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ANN-based procedure to obtain the optimal design and operation of the compression chiller network – Energy, economic and environmental analysis

Navid Moghaddas-Zadeh [a], Mahmood Farzaneh-Gord [a,*], Amir Ebrahimi-Moghadam [b], William P. Bahnfleth [c]

[a] Mechanical Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Mechanical Engineering Department, Faculty of Engineering, Quchan University of Technology, Quchan, Iran
[c] Department of Architectural Engineering, Pennsylvania State University, University Park, PA, 16802, USA

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ABSTRACT

In a large-scale chiller plant, a network of chillers is a suitable solution to respond to the variable cooling demand. The energy consumption of a chiller network depends on the configuration and the control strategy of the chiller network in different conditions. This study presents a general procedure for designing a chiller network for a building with an arbitrary annual cooling demand distribution. The procedure determines the optimal configuration considering the quantity, the size ratio, and the energy performance of chillers. The particle swarm optimization (PSO) algorithm is used for each configuration to find the optimal chiller loading distribution. Then, the optimal configuration is selected through a life cycle cost analysis. In order to predict a general chiller performance curve with an arbitrary nominal capacity, an artificial neural network model is developed based on 20 available commercial chillers in the market. The chiller performance prediction includes determination of COP and actual capacity of a chiller in terms of nominal capacity, chilled water temperature, cooling water temperature, and partial load ratio. The simulation is carried out in TRNSYS, which linked to MATLAB to implement the PSO optimization strategy. The results show that for networks with two, three, and four chillers, the optimal selection of chiller network configuration under the PSO strategy reduces the energy consumption by 26.30, 26.06, and 26.18%, respectively, compared to the conventional configuration under the baseline strategy. The life cycle cost for these configurations is also reduced by 17.93, 17.69, and 18.56%, respectively.

Nomenclature

Symbols

C	heat capacity [J/K]
CL	cooling load [kW]
C_p	specific heat [J/(kg.K)]

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* Corresponding author.

E-mail addresses: n.moghaddaszadeh@mail.um.ac.ir (N. Moghaddas-Zadeh), m.farzanehgord@um.ac.ir (M. Farzaneh-Gord), amir_ebrahimi_051@yahoo.com (A. Ebrahimi-Moghadam), wbahnfleth@psu.edu (W.P. Bahnfleth).

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CAP	capacity [kW]
E	energy consumption [MWh]
Em	emission [tons]
EC	environmental cost [$]
H	head [m]
IC	investment cost [$]
$\dot{m}$	mass flow rate [kg/s]
MC	maintenance cost [$]
N	lifetime [year]
OC	operating cost [$]
OF	objective function [−]
P	power [kW]
PF	price factor [−]
$\dot{Q}$	load [kW]
r	discount rate [−]
S	chiller on/off status [−]
t	time [hr]
T	temperature [°C]
UA	overall heat transfer coefficient [W]

Greek letters

γ	specific weight [−]
ε	effectiveness [−]
η	efficiency [%]
μ	equilibrium factor [−]

Abbreviations

ANN	Artificial Neural Network
CEPCI	Chemical Engineering Plant Cost Index
COP	Coefficient of Performance
ELD	Equal Load Distribution
EP	Electricity Price
FFLP	Fraction of Full Load Power
HVAC	Heating, Ventilation, and Air-Conditioning
LCC	Life Cycle Cost
MSE	Mean Square Error
OCL	Optimal Chiller Loading
PLR	Partial Load Ratio
PVF	Present Value Factor
SF	Safety Factor
SLS	Sequential Load Sharing

Subscripts and superscripts

a	air
act	actual
Ch	chiller
chw	chilled water
cw	cooling water
cond	condenser
CT	cooling tower
elec	electricity
eva	evaporator
des	design
in	inlet
M	average
out	outlet
rej	reject
set	set-point
t	time
tot	total
wb	wet-bulb

1. Introduction

The British Petroleum Statistical Review of World Energy [1] states that in 2021, after temporarily decreasing in 2020 due to the COVID-19 pandemic, energy demand and emissions rebounded to near their pre-pandemic levels. In 2021, primary energy demand climbed by 5.8%, topping 2019 levels by 1.3%. Last year, 82% of all primary energy came from fossil fuels. The global consumption for natural gas increased by 5.3% in 2021, surpassing 2019 pre-pandemic levels. In 2021, the energy prices around the world rose dramatically. The natural gas price increase was the most significant.

Several studies have shown that buildings account for more than 40% of global energy consumption [2]. The heating, ventilation, and air-conditioning (HVAC) system consumes considerable amount of energy in the buildings. There are various ways to reduce the energy consumption of HVAC systems. One strategy is to decrease the cooling and heating demand of the building, e.g., by using renewable energy, phase change materials, and heat recovery [3–6]. Another strategy is to effectively design the HVAC system for a specific demand during the early design stage [7]. This research focuses on the design and control of the cooling plant of the HVAC system. The system consists of chiller network, chilled water pumps, cooling water pumps, and cooling towers. The use of centralized plants is frequently attributed for improving the performance and reliability of HVAC system. The use of a centralized plant also has the advantage of decoupling the airside and waterside parts, which has operational and computational advantages [8].

The first stage in designing a chiller network, is to determine the total cooling demand and its hourly distribution in a cooling season. Then, type, arrangement, and total number of the plant equipment must be designed to satisfy the cooling demand. A correct design leads to the choosing of an optimal system in terms of economy and energy consumption. The chillers in a plant are the primary energy consumers and the most expensive equipment. For a chiller network, the capacity arrangement of the chillers could be determined symmetrically or asymmetrically, which describes the nominal load distribution. As a simple baseline, ASHRAE [9] recommends using symmetrical chillers. The ease of maintenance provided by the symmetrical arrangement is the primary benefit of this layout, although the configuration of this layout results in lower levels of efficiency when it is used under partial cooling loads. For a building with a significant variation in cooling demand, it is recommended to install several chillers with different capacities. An asymmetric configuration makes it possible for the system to adapt to changes in the cooling demand [10]. The quantity and capacity ratio of chillers should be based upon the chillers' characteristics and frequency distribution of the cooling demand [11]. To predict the performance of a chiller network, it is necessary to perform a comprehensive analysis, which considers the distribution of the building cooling demand and weather conditions [12].

After determining the quantity and capacity ratio of chillers in a plant, determining the performance control strategy is the next important issue. Any proposed plant should be evaluated in terms of energy efficiency and economic cost of operation during a cooling period. Search for optimal load sharing and sequencing has been recognized to be of utmost importance to achieve the optimal performance at the whole-plant level [10].

1.1. *Chiller loading strategies*

The Optimal Chiller Loading (OCL) problem entails finding the load fraction that each chiller must produce to reduce the system energy consumption in a chiller network [13]. The main goal of the OCL problem is to minimize the total power utilized by the chillers over the studied period. The output cooling of each chiller is chosen as the decision variable. The cooling capacity of the chillers is handled in the hour-ahead economic dispatch problem using the partial load ratio (PLR). Then, the energy requirement of the chillers is determined based on their PLRs [14]. A baseline chiller loading method is usually specified to achieve a suitable comparison.

1.1.1. *Conventional strategy*

Equal Load Distribution (ELD) and Sequential Load Sharing (SLS) are the two most common conventional strategies for controlling chiller loading. Although these methods successfully meet the cooling demand and the design set-point temperature, both of these conventional control strategies have limitations that cause considerable energy waste by the HVAC system.

The ELD strategy divides the load equally among the chillers. The SLS strategy turns the chillers on, one at a time when the building cooling demand increases, and the part-load of the chillers that are already running is above a certain value (typically 95%) [15].

1.1.2. *Optimal strategy*

The OCL problem has been studied by many scholars over the past two decades. Cheng [16] solved the OCL problem and minimized the energy consumption of a centrifugal chiller network, using the Lagrangian method. The chiller's energy consumption was calculated using the chillers performance curve (COP in terms of PLR). The results demonstrated a 2% reduction in energy consumption compared to the conventional method (ELD). Yu and Chan [17] solved the OCL problem by applying an uneven load sharing strategy for a screw chiller network. The annual electricity consumption reduction is reported to be about 5% for chillers and 7% for pumps of the plant compared to the conventional method (ELD). Yu and Chan [18] presented a 16.3–21.0% reduction in the annual electricity consumption of a centrifugal chiller network, by applying the optimal staging of chillers and pumps. The results showed that the optimization of the set-point temperature of cooling water and the flow rate of chilled water, can increase the COP from 0.8 to 191.7%, depending on the demand load and ambient conditions.

Dulce-Chamorro and Martinez-de-Pison [19] improved the performance control of a hospital compression chiller plant by adjusting the set-point of chilled water temperature. The optimization method not only resulted in an energy savings of up to 10%, but also reduced the number of chillers' starts by 82.5%. Zhoua et al. [20] proposed a method for improving the performance of a water-cooled compression chiller plant. The proposed method has been developed in such a way that optimizes the entire system, including chillers, pumps, and cooling towers, rather than just one single equipment. Although this method may occasionally decrease the operating efficiency, it reduces the energy consumption on a typical summer day by 11.60%. Pargas-Carmona et al. [21] evaluated various chiller plants with 2–6 chillers, which were chosen from a total of 13 air-cooled screw chillers. A mathematical programming method was suggested such that it solves the problem of chiller selection. The optimum result showed that the annual energy consumption drops as capital costs rise. Wei et al. [22] proposed a strategy for controlling the frequency of chilled water pumps in a chiller plant. Compared to the original control scheme, the proposed strategy can reduce the energy consumption by up to 63% for the chilled water pumps and 6% for the chillers. Yu and Ho [23] demonstrated a control strategy to reduce the number of on/off cycles for the chiller plant's component. The analysis helped to create an analytical tool for figuring out the optimum way of running the system at its highest COP. It was successful to save up to 2.72% of the electricity consumption. Niu et al. [24] suggested a chiller plant energy-saving control strategy. The suggested strategy optimizes the number of active chillers and pumps, as well as the chilled water supply temperature set-point. The results demonstrate an 8.5% reduction in the chiller plant's energy consumption. Abd-Rahman et al. [25] proposed an energy audit method to optimize the energy performance of an air-cooled chiller plant, predicting 45.54% energy savings with a discounted payback period of 7.15 years. Applying the proposed method on a hospital chiller plant led to an actual energy saving of 50.08% with the discounted payback period of 6.29 years.

