DB} - T_r) + \dot{m}_{sys} C_p \left(T_{sup} - T_r\right)
\end{aligned} \tag{4}
$$

Meanwhile cooling capacity is determined as a function of chilled water mass flow rate as written in the Eq. (5).

$$\dot{Q}_{coil} = \dot{m}_{CHW}\, c_{p,w}\, \Delta T_w \tag{5}$$

2.4 Simulation condition

Building energy performance is simulated by adopting the weather data of Depok city obtained from Meteonorm [26] . All parameters affecting the thermal comfort and energy consumption are considered for simulation inputs. The amount of internal heat gains from occupant, lighting, and electricity equipment are set as the actual building performance presented in Table 3. The schedule of HVAC operation, occupancy, lighting, and equipment are provided in Fig. 3.

Table 3 Internal heat gain condition

Type (Auditorium zone)	Value
Occupancy	0.7739 m^2/person
Light	763.818 Watt
Equipment	50 Watt/m^2

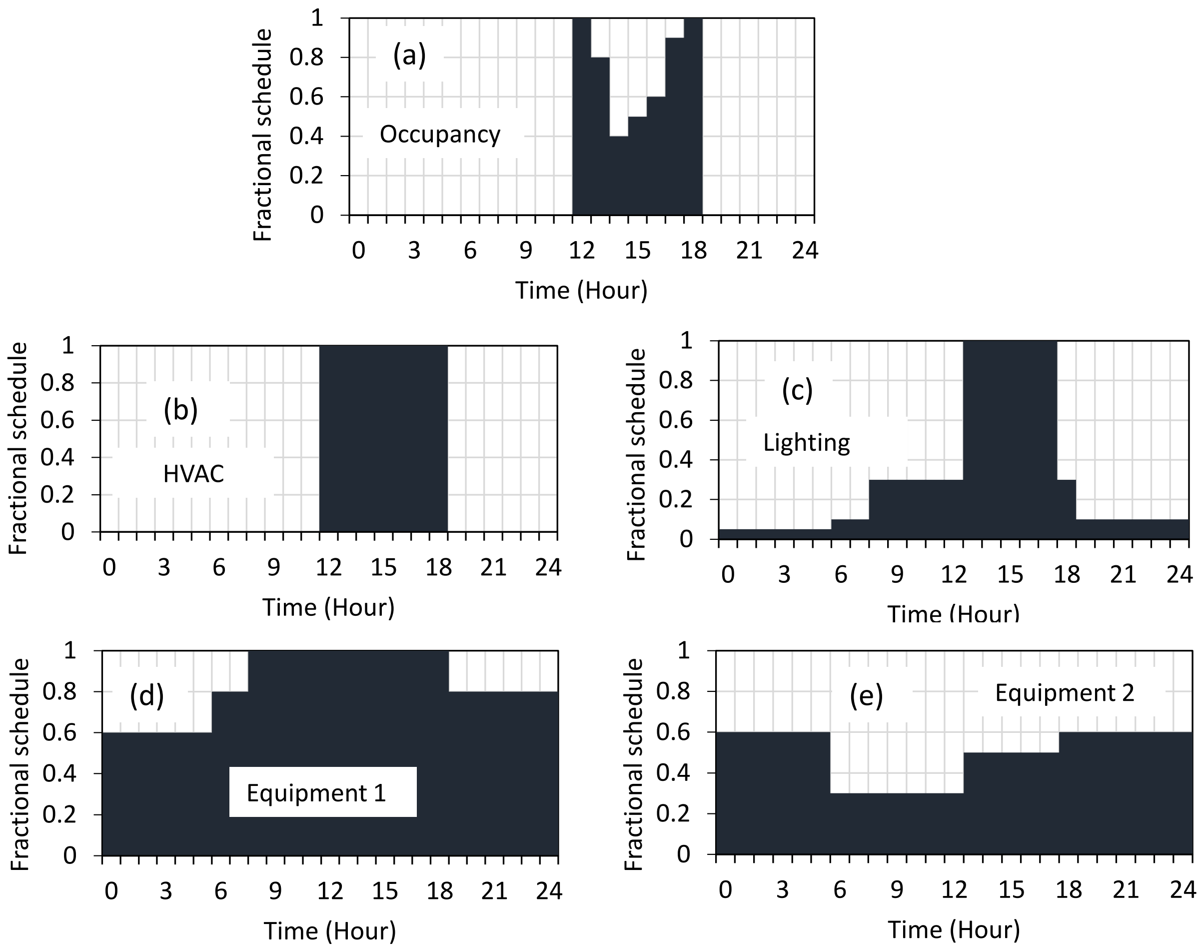

Fig. 3 Fraction of simulation input schedule (a) Occupancy, (b) HVAC, (c) Lighting, (d) Equipment 1, (e) Equipment 2

2.5 Simulation validation

To verify the reliability of building and HVAC system model, the simulation results obtained from EnergyPlus are validated with actual data measured in MAC building including air temperature, humidity, and total energy consumption. It aims to ensure that the building energy system model can represent the actual system to characterize the system in various conditions. The accuracy of each measurement sensors can be seen in Table 1.

Table 4 List of sensor accuracy

Sensor	Measured parameter	Accuracy
Temperature and humidity logger (Hioki LR5001)	Room temperature	±0.5 °C
	Room humidity	±5%
Power quality analyzer (PQA HIOKI PW3198)	Power	±0.2%

Comparison of the actual system performance and simulation results is presented in Fig. 4. It covers 3 parameters including room temperature, relative humidity and total building energy consumption when operates from 14.00 to 18.00 in unsteady condition. The accuracy of validation results is measured by mean absolute percentage error (MAPE) as written in Eq. (6).

According to Fig. 4, the results show good agreement between experiment and simulation data with the errors are below 10%. The deviation on validation results is caused by the difference between actual and simulation cooling load specifically on occupancy schedule. Moreover, the measurement technique for temperature and humidity also affects the accuracy. Room temperature and humidity are measured at two different locations, then the average of measured values is considered as the reference value. Furthermore, the deviation on total energy consumption can be due to the gap between actual and simulation input of electrical equipment schedule. By considering the acceptable error of validation results in temperature, humidity, and total energy consumption (below 10%), it confirms that the developed simulation model can be used to characterize the system behavior for further control development.