Numerous studies have employed varying optimization methods to solve the OCL problem [26–32]. Ma and Wang [26] applied genetic algorithm to optimize chilled water temperature and cooling water temperature. Applying this optimization algorithm led to a reduction in the energy consumption of cooling towers and chillers, while the energy consumption of pumps increased. Overall, comparing to a conventional control strategy, this strategy led to a saving of 0.73–2.55% of daily energy consumption of the chiller plant.

Particle Swarm Optimization (PSO) algorithm is one of the most common algorithms for solving the OCL problem [27–29]. Chen et al. [29] used PSO algorithm to solve the OCL problem for minimal power consumption in a chiller network. The power consumption of the chiller is considered dependent on chilled water temperature, cooling water temperature, and PLR. The proposed method leads to a 12.68–17.63% reduction in the chillers power consumption as compared with the ELD method.

1.2. Chiller network design

There are few studies that have investigated the chiller network design problem. These studies typically design chiller network options with available chillers for a specific cooling demand, and calculate the associated investment cost for each option. Then, the related annual performance cost of different options is determined by applying a performance control strategy. Finally, the optimal solution is determined, by employing an economic analysis such as Life Cycle Cost (LCC) analysis.

Chen et al. [33] evaluated the effects of chiller design on the energy performance of the chiller network, under three different control strategies (weekly, daily, and hourly). They evaluated 50 possible design options with 13 available centrifugal chillers. The electric chiller model is used to evaluate the chillers power consumption. This model considers the COP and capacity of the chiller as functions of chilled water temperature and cooling water temperature. Hourly control strategy reduced energy consumption compared to weekly and daily control strategies. Although they have only examined the on/off status of the chillers, they have specified that the chiller performance curves in terms of PLR are required for applying the optimal control strategy. Catrini et al. [34] performed an exergoeconomic analysis on symmetric and asymmetric configurations of chiller network, with two and three scroll chillers. They proposed an approach to compare the investment cost and operation cost of chiller network. The proposed method is evaluated for a chiller plant as a case study with a capacity of 750 kW. Different configurations of chillers' capacity are provided based on 50 kW steps. Their results showed that the asymmetric design of chillers leads to a 30% exergoeconomic cost reduction compared to the symmetric design.

Bhattacharya et al. [35] evaluated a chiller network with different number of chillers. They tested the plants with two and three chillers. The chillers are selected from 16 screw and centrifugal chillers with capacity in range of 531–4677 kW. They used the Bayesian optimization method to determine the optimal switching thresholds and chiller staging for the chiller network. The proposed method has resulted in capital cost savings of about 0.7 million USD, and a reduction in annual energy consumption of nearly 33%. Torres et al. [10] proposed a method for determining the optimal capacity ratio of chillers in a chiller network. They proposed a procedure to determine configurations of chiller network with some available screw chillers, based on cooling demand profiles. The genetic optimization algorithm is used to solve the OCL problem. The results of the case study showed that an asymmetric configuration (33/67) for chiller network leads to 14%, 11%, and 15% savings in energy consumption, LCC, and emission pollution, respectively.

1.3. Novelty

As discussed in the literature review, many studies have investigated the performance control strategies of chiller networks. However, only a few studies have analysed the problem of optimal design of these networks. These studies have solely focused on the number of available chillers. In this study, we argue that while the initial investment costs are important, the system performance cost during its lifetime (as well as engineering and local considerations), should also be evaluated. The dearth of chillers with an arbitrary capacity on the market and the absence of their performance curve to solve the OCL problem are among the main reasons for why previous studies have not examined all the potential design alternatives.

The innovation of this research is to present a general procedure based on ANN and PSO, to design a compression chiller network for a specific cooling demand distribution. In order to provide the possibility of checking all potential configurations, first, the performance curve of a chiller with an arbitrary capacity is determined. This has been carried out by applying an ANN model to the performance curve data of the available commercial chillers in the market. Next, the PSO control strategy is applied on the chiller network to minimize the hourly energy consumption of the chiller plant. Finally, the optimal plant is determined by the detailed analysis of the investigated options in terms of energy, economic, and environmental analyses. The PSO algorithm was selected to solve

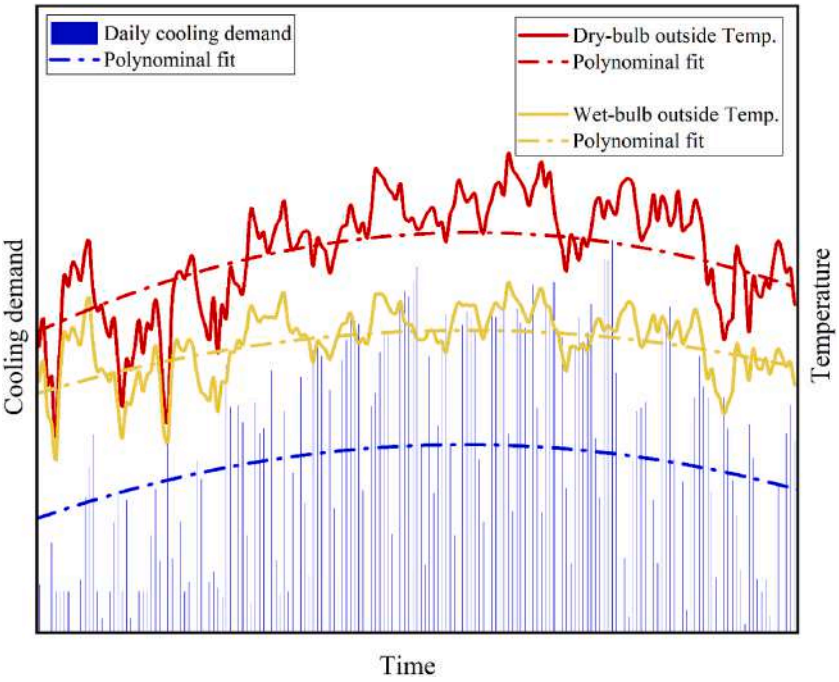


Fig. 1. The schematic diagram of cooling demand and outside weather conditions.

the OCL problem, and the LCC method was chosen for the economic analysis.

This paper is organized as follows. Section 2 presents the system description and the different generated configurations for the chiller network. Section 3 describes the methodology of the study including ANN model, energy and economic equations, as well as the applied PSO control strategy. The results of the energy, economic, and environmental analyses for different configurations of the chiller plant are presented and discussed in Section 4. Finally, the conclusions are drawn in Section 5.

2. System description

In this section, cooling demand, weather conditions, chiller plant layout, and chiller network configurations are presented.

2.1. Cooling demand and weather conditions

The cooling demand and weather conditions should be determined, as shown schematically in Fig. 1. The cooling demand distribution during a cooling season is required to determine the total capacity of the cooling system, taking into account the unmet hours and building usage considerations. The cooling demand is not only necessary to detect the peak load, but also needs to be determined hourly to apply the control strategy. After determining the building cooling demand peak, the design cooling load will be determined by considering a safety factor. Also, the cooling demand histogram and accumulation help to solve the design problem.

2.2. Chiller plant layout

The primary-secondary pumping system is one of the most common chilled water distribution systems [36]. In this system, primary circuit pumps have the task of circulating chilled water inside the chillers and overcoming the pressure drop of the chillers. The secondary circuit pumps have the task of circulating chilled water and overcoming the pressure drop of the building and air conditioners or fan coils. The primary pumps are usually selected from the constant-speed type to keep the water flow rate of the chillers at a constant nominal flow rate, while the secondary circuit pumps are usually selected from the variable-speed type to work according to the chilled water needs of the building.

The schematic diagram of a typical decoupled chiller plant is illustrated in Fig. 2. This chiller plant consists of several subsystems, including chiller network, chilled water pumps, cooling water pumps, and cooling towers. The primary chilled water circuit and the secondary chilled water circuit are decoupled by a bypass line. The primary circuit consists N chillers with different rated capacities for different configurations, M constant-speed chilled water pumps, L constant-speed cooling water pumps, and G cooling towers. Considering that the focus of this study is on the design of chiller network, a specific arrangement is considered for cooling towers and pumps in the primary loop. In this study, the flow rate of chilled water through each chiller is assumed to be constant and equal to its nominal flow rate. The primary loop pumps are controlled based on the on/off status of the chillers in a way that provides the required flow rate of each chiller. The mixed chilled water from the primary circuit is delivered to variable speed pumps in the secondary circuit and directed to the building.