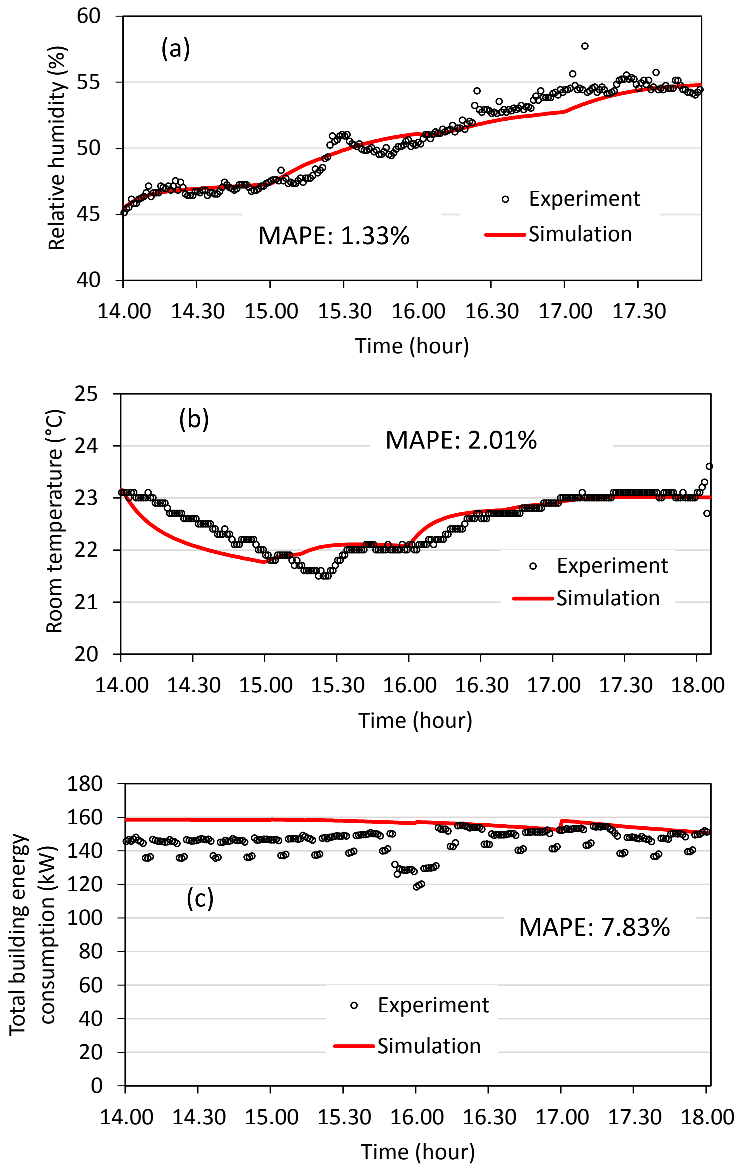

Fig. 4 Validation of simulation (a) Relative humidity (b) Room temperature (c) Total building energy consumption

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{y_s - y_m}{y_m}\right| x\ 100 \tag{6}$$

Where y_m and y_s shows measured and simulated values. The notation n is the amount of data.

3. Predictive control development

3.1 Co- simulation

To generate dynamic optimization in EnergyPlus environment a co-simulation between EnergyPlus and MATLAB is established through BCVTB program to apply the control method in related building model. Building with HVAC system model and HVAC schedule is implemented via EnergyPlus using ExternalInterface and ExternalInterface: Schedule Object for co-simulation. The co-simulation diagram can be seen in Fig. 5. The dynamic optimization model was implemented by using optimization toolbox function included in the MATLAB program. The dynamic optimization of chilled water flow is carried out continuously during real time operation while BCVTB keeps data exchange ongoing during the optimization process. Timestep was set to 1 min intervals for the accuracy of co-simulation. The optimization is to implement the real-time optimal control of chilled water flow by minimizing the sum of energy consumption of Chilled Water Pump in real-time through the dynamic genetic algorithm optimization.

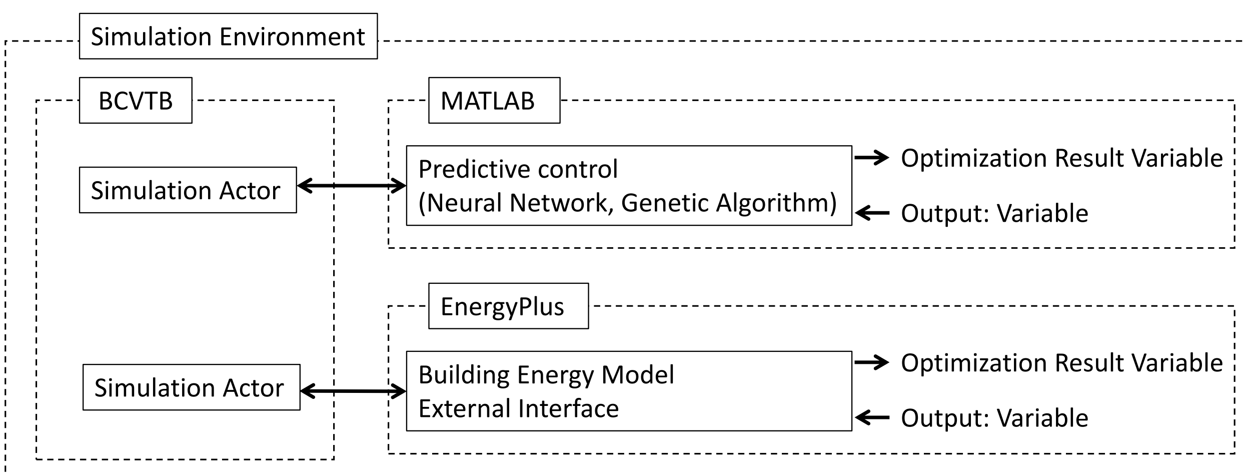

Fig.5. Diagram on the BCVTB platform

The data exchange between EnergyPlus and MATLAB can be seen in Table 5. The data exchange process is carried out every 1 minute at the time in the software. There are 3 files on the BCVTB (Building Controls Virtual Test Bed) platform, 2 files from EnergyPlus and 1 file from MATLAB which are simulated simultaneously.

Table 5 Data Exchange MATLAB with EnergyPlus on the BCVTB Platform

EnergyPlus → MATLAB	MATLAB → EnergyPlus
Outdoor dry-bulb temperature [°C]	Chilled water mass flow rate [kg/s]
Outdoor relative humidity [%]	
Diffuse solar radiation [W/ m^2]	
Direct solar radiation [W/ m^2]	
Room temperature [°C]	

3.2 System identification by ANN

Application of ANN model for identification of system dynamic behavior got significant attention in recent years [27]. In present study, the ANN model is developed to identify building and HVAC system performance using input parameters. It aims to characterize the system and teach ANN the relationship between controllable parameter, disturbances, and system performance. Training and testing of ANN model is performed using ANN toolbox provided by MATLAB version 2020a [28]. The configuration of ANN model can be seen in Fig. 6. It describes one step ahead prediction of room temperature using outdoor dry bulb temperature, outdoor air humidity, diffuse solar radiation, direct solar radiation, chilled water flow rate, and previous time step of room temperature as input parameters. Multi-layer perceptron ANN type is selected for identification as it has good capability in data approximation [29]. The ANN model is trained with one hidden layer, Levenberg-Marquardt learning method [30, 31], and Bayesian regularization to avoid over fitting [27].

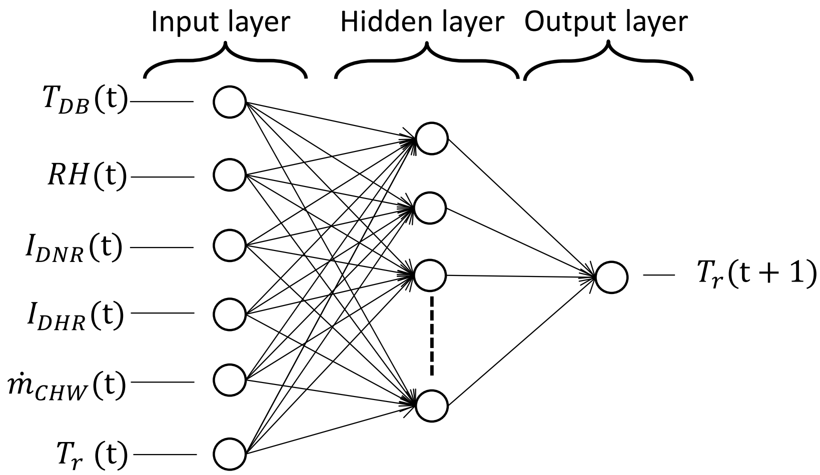

Fig. 62 ANN structure for system identification

The training data for room temperature are generated by simulation results from EnergyPlus. Meanwhile all disturbances including humidity, temperature, and solar radiation refer to the weather data. The chilled water pump pattern which is considered as control actuator is manipulated by following N-sample constant method [32]. As this signal characteristics covers various amplitude and wide range of system behavior, it is appropriate to demonstrate the dynamic system characteristics [27]. The signal of chilled water pump is kept constant for 90 min (hold time) and changed to other amplitude randomly. The hold time is taken in between 1 and 2 time constant to avoid data redundancy in steady condition but still represent dynamic characteristic [27]. The detail procedure of step change response test related to the time constant of system can be found in [17]. The simulation is run for 6 days to provide sufficient data for ANN training. Then the response of room temperature is recorded. The input output data patterns for ANN training with 60 s sampling time are shown in Fig. 7 with data range provided in Table 6. It should be noted that the training data for each day are selected based on the simulation results from 05.30 to 18.00 considering the weather condition on the day.