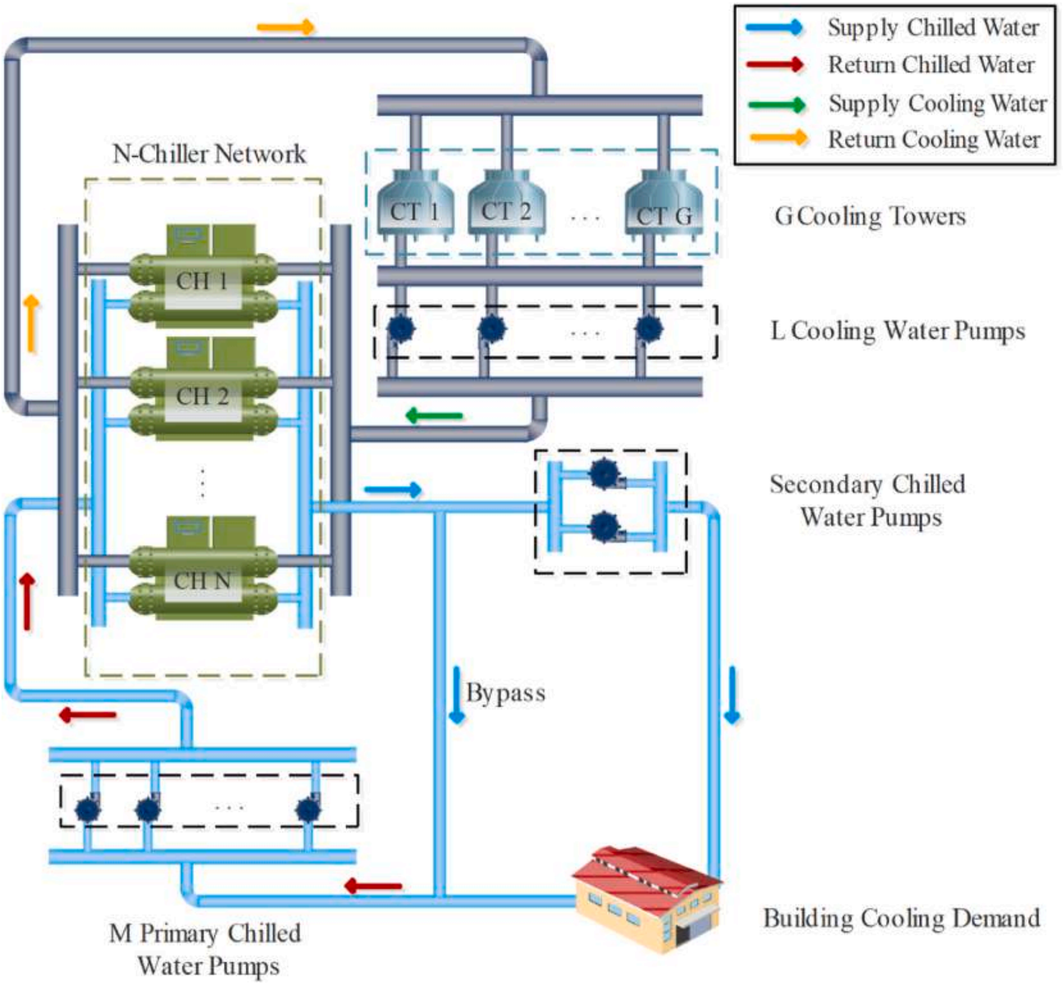


Fig. 2. The schematic diagram of a typical decoupled chiller plant.

2.3. Chiller network configuration

The total capacity of the chiller network is determined based on peak cooling demand, unmet hours, and a safety factor. A chiller network configuration includes the capacity and quantity of chillers. Various configurations of chiller capacity and quantity could be selected here. There are no engineering requirements dictating that the design of a chiller network be symmetrical. Despite the maintenance benefits of symmetrical chiller configuration due to common components, asymmetrical chiller configuration results in higher energy efficiency [7]. In this study, both symmetrical and asymmetrical chiller configurations are investigated.

Fig. 3 lists the configuration alternatives for a chiller network. All possible configurations for chiller networks with the number of one, two, three, and four chillers are presented by applying a capacity ratio step of 1 on a scale of 10. The naming of each case indicates the quantity and capacity ratio of the chillers of that network. For example, case “8/2” indicates the network has two chillers with a capacity ratio of 2–8 on a scale of 10. For a 1000 TR network, it means one 800 TR chiller and one 200 TR chiller.

3. Methodology

In this section, the system analysis method is presented from the perspective of energy, economy, and environment. The performance strategy control methods are also presented.

3.1. Chiller’s COP prediction

The nominal COP (which defines in a certain reference conditions) of compression chillers depends on the nominal capacity of chillers. The higher nominal capacity, the higher nominal COP, based on the performance data of manufacturing companies [37]. The COP of chillers varies with the changes in operating conditions. The most significant variables are the chilled water temperature, the cooling water temperature, and PLR. Also, the nominal capacity for a chiller, is the cooling capacity that this chiller can meet in reference conditions. The available cooling capacity for a chiller (which is called actual capacity in this study) also depends on two variables: the chilled water temperature and the cooling water temperature.

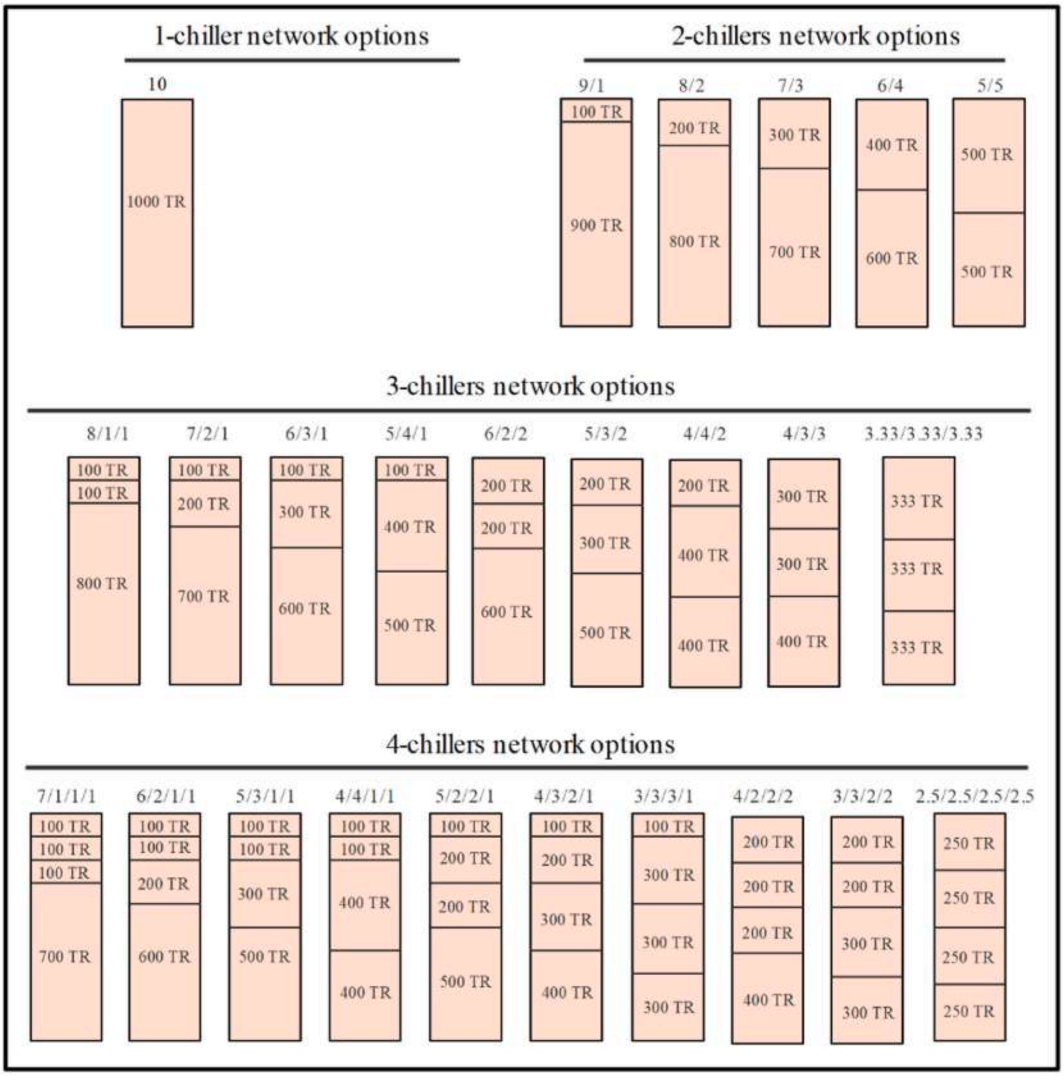


Fig. 3. Sizing ratio alternatives of chiller configuration.

Determining COP and the actual cooling capacity of chillers is one of the requirements of the design and control of a chillers network. In the issue of chiller network design, when the designer intends to select the chillers for a plant, it is necessary to know the COP value of each chiller. Although knowing the nominal COP of different chillers with different capacities is necessary, it is not enough. Due to the variability of the cooling demand with respect to time in the air conditioning systems, the chillers of such a plant do not always work at full load. Based on the selection of the number of chillers and their capacity ratio at the design stage, most of the time, the chillers operate at partial load. So it is necessary to know the COP variation in terms of PLR.

The COP prediction model is the basis for the optimization analysis of energy saving operations in a chiller network. How to make an accurate prediction is a critical issue for a researcher. There are mainly three methods to obtain chiller COP. The first method is to use the theoretical physical equations to obtain the operation of a chiller, which includes some simplifications for the thermodynamic analysis of the refrigeration cycle [17,18,38]. The second method is to predict the chiller performance in terms of a series of data related to the operation of an existing chiller (using black-box models to predict the performance of chiller [39–42]). The third method is to use the data and relationships provided by the manufacturer for chillers [43] (which is provided by references such as DOE-2). Among these three methods, the first can be used for any arbitrary capacity, but it will not necessarily match the output of commercial chillers. The second method leads to a prediction very close to reality, but it can only be applied to a specific chiller in operation, after a long time of data collection. The third method can be used for new chillers in the market, but is only available for the nominal capacities produced by the manufacturers.

Based on the purpose of this research, which is to provide a general procedure for the optimal selection of chillers in a chiller network, it is necessary to have performance information of chillers with an arbitrary nominal capacity. It is essential to know the performance of chillers with an arbitrary nominal capacity in different operational conditions from the point of view that it is necessary

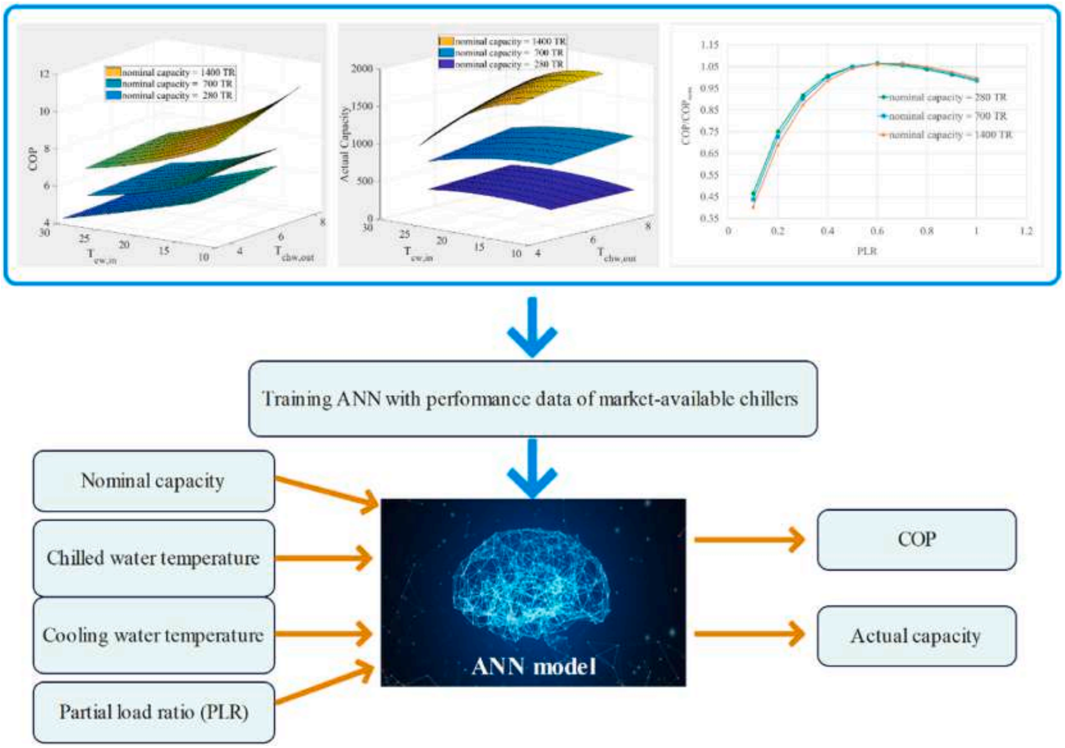


Fig. 4. The chiller performance evaluation based on ANN.

to know the behaviour of each chiller in applying the optimal control of the chiller network.

Therefore, in this study, the idea of applying an Artificial Neural Network (ANN) to the existing performance data of available commercial chillers in the market is presented. As a result, there will be no limit in terms of evaluating chillers of any capacity. After applying this general procedure and reviewing the optimal proposals in terms of energy consumption and economic analysis, it is possible to choose the closest capacities available in the market.

EnergyPlus presents energy model for many market-available commercial chillers. This model helps designer to predict chiller performance under various conditions. This model evaluates COP as a function of chilled water temperature, cooling water temperature, and PLR. It also adjusts the actual capacity dependent on the chilled water temperature and cooling water temperature. Fig. 4 shows the COP performance curves as a function of chilled water temperature, cooling water temperature, and the PLR for three available chillers in the market with different nominal capacities. The ANN model makes it possible to determine these performance curve for an arbitrary nominal capacity between them.

An ANN model is developed as a data-driven model in this study to predict chiller performance (COP and CAP_{act}) in various conditions (CAP_{nom}, T_{chw}, T_{cw}, PLR). The ANN model is commonly used to describe the nonlinear physical relationship between input and output variables [44,45]. The ANN consists of an input layer, an output layer, some hidden layers, learning algorithm, and transfer function. The biases and weights on the connections are defined during the learning process. The transfer function converts input values to output values [44,46]. The input data must be separated into three group at random: training, validating, and test data [46].

The output of a neuron is determined by the following equation [46]:

$$x_j = f\left(\sum_{i=1}^{N} w_{ij} x_i + b_j\right) \tag{1}$$

where x_j is the output of the j_{th} neuron, x_i is i_{th} neuron's output of previous layer, w_{ij} is the weight, b_i is the neuron's bias, and f refers to the transfer function.

To assess the precision of the neural network, Mean Square Error (MSE) and R^2 calculate as follows [44]:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_{i,target} - Y_{i,output}\right)^2 \tag{2}$$

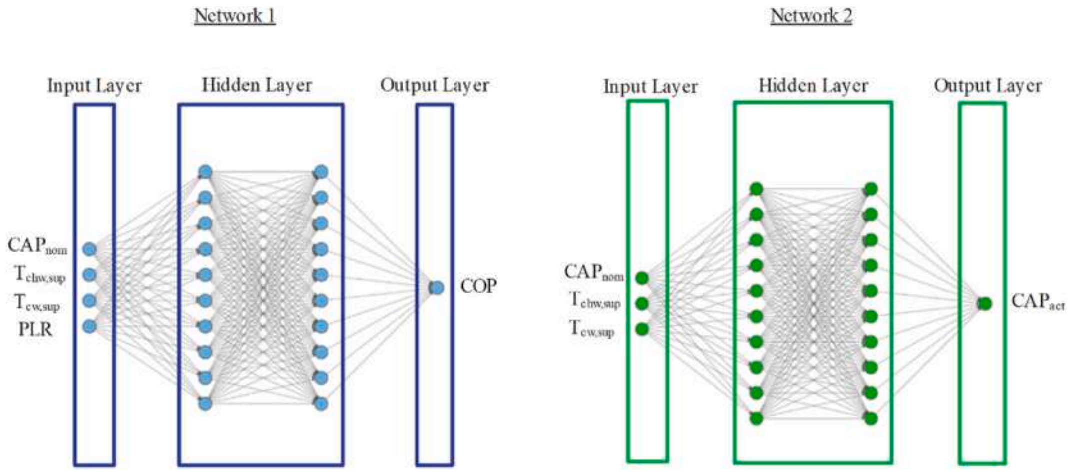


Fig. 5. BP neural network structures.

Table 1
The details of the concerned ANN model.

Item	Value (COP)	Value (CAP)
Number of samples	20,000	1,5000
Number of hidden layers	2	2
Number of neurons in the hidden layer	10	10
Number of input variables	4	3
Number of output variables	1	1
The ratio of train data	80%	80%
The ratio of validation data	10%	10%
The ratio of test data	10%	10%
Maximum number of iterations	1000	1000
Maximum number of epochs	100	100
Train algorithm	Levenberg-Marquardt	Levenberg-Marquardt
Activation function for the hidden layer	Tanh	Tanh
Activation function for the output layer	Purelin	Purelin

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(Y_{i,target} - Y_{i,output}\right)^2}{\sum_{i=1}^{n} \left(Y_{i,target} - \overline{Y}_{target}\right)^2} \tag{3}$$

$$\overline{Y}_{target} = \frac{1}{n} \sum_{i=1}^{n} Y_{i,target} \tag{4}$$

where n is the samples number, $Y_{i,\ output}$ is the output value of the ANN, and $Y_{i,\ target}$ is the target value.

To predict the COP and CAP_{act} of a chiller (outputs of the network) as a function of nominal capacity, chilled water and cooling water temperatures, and PLR (input of the network), multi-layer perceptron ANN method with feed-forward type is implemented according to the behaviour of chillers' performance. Due to the difference in the nature of the COP and CAP_{act} changes, two separate models have been applied to predict the outputs. Fig. 5 shows the structure of these two networks. Each network has two hidden layers, each containing 10 neurons. The ANN models were developed by using MATLAB Neural Network toolbox. More details of the concerned ANN model, is presented in Table 1.

3.2. Energy analysis

In this section, the equations used to perform energy analysis are presented for all components (chillers, cooling towers, and pumps). A schematic diagram of TRNSYS model, which is used to simulate the system components, is shown in Fig. 6. By determining the energy consumption of each component, the total energy consumption of the system is determined for each hour.