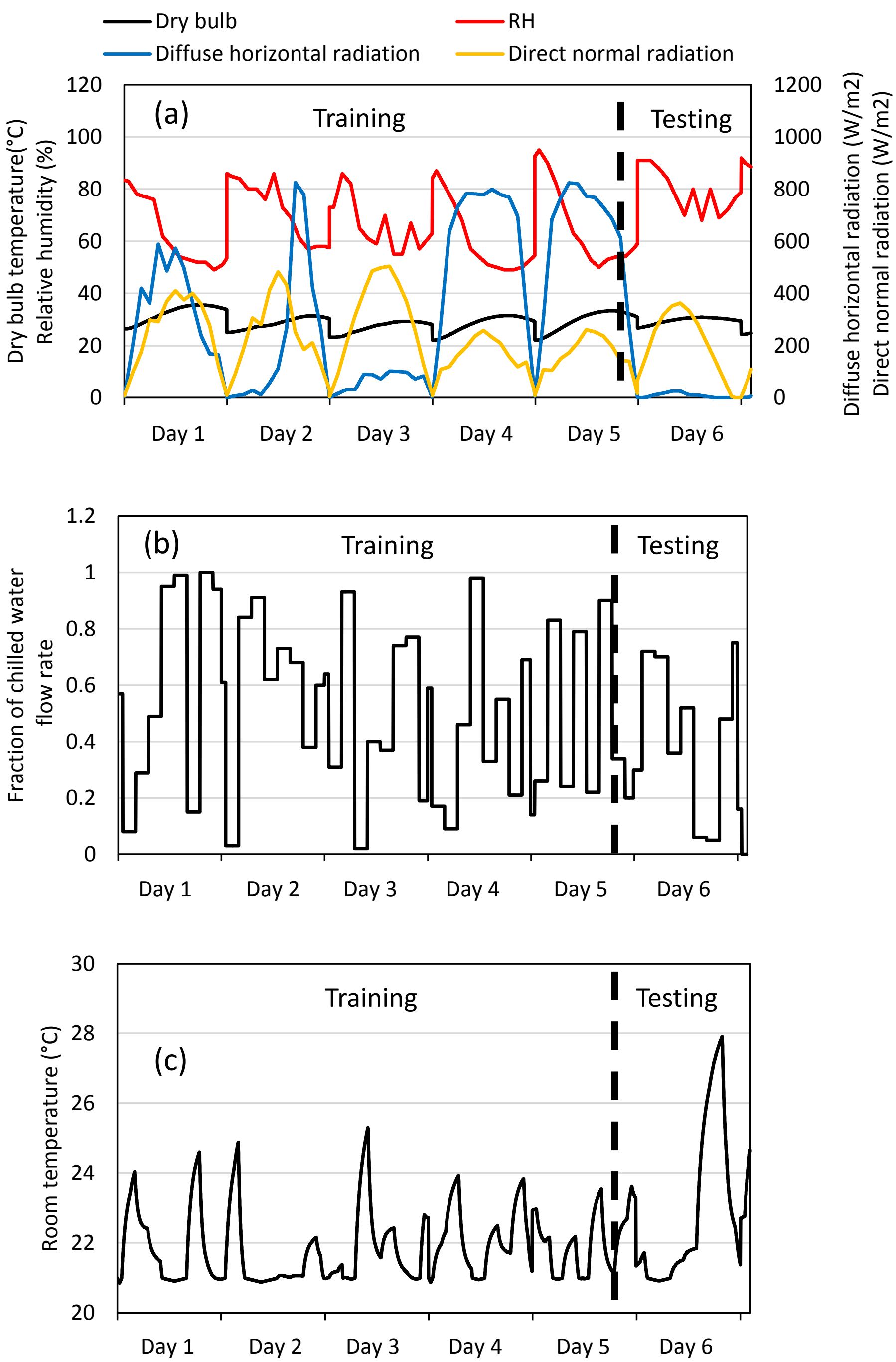

Fig. 7 Data pattern (a) disturbances (b) control input (c) control target

Table 6 Range of input and output data for prediction

Symbol	Parameter	Range	Input	Output
T_{DB}	Outdoor air dry bulb temperature (°C)	22.1- 35.6	●	
RH	Outdoor air relative humidity (%)	49- 97	●	
I_{DHR}	Diffuse horizontal radiation (W/m2)	0- 825	●	
I_{DNR}	Direct normal radiation (W/m2)	0- 504	●	
$\dot{m}_{CHW}$	Chilled water flow rate (kg/s)	0- 1	●	
T_r	Room temperature (°C)	20.9- 28.4		●

Totally, there have been 10078 data pairs generated for identification. The data are divided into two groups as 70% and 30% intended for training and testing, respectively. Number of neurons is varied from 1 to 20 and the network with highest accuracy on testing result is considered as the optimum one. The prediction accuracy is measured by root means square error (RMSE) as expressed in Eq. (7). Before the training, the input and output data are normalized in the range of [-1, 1]. The normalization aims to treat the input in the same manner and therefore avoid the domination of input with high magnitude. After several trials of training, the structure with 3 neurons (see Fig. 8) is selected as the best ANN model. Fig. 9 shows prediction results of selected ANN model which indicate good agreement between predicted and corresponding temperatures. According to this result, the ANN model with 3 neurons is applied for identification of optimal control in the following study.

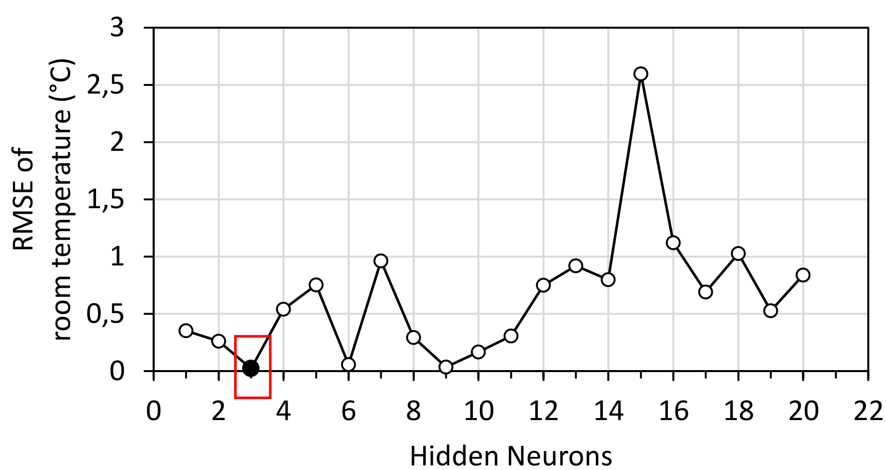

Fig. 83 Prediction accuracy with various number of neurons

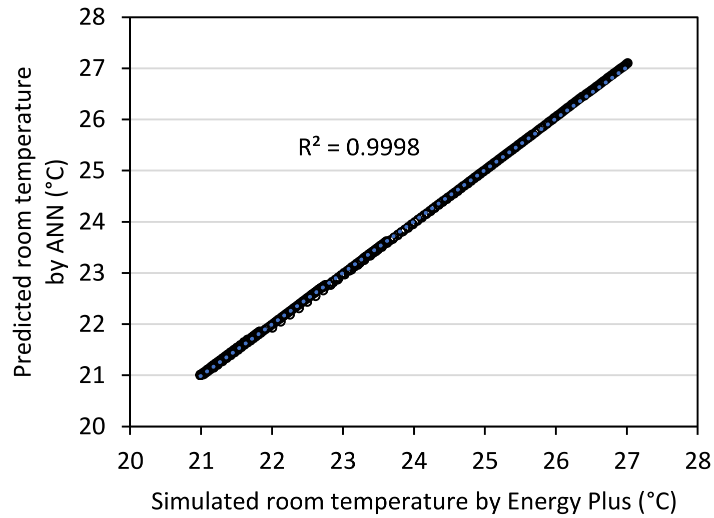

Fig. 9 Testing results of optimal ANN model

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_s - y_p\right)^2} \quad (7)$$

Where y_s and y_p shows the simulated data by EnergyPlus and predicted data by ANN, respectively. The number of data points is represented by n.

3.3 Dynamic optimization using genetic algorithm

Dynamic optimization is applied to search the optimum of chilled water flow rate while to maintain the room temperature as desired set point. Optimization is carried out with genetic algorithms using global optimization toolbox in MATLAB [28]. The optimization parameters for lower and upper bound of decision variables can be seen in Table 7.

Table 7 Configuration parameter in genetic algorithms

Number of variables	Value
Upper Bound	1
Lower Bound	0.001
Max Stall Generation	50

In present study, the optimal control is designed only for chiller system. While the split duct systems are operated by other ON/OFF to maintain the temperature and humidity at 24 °C and 57-50%, respectively. The configuration of chiller system can be seen in Fig. 11. The main component of chiller system is operated according to PLR based model as explained in section 2.3.

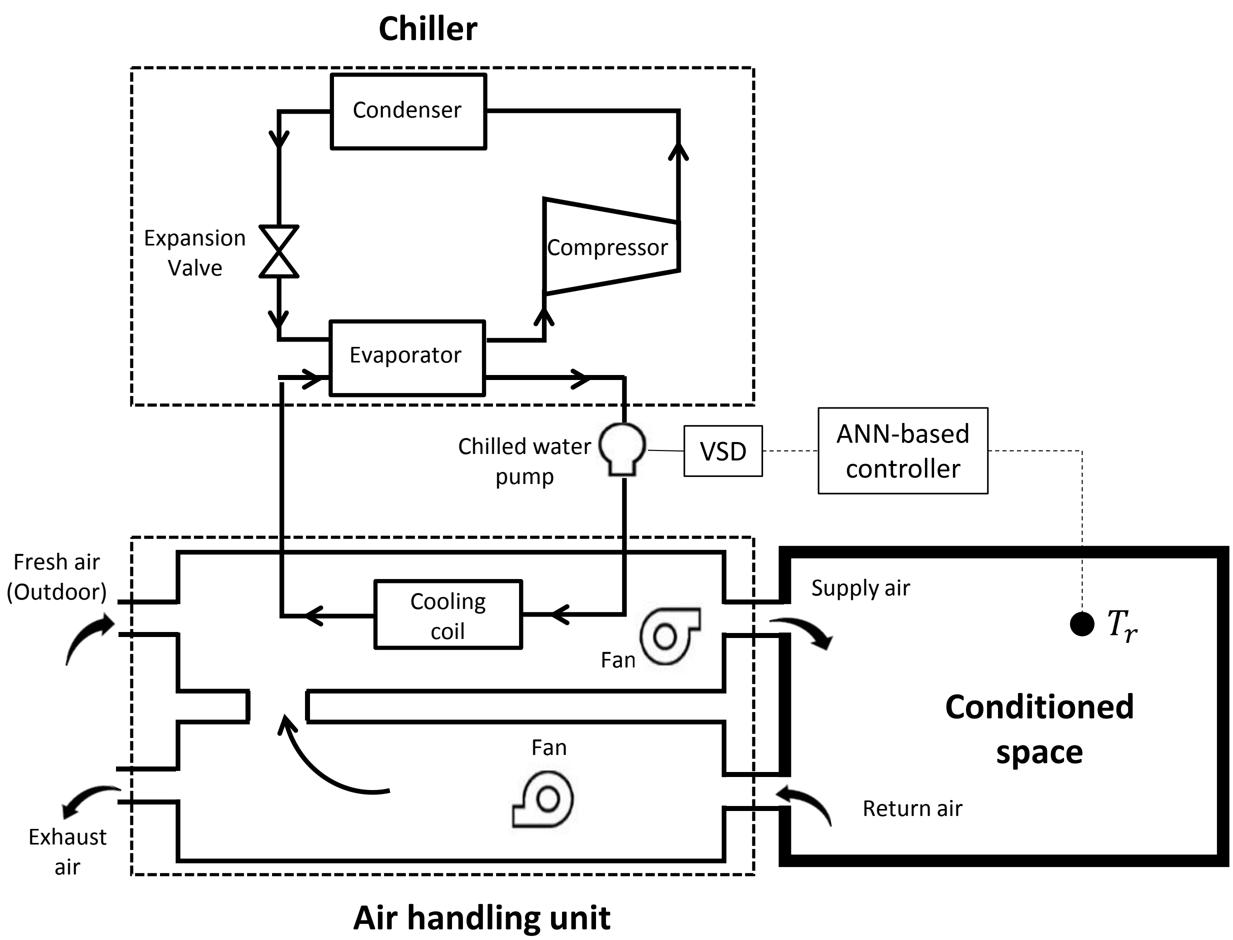

Fig. 11 Schematic diagram of ANN controller

The dynamic optimization problem is presented as follows:

Decision variables : $\dot{m}_{CHW}$ (t)

Constraint : T_{DB} (t), RH (t), I_{DHR} (t), I_{DNR}(t)

Objective function : $\left|T_{r,set}(t+1) - T_r(t+1)\right|$

The current time of chilled water flow rate $\dot{m}_{CHW}$ (t) is selected as decision variable. Meanwhile the current time of dry bulb temperature T_{DB} (t), humidity RH (t), direct normal radiation I_{DNR}(t), and diffuse horizontal radiation I_{DHR} (t) are considered as constraint. These parameters refer to the disturbance from weather that affect the building performance. Then the optimization is conducted to minimize the difference between actual and set point room temperature for the future time step. The dynamic optimization is run continuously during the building operation.

4. Result and Discussion

The additional simulation is conducted to verify the control performance using representative weather data of Depok city as shown in Fig. 12. The simulation is run from 12.00 to 18.00 P.M to consider the effect of external load sourced from solar radiation and outdoor temperature. The performance of ANN control is compared with ON/OFF control which is currently installed in the actual building. This simulation is mainly demonstrated to evaluate the capability of developed optimal control ANN based to maintain room temperature on the desired scenarios and analyze the energy efficiency improvement. Two different test scenarios including reference tracking under normal operative condition and disturbance rejection in different room temperature settings are conducted.