3.2.1. Chillers

The chiller cooling load is calculated by:

$$\dot{Q}_{load} = \dot{m}_{chw} C_{p_{chw}} \left(T_{chw,in} - T_{chw,set}\right) \tag{5}$$

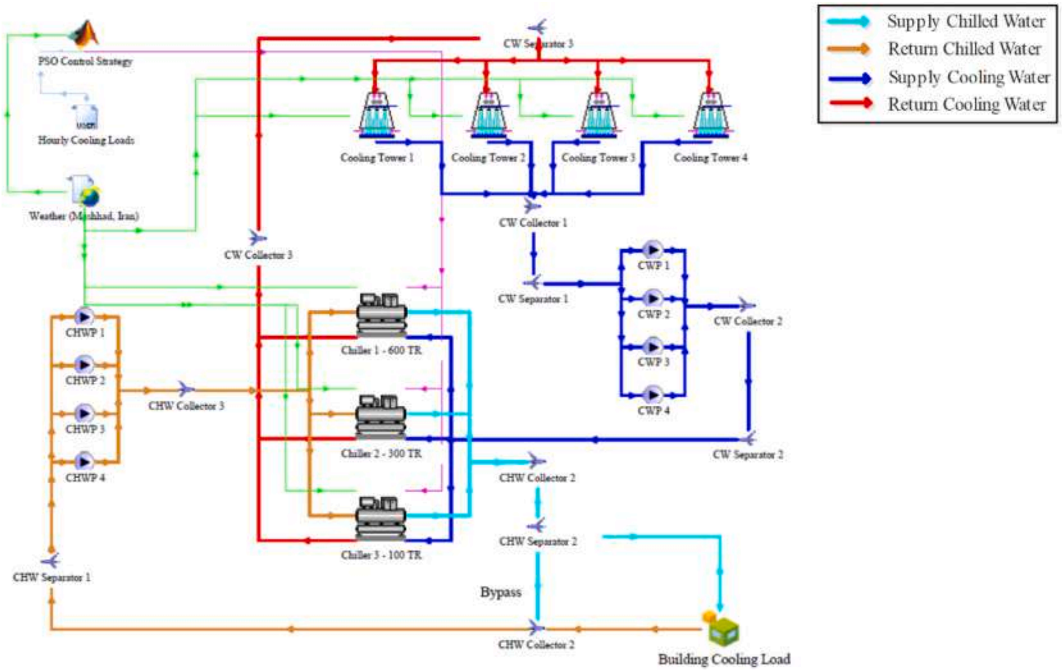


Fig. 6. A schematic diagram of TRNSYS model.

where $T_{chw,in}$ and $T_{chw,set}$ are return chilled water temperature and chilled water set-point temperature, $C_{p_{chw}}$ is chilled water's specific heat, and $\dot{m}_{chw}$ is the flow rate of chilled water stream. PLR is defined as follows:

$$PLR = \frac{\dot{Q}_{output}}{CAP_{act}} \tag{6}$$

where $\dot{Q}_{output}$ is chiller output cooling load and CAP_{act} is actual chiller capacity at current conditions.

The chiller's power consumption at current conditions is calculated as follows:

$$P = \frac{CAP_{act}}{COP_{nom}} FFLP \tag{7}$$

where COP_{nom} is chiller nominal COP at the current conditions, and FFLP is fraction of full load power.

COP is calculated as:

$$COP = \frac{\dot{Q}_{met}}{P} \tag{8}$$

The rejected energy to the cooling water flow is calculated as:

$$\dot{Q}_{rejected} = \dot{Q}_{met} + P \tag{9}$$

The outlet chilled water temperature ($T_{chw,out}$) is determined as:

$$T_{chw,out} = T_{chw,in} - \frac{\dot{Q}_{met}}{\dot{m}_{chw} C_{p_{chw}}} \tag{10}$$

The outlet cooling water temperature ($T_{cw,out}$) is:

$$T_{cw,out} = T_{cw,in} - \frac{\dot{Q}_{rejected}}{\dot{m}_{cw} C_{p_{cw}}} \tag{11}$$

where $T_{cw,in}$ is inlet cooling water temperature.

Finally, the temperature of mixed chilled water leaving the chiller network is obtained by the following expression:

$$T_{chw,out,M}=\frac{\sum_{i=1}^{n}\dot{m}_{chw,i}T_{chw,out,i}}{\sum_{i=1}^{n}\dot{m}_{chw,i}} \tag{12}$$

In this work, the modelling of each chiller is based on the predicted data provided by the ANN using the data from manufacturers. According to the above equations, to calculate the energy consumption of each chiller, COP and actual cooling capacity of each chiller predicted by ANN will be calculated as follows:

$$CAP_{act,i}=f\left(T_{chw,out,i},T_{cw,in,i}\right) \tag{13}$$

$$COP_i=f\left(PLR_i,T_{chw,out,i},T_{cw,in,i}\right) \tag{14}$$

3.2.2. Cooling Towers

The model employed in this research provides performance estimates for a cooling tower without requiring knowledge of its detailed configuration. Instead, it calculates an overall heat transfer coefficient (UA) for the tower by using the design inlet and outlet conditions. That UA value is then used to estimate performance under other different inlet conditions.

The inlet saturated air enthalpy is calculated based on the inlet dry bulb and a relative humidity of 100%. The capacity rate of the cooling water stream is determined.

$$C_{cw}=\dot{m}_{cw}C_{p_{cw}} \tag{15}$$

The component then guesses an outlet wet-bulb temperature and calculates the tower performance for those conditions. The outlet saturated air enthalpy is calculated based on the outlet wet-bulb temperature and a relative humidity of 100%. A fictitious specific heat and capacity rate are calculated from the saturated enthalpies and airflow rate:

$$C_{p_{air,fictitious}}=\frac{h_{air,out}-h_{air,in}}{T_{wb,out}-T_{wb,in}} \tag{16}$$

$$C_{air}=C_{p_{air,fictitious}}\dot{m}_{air} \tag{17}$$

The maximum and minimum of the water and air capacity rates are determined, and the ratio of the capacity rates is calculated.

$$C_{min}=Min(C_{cw},C_{air}) \tag{18}$$

$$C_{max}=Max(C_{cw},C_{air}) \tag{19}$$

$$C_{ratio}=\frac{C_{min}}{C_{max}} \tag{20}$$

The design UA value is adjusted based on the fictitious specific heat.

$$UA_{fictitious}=UA_{design}\frac{C_{p_{air,fictitious}}}{C_{p_{air}}} \tag{21}$$

The NTU for the adjust UA value is calculated.

$$NTU=\frac{UA_{fictitious}}{C_{min}} \tag{22}$$

The effectiveness of the tower with the current conditions is calculated from the NTU. If the ratio of the capacity rates is greater than 0.995 then:

$$\varepsilon=\frac{NTU}{NTU+1} \tag{23}$$

Otherwise:

$$\varepsilon=\frac{1-e^{(-NTU(1-C_{ratio}))}}{1-C_{ratio}.e^{(-NTU(1-C_{ratio}))}} \tag{24}$$

With the effectiveness, the heat transfer of cooling tower and leaving wet bulb temperature are calculated.

$$Q_{CT}=\varepsilon C_{min}\left(T_{cw,in}-T_{wb,in}\right) \tag{25}$$

$$T_{wb,out}=T_{wb,in}+\frac{Q_{CT}}{C_{air}} \tag{26}$$

The component iterates until the guessed and calculated outlet wet-bulb temperatures agree, and then the outlet water temperature is calculated.

$$T_{cw,out} = T_{cw,in} - \frac{Q_{CT}}{C_{water}} \tag{27}$$

3.2.3. Pumps

The power consumptions of chilled water and cooling water pumps are given by Ref. [47]:

$$P_{pump,chilled\ water,i} = \frac{\gamma_w H_{chw,i} m_{chw,i}}{\eta_i} \tag{28}$$

$$P_{pump,cooling\ water,i} = \frac{\gamma_w H_{cw,i} m_{cw,i}}{\eta_i} \tag{29}$$

where γ_w is the specific weight of water, $H_{chw,i}$ and $H_{cw,i}$ are the heads of chilled water and cooling water streams, and η_i is the efficiency of pump.

3.2.4. Total energy consumption

The total energy consumption of the chiller plant consists of the energy consumed by the chillers, cooling towers, chilled water pumps, and cooling water pumps. The energy consumption for various configurations can be obtained at each time step by solving the OCL problem. The following equation shows the energy consumption of the chiller plant in each time step:

$$E_{plant}(t)(MWh) = \sum_{i=1}^{N} E_{Chiller,i}(t) + \sum_{j=1}^{G} E_{CoolingTower,j}(t) + \sum_{k=1}^{K} E_{Pump,k}(t) \tag{30}$$

The annual energy consumption for chiller network ($OC_{Chillers,\ annual}$), cooling towers ($OC_{CoolingTowers,\ annual}$), and pumps ($OC_{Pumps,\ annual}$) are calculated as:

$$OC_{Chillers,annual} = \sum_{t=2160}^{6528} \sum_{i=1}^{N} E_{Chiller,i}(t) \tag{31}$$

$$OC_{CoolingTowers,annual} = \sum_{t=2160}^{6528} \sum_{j=1}^{G} E_{CoolingTower,j}(t) \tag{32}$$

$$OC_{Pumps,annual} = \sum_{t=2160}^{6528} \sum_{k=1}^{K} E_{Pump,k}(t) \tag{33}$$

Then the annual total energy consumption for chiller plant is calculated as follows:

$$OC_{plant,annual}(MWh) = OC_{Chillers,annual} + OC_{CoolingTowers,annual} + OC_{Pumps,annual} \tag{34}$$

The annual COP for the chiller plant is defined as follows:

$$COP_{annual} = \frac{Cooling_{output,annual}}{OC_{plant,annual}} \tag{35}$$

where $Cooling_{output,\ annual}$ is the total cooling produced by chiller plant in a cooling season.