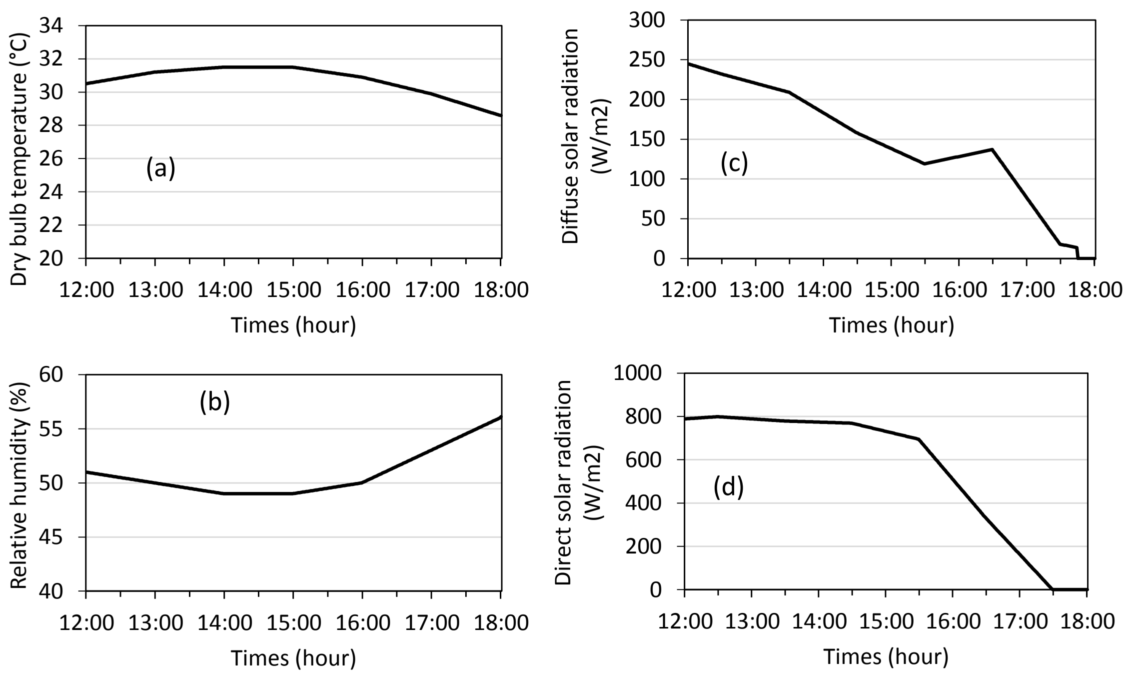

Fig. 12 Weather data for simulation (a) outdoor dry bulb temperature; (b) outdoor relative humidity; (c) diffuse horizontal radiation; (d) direct normal radiation

4.1 Controller performance for reference tracking

Firstly, the control performance is examined under normal operative condition where all internal loads from occupant's behavior and electricity equipment are designed following the normal schedule (see Fig. 3). It indicates that the controller verification includes the disturbance as actual operative conditions. The controllers are tested to follow the step change of room temperature trajectory. As shown in Fig. 13, room temperature is initially controlled at 26 °C until steady condition is reached for 120 min. Then the reference set point is changed to 25 °C and 24 °C consecutively for 120 min in each step.

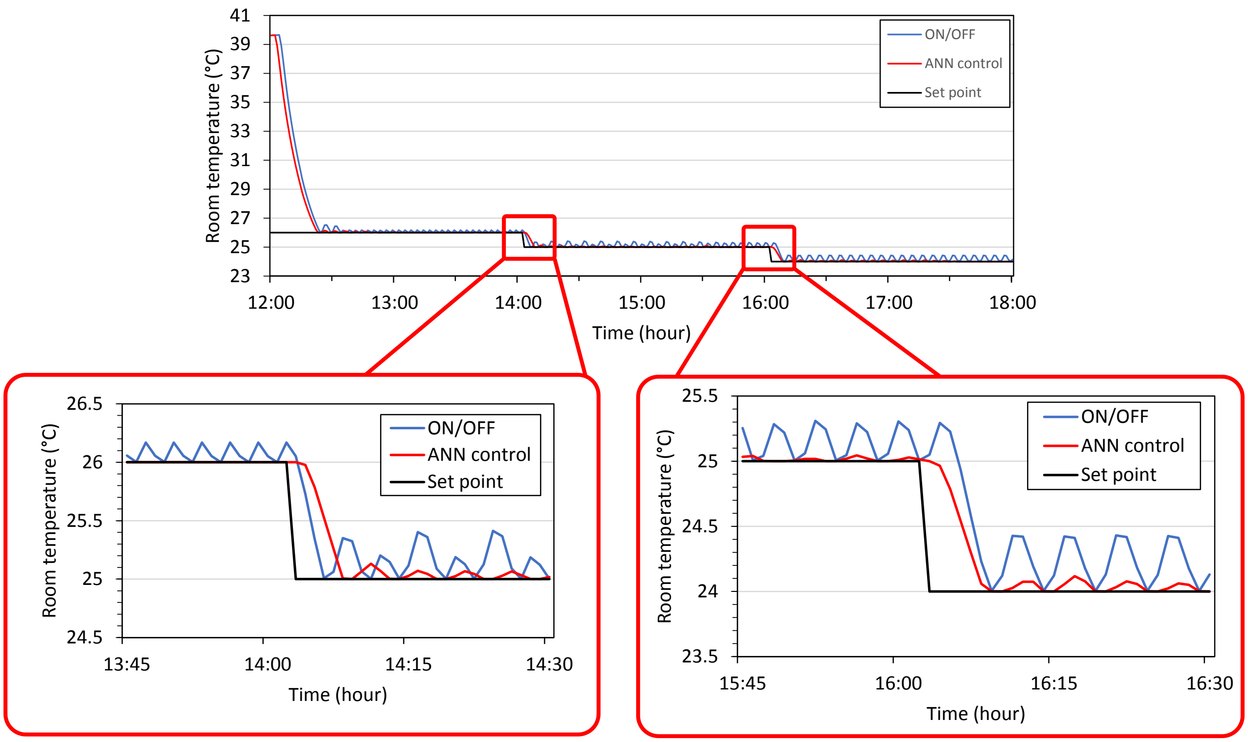

Fig. 13 Room temperature tracking by optimal ANN control and ON/OFF control under normal operative condition

Figure 13 shows the comparison of ANN and ON/OFF control performance while maintaining different temperature set point. It shows that both controllers could immediately respond the change of temperature set point by increasing the mass flow rate of chilled water to maximum level to ensure that the room temperature decreases to approach the corresponding set point in short time. According to Fig. 13 (see the enlarged graph), both controllers respond to the set point aggressively within 10 s. There is no significant different in rise time of both controllers. However, ANN control has better results in steady condition with deviation is ± 0.1°C, while ON/OFF control has deviation of ± 0.5°C. As ON/OFF control is designed with single-speed only, it generates high oscillation in temperature response during steady state condition. Small deviation shown in ANN control indicates that pre-trained ANN model has accurately identified the system behavior and GA has successfully optimized the signal for chilled water flow rate.