3.3. Environmental analysis

The indirect environmental impact of the analysed system is quantified by calculating the greenhouse gas emissions in terms of CO_2 equivalents as a result of the chiller plant operation [48]. Considering that the chiller's electricity consumption originates from a thermal power plant, each unit of power consumption is accompanied by fuel combustion-related emissions. The electricity generated by thermal power plants emits about 0.9 tons of carbon dioxide for each MWh [49]. Therefore, the CO_2 emissions is estimated as follows;

$$Em_{CO_2}\ (tons) = P_{plant}\ (MWh) \times 0.9 \tag{36}$$

The environmental impact will be converted into an economic impact through the implementation of a carbon tax, which will in turn have an effect on the cost performance of the system [50]. The carbon tax is assumed to be 50 ($\$/t_{CO_2}$) in this study. The environmental cost is calculated as:

$$EC = Em_{CO_2}\ (tons) \times 50\ (\$/t_{CO_2}) \tag{37}$$

3.4. Economic analysis

In this section, the LCC analysis is presented, which takes into account the chiller plant lifetime and the consumer discount rate. The following equation shows the LCC relation [7]:

Table 2
Cost functions.

Name	Cost function	NO	Ref.
Chiller	$IC_{Chiller}(\$)\ = IC_0 * \left(\frac{Qch_n}{Qch_0}\right)^{0.75}$	(41)	[34]
Cooling tower	$IC_{Cooling\ Tower}(\$)\ = 746.749 \times \dot{m}_{CT}^{0.71} \times \Delta T_{CT}^{0.57}(T_{in,CT} - T_{out,CT})^{-0.9924} \times (0.022 \times T_{wb,out} + 0.39)^{2.447}, year_{ref}\ = 2006$	(42)	[51]
Pump	$IC_{Pump}(\$)\ = 705.48 \times P_{Pump}^{0.71} \times \left(1 + \frac{0.2}{\eta_P}\right), year_{ref}\ = 2006$	(43)	[51]

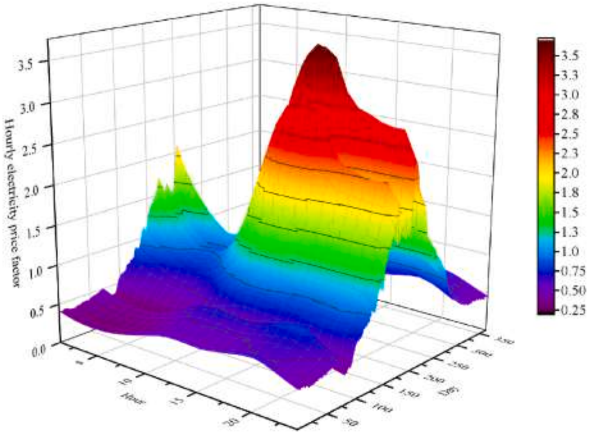


Fig. 7. The hourly electricity price factor.

$$LCC\ (\$) = IC + PVF * (OC + MC + EC) \tag{38}$$

where IC, OC, MC, and EC are investment cost, operating cost, maintenance cost, and environmental cost, respectively, and PVF is the Present Value Factor:

$$PVF = \sum_{t=1}^{N} \frac{1}{(1+r)^t} = \frac{1}{r}\left[1 - \frac{1}{(1+r)^N}\right] \tag{39}$$

where r is the discount rate (considered 0.1), and N is the chiller plants lifetime (considered 25 years [10]).

Operating Costs (OC), Maintenance Costs (MC), and environmental costs (EC) are presented in the following sections.

3.4.1. *Investment costs*

The investment cost of the chiller plant consists of the cost of purchasing chillers, cooling towers, and pumps.

$$IC_{Plant}(\$) = IC_{Chillers} + IC_{Cooling\ Towers} + IC_{Pumps} \tag{40}$$

The cost functions used to determine the investment cost for chillers, cooling towers, and pumps are presented in Table 2.

The last available Chemical Engineering Plant Cost Index (CEPCI) should be used to update these cost functions from their reference year to the current year:

$$IC_{Present\ year} = IC_{Reference\ year} \times \left[\frac{CEPCI_{Present\ year}}{CEPCI_{Reference\ year}}\right] \tag{44}$$

3.4.2. *Operation costs*

The cost of electricity consumption of each configuration in each time step is calculated as follows:

$$OC(t)(\$) = E_{plant}(t) * Cost_{elec}(t) \tag{45}$$

where $Cost_{elec}(t)$ is the cost of electricity in each time step, calculated as:

$$Cost_{elec}(t) = PF_{elec}(t) * Tariff_{elec} \tag{46}$$

where $Tariff_{elec}$ is the electricity tariff which is different in different parts of the world, based on the primary source used and different policies [52]. The tariff varies between 2 and 536 USD/MWh in different parts of the world. The world average price is 160 USD/MWh. $PF_{elec}(t)$ is the hourly price factor, which is a measure for valuing electricity at different hours of the day and night and during different days of the year. Hourly price factor information is available for 8,760 h in one year for Iran [53], which is shown in Fig. 7.

Therefore, the annual cost of electricity consumption of the chiller plant is calculated as:

$$\mathrm{OC}(\$) = \sum_{t=2160}^{6528} \mathrm{OC}(t) \tag{47}$$

3.4.3. Maintenance cost

The maintenance cost ($\mathrm{MC_i}$) for a chiller is proportional to its nominal capacity ($\mathrm{CAP_{nom}}$) [7]:

$$\mathrm{MC_i} = \mathrm{CAP_{nom,i}} * \mathrm{Mc_i}, \mathrm{Mc_i} = \left\{ \begin{array}{c} 6.17 \left(\mathrm{US\$}/_{\mathrm{kW}}\right) \left(\mathrm{CAP_{nom,i}} < 528\ \mathrm{kW}\right) \\ 4.63 \left(\mathrm{US\$}/_{\mathrm{kW}}\right) \left(528\ \mathrm{kW} < \mathrm{CAP_{nom,i}} < 1,055\ \mathrm{kW}\right) \\ 2.57 \left(\mathrm{US\$}/_{\mathrm{kW}}\right) \left(\mathrm{CAP_{nom,i}} \geq 1,055\ \mathrm{kW}\right) \end{array} \right\} \tag{48}$$

The maintenance cost for the chiller plant is calculated as follows:

$$\mathrm{MC_{plant}}(\$) = \mu * \sum_{i=1}^{N} \mathrm{MC_i} \tag{49}$$

where μ, is an equilibrium factor equal to 0.8 for a plant with one to two chillers, and 0.7 for a plant with three or more chillers [7].

3.5. Control strategy

In a chiller network, how to control the chillers is a crucial issue discussed in the literature review. In this research, two control strategies have been applied to the proposed chiller network. One strategy is a conventional control strategy in order to enable comparison, and the other strategy is the optimal control strategy.

In both strategies, the flow rate of chilled water and cooling water of all chillers are considered constant. As it will be explained later, the set-point temperature of each chiller is used as a chiller load controller. According to the considered decoupled system, the temperature of the chilled water returning from the building is set at a constant value (14 °C) in all conditions.

3.5.1. Baseline control strategy (same load sharing)

The baseline strategy is the most common and straightforward control method of chillers, which does not require complex operations or measurements. This strategy can only be applied to the plant with the same chillers. This strategy distributes the same load among the chillers. In this method, the set-point temperature for supply chilled water is fixed at a specific value. This value could be a temperature between the minimum and maximum allowable temperature (for example, (5–10 °C) which is defined for supply chilled water temperature. The lower the value of this set-point, the lower the COP of the chiller and the higher its actual cooling capacity. So, if this set point is set to its minimum value (5 °C), it will result in the highest potential for cold production and the lowest COP. Moreover, if it is set to the maximum value (10 °C), it will have the lowest cooling potential and the highest COP. In this strategy, according to the return chilled water temperature (which changes with the building's cooling demand change), the PLR of each chiller that must work to reach the set point is determined.

3.5.2. Optimal control strategy (PSO algorithm)

In optimal control strategy, the PSO algorithm [54] is used to determine the on/off status of chillers and the PLR of each chiller. In this strategy, in each hour of the simulation, a way to optimally control the chiller network is determined. Optimal mode detection is done by knowing the cooling demand and weather information in each hour, and performance information of each chiller. This strategy determines the number of chillers in operation and the PLR of each that results in the lowest energy consumption per hour of simulation.

3.5.2.1. Optimization method (PSO). The goal of the optimization problem is to minimize the chiller network's electricity consumption. As a first step, the system (the chiller plant) is decoupled to examine only the direct interaction between the chiller network and the building's cooling demand. It is necessary to choose the objective functions, decision variables, and constraints for the problem as part of the optimization process [51].

One objective function is considered in the optimization, which is minimizing the power consumption by N chillers as an energy criterion.

$$\mathrm{OF} = \min_{\mathrm{PLR}} \sum_{i=1}^{N} \mathrm{P_i^t} \tag{50}$$

The PSO algorithm is used to report the optimal values of the objective function. Two decision variables are defined as $\mathrm{PLR_i^t}$ (PLR of chiller i at hour t) and $\mathrm{S_i^t}$ (status of chiller i at hour t). $\mathrm{S_i^t}$ is a binary decision variable that equals to 1 if the chiller i turns on at hour t, otherwise it will be zero.

One constraint is the cooling demand of the building at each hour t ($\mathrm{CL_t}$) that should be satisfied by the chillers. In which, $\mathrm{CAP_{act}}_i^t$

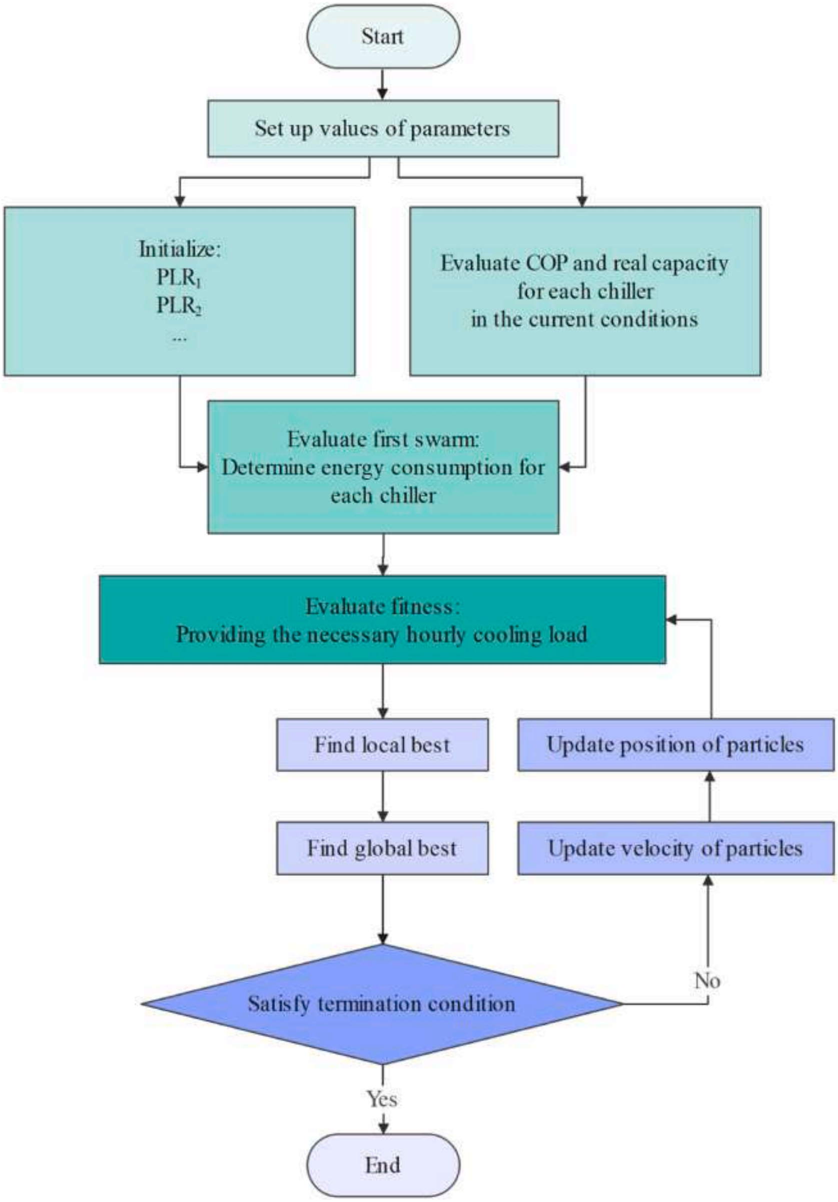


Fig. 8. PSO algorithm flowchart.

Table 3
Parameters for PSO algorithm [29,56].

Parameter	Value
Population size	50
Maximum number of iterations	100
w	1
w_{damp}	0.99
c_1	2
c_2	2

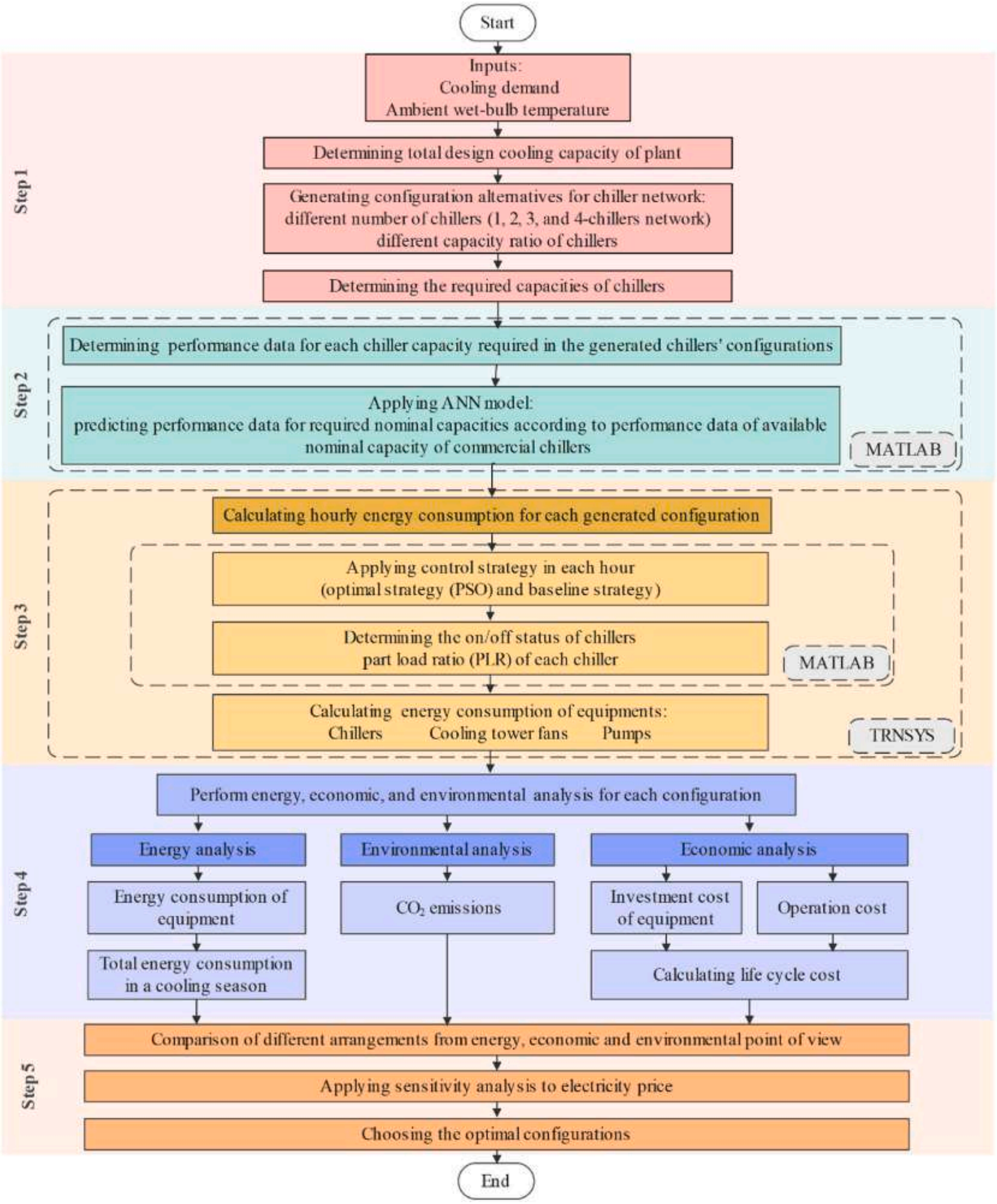


Fig. 9. Simulation process flowchart.

indicates the actual cooling capacity of chiller i at hour t [14].

$$CL_t = \sum_{i=1}^{N} \left(S_i^t \times PLR_i^t \times CAP_{act_i}^{\,t} \right) \text{ s.t. } PLR_{min} \leq PLR_i \leq 1 \tag{51}$$

Another constraint is the time interval between chiller shutdown and restart. This constraint prevents damage caused by frequent on/off switching. Chang et al. [55] recommend a time interval of 30 min to an hour. Fig. 8 depicts the flowchart of the PSO algorithm. The parameters for PSO algorithm are presented in Table 3. The population size and the maximum number of iterations should be properly specified to attain a reliable convergence. w is the inertia weight utilized for balancing the global search and local search and w_{damp} is the inertia weight damping ratio. The w_{damp} is multiplied by w at the end of each iteration, which is applied to update the particles' velocity in each iteration. c_1 and c_2 are acceleration coefficients. The appropriate selection of these coefficients prevents getting stuck in a local optimal solution, as a result, the algorithm works more efficiently [56].