The comparison of chilled water pump operation by two controllers is shown In Fig. 14. The ON/OFF control regulate the flow rate from the maximum to the minimum condition which relies on the switch principle. In the other hand the ANN control calculates the flow rate using optimization process with considering the disturbance as constraint. Therefore, the optimum flow rate can be properly determined to achieve the desired room temperature with minimum error. Accordingly, the ANN control can appropriately adjust the optimum flow rate during dynamic operative condition.

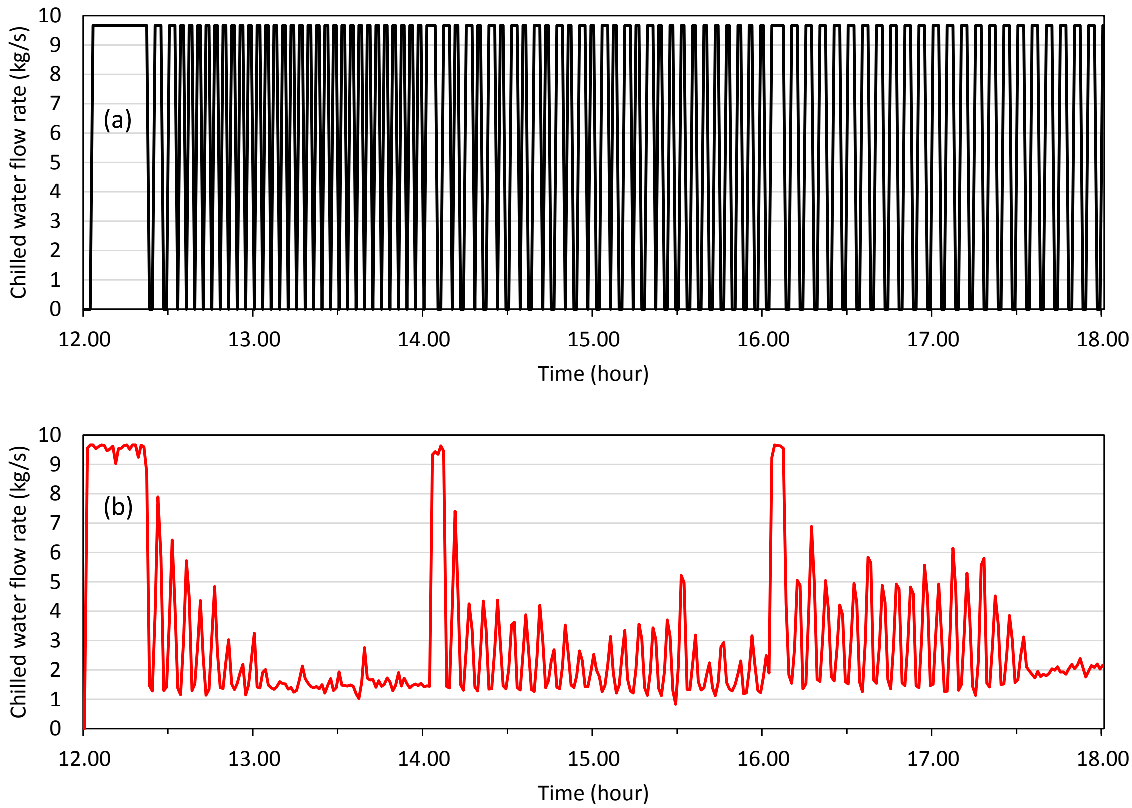

Fig. 14 Comparison of mass flow rate (a) ON/OFF control (b) ANN control

The comparison of energy consumption of both controllers is presented in Fig. 15. It shows that the energy use for chiller and fans are identical for both control strategy. Nonetheless the effective ANN control operation can reduce the pump energy consumption as 51.11% compared to the one spent by ON/OFF control. The energy used by the pump is associated with the modulation of chilled water pump operation. The higher flow rate leads the energy consumption increases, vice versa. The pump power is a function of the rotational speed which is directly correlated to the flow rate. The higher the rotational speed, the greater the energy required to generate higher flow rate. This result reveals that the effective operational strategy for chilled water pump can be considered to improve building energy efficiency.

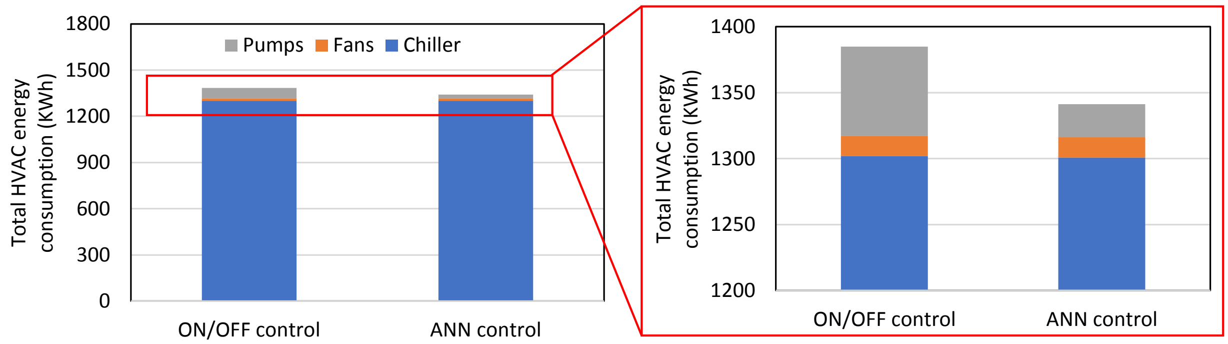

Fig. 15 Comparison of total HVAC energy consumption by ON/OFF and ANN control

4.2 Controller performance under sudden load change

In this section, the controller performance is tested under extreme conditions where sudden load change is introduced in different temperature set point. It aims to evaluate the controller capability while facing instantaneous high load. This phenomenon illustrates the condition where large number of people come into the room at the same time and leads the cooling load exceeds the maximum cooling capacity of the system. Ideally, when the cooling load decreases in normal condition, the controller should respond this condition to operate the system to achieve the desired room temperature immediately.