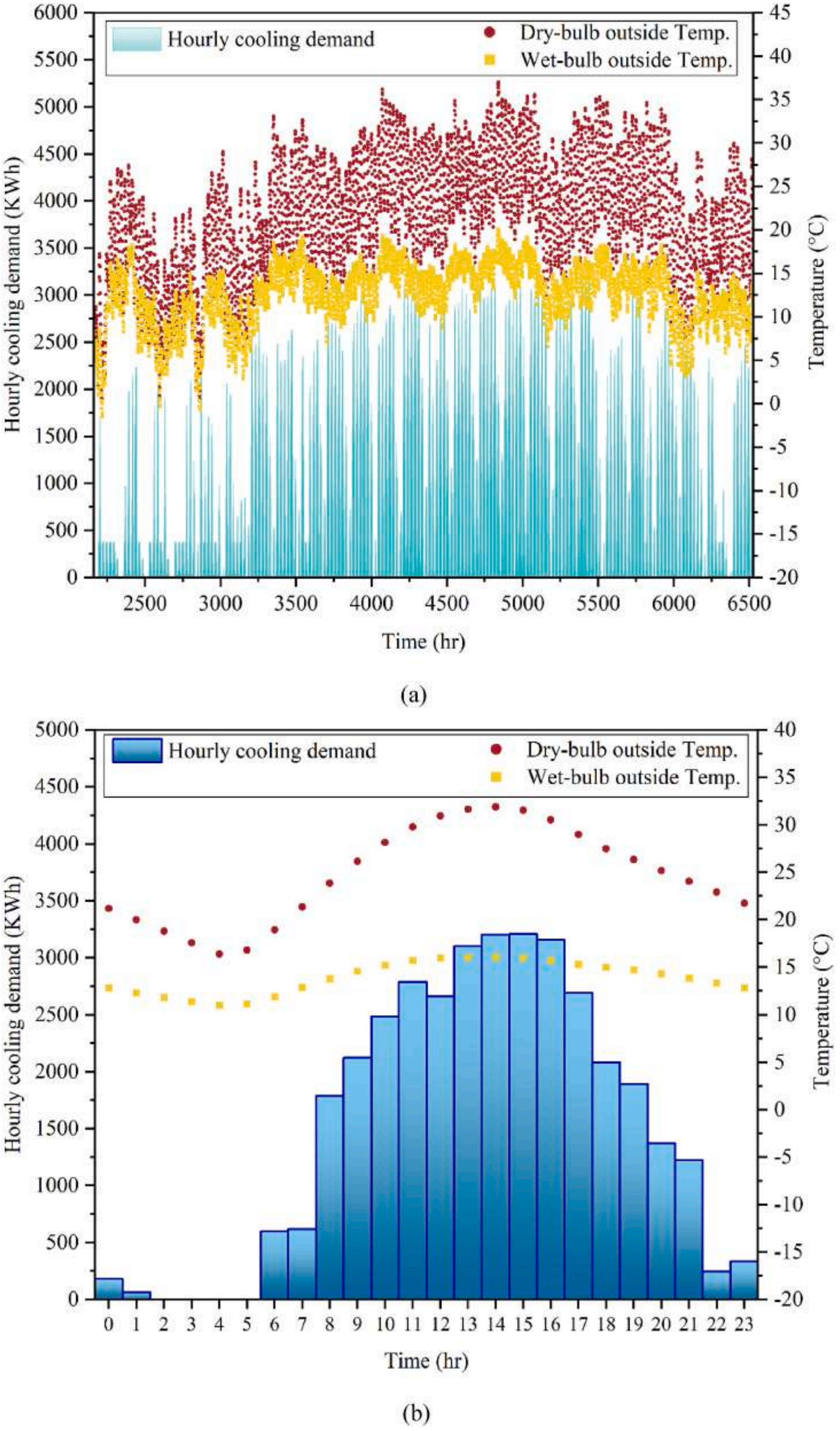
Fig. 10. The building of the faculty of engineering.

Table 4
The specification of the HVAC system in the selected case study.

Term	Value	Term	Value
Chillers quantity	1-N	Primary chilled water pump quantity	4
Chillers rated cooling capacity (RT)	100–1000	Primary chilled water pump rated flow ($\mathrm{m}^3/_\mathrm{h}$)	100
Chillers rated COP	3–6	primary chilled water pump rated power (kW)	17.4
Chilled water outlet temperature (°C)	5–10	Primary chilled water pump head (m)	5
Cooling water inlet temperature (°C)	15–30	Cooling water pump quantity	4
Refrigerant	R134a	Cooling water pump rated flow ($\mathrm{m}^3/_\mathrm{h}$)	150
		Cooling water pump rated power (kW)	18.2
		Cooling water pump head (m)	3.5
		Cooling tower quantity	4
		Cooling tower rated flow ($\mathrm{m}^3/_\mathrm{h}$)	150
		Cooling tower fans rated power (kW)	7.5

3.6. Simulation process

The energy analysis of the problem is carried out in TRNSYS software. In order to apply the PSO algorithm as an optimal performance control strategy, TRNSYS software is linked with MATLAB software. The simulation process flowchart is demonstrated in Fig. 9. For each configuration, the total energy consumption of the chiller plant during a complete cooling season is calculated. For each configuration, in each time step (1 h), the PSO algorithm provides the optimal PLR values for each chiller, which leads to the minimum energy consumption by the chillers while satisfying the constraints of the problem. In each time step, the cooling demand, weather conditions (including dry-bulb and wet-bulb temperatures) change, which leads to a change in chiller performance.



(a)

(b)

Fig. 11. (a) Hourly cooling demand and the hourly weather conditions for the case study (b) Hourly cooling demand, dry-bulb, and wet-bulb temperature for a typical hot day in summer (13th august) [57].

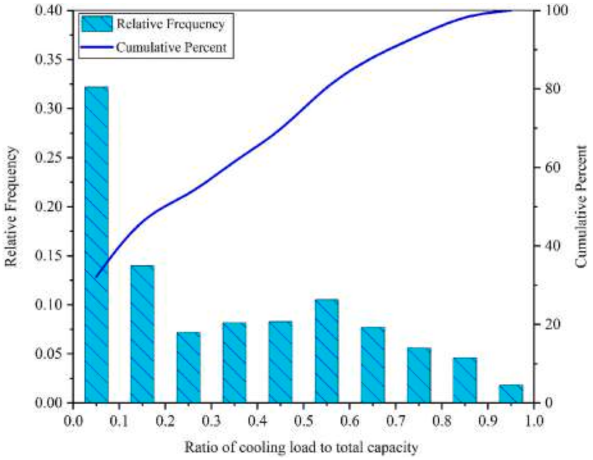


Fig. 12. Cooling demand histogram and accumulation.

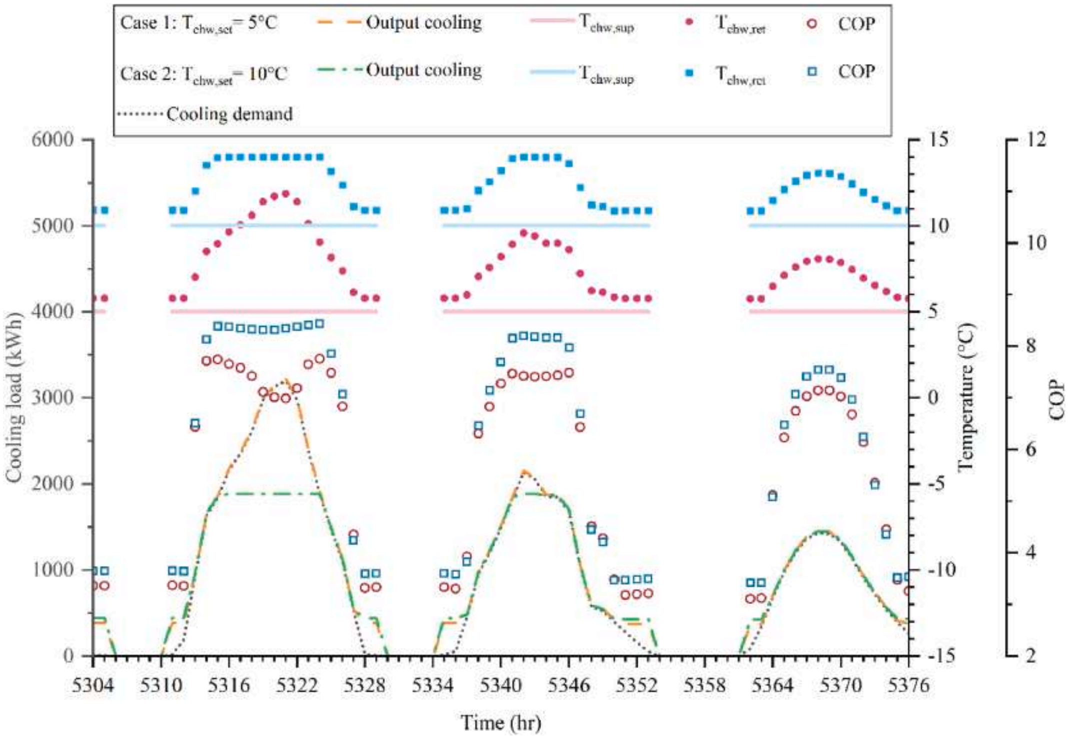


Fig. 13. Baseline strategy: effect of set-point temperature.

4. Results and discussion

In this section, the investigated case study is explained first. Then the results of energy analysis, economic analysis, and environmental analysis are presented. In addition, the decision of choosing the optimal chiller network is discussed.

4.1. Case study

As a case study, the Faculty of Engineering at Ferdowsi University of Mashhad was chosen (Fig. 10) as the case study. The city of Mashhad located in the northeast of Iran (36.2972°N, 59.6067°E) has cold winters and relatively hot and dry summers. This building has three floors above ground. The building height and its total area are 22.5 m and 29,510 m^2, respectively.

Considering that the focus of the present study is on the design of chiller network, the number of primary chilled water pumps, cooling water pumps, and cooling towers has been chosen to equal 4 for all the investigated configurations. The total flow rate of cooling water and chilled water required for the cooling system with a capacity of 1000 RT is calculated to be 600 m^3/h and 400 m^3/h,

Table 5
Comparison of the effect of chilled water set-point temperature.

Case	1	2
Set-point (°C)	5	10
Total annual energy consumption (MWh)	1,112	1,044
Unmet cooling demand (MWh) (%)	0.12 (0.01%)	363.61 (11.65%)
Unmet hours (hr) (%)	4 (0.09%)	681 (15.64%)
Extra output cooling (MWh) (%)	367.22