The simulation has been conducted from 12.00 to 16.00 using the weather data depicted in Fig. 12. Two different temperature set points 26 °C and 25 °C are proposed for simulation. The additional occupancy is included to increase the cooling load for 30 min. In Fig. 16, it can be observed that the extreme condition (during sudden load change) leads the actual room temperature is uncontrollable (move away from reference set point) due to the cooling load is extremely higher than maximum cooling capacity. However, after the cooling load is reduced following the occupancy schedule in Fig. 12, both controllers can adapt the load reduction and could successfully maintain the room temperature as desired set point.

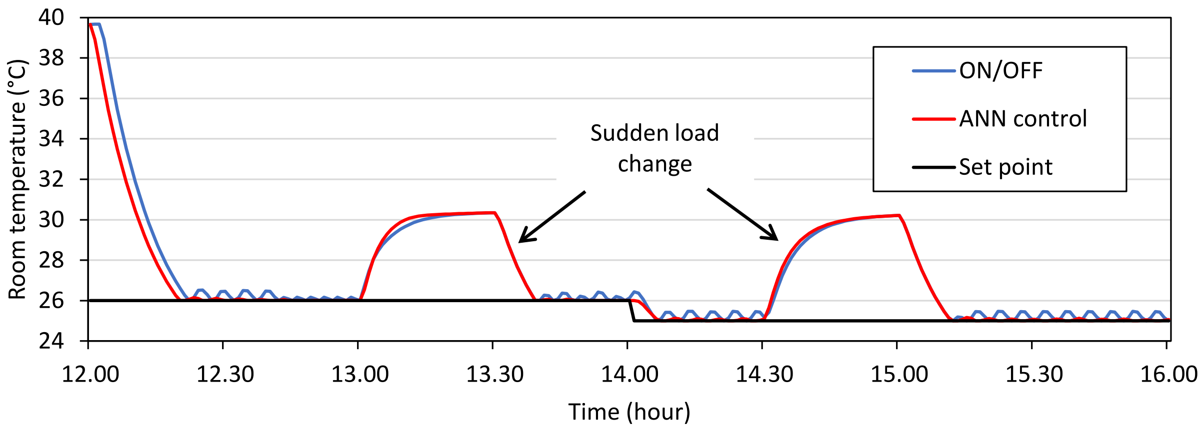

Fig.16 Control performance under sudden load change

The modulation of chilled water flow rate by ON/OFF and ANN control is shown in Fig. 17. Both controllers have similar response in which the chilled water pump operates with maximum flow rate at high cooling load (specifically shown at 13.30 and 15.00). However, at the steady state condition ANN control has optimum flow rate while maintaining the temperature. The results presented in this section confirm that ANN control can aggressively adapt the system operation while sudden load change is introduced.

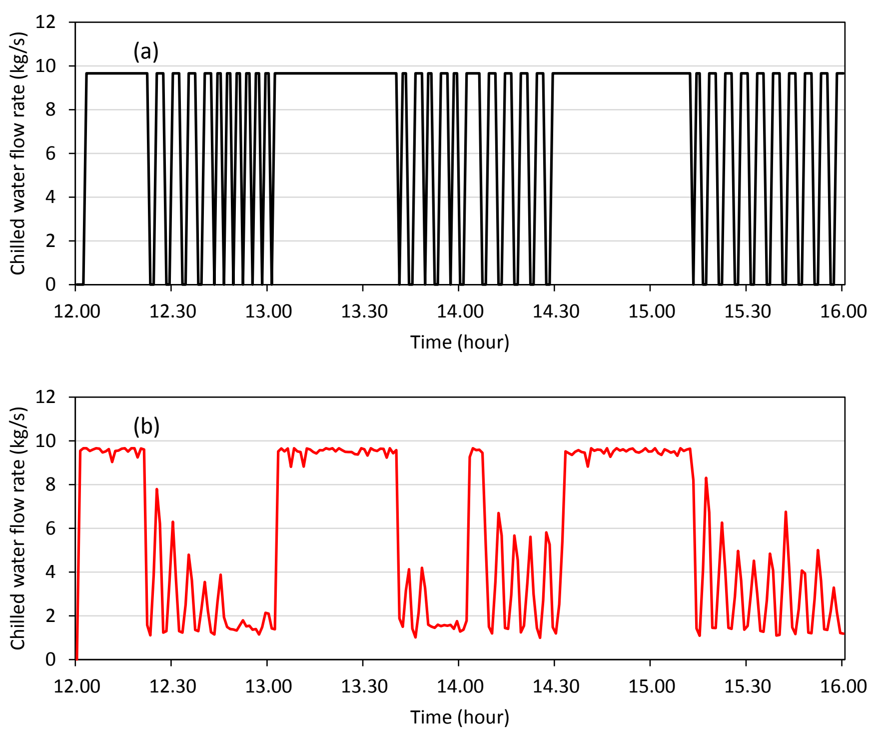

Fig. 17 Mass flow rate comparison at two setpoint given the extreme condition (a) ON/OFF control (b) ANN control

5. Conclusion

A control strategy for optimal chilled water pump operation has been developed using combined ANN technique and genetic algorithm. The ANN model has successfully predicted the dynamic system behavior considering disturbance, chilled water flow rate, and output temperature as control objective. Besides Genetic algorithm has solved the dynamic optimization problem to determine the optimum chilled water rate for achieving the desired room temperature reference. The controller performance test results show that the ANN control can aggressively respond the temperature set point change during normal and extreme load conditions. Comparative assessment is performed on the proposed ANN control and ON/OFF control strategy which is currently used in related building applications. The results indicated that ANN control outperformed ON/OFF control with the difference in energy consumption is 51.11% approximately. It reveals that the proposed control strategy with considering variable pump speed can be suggested to improve HVAC system efficiency in the existing building.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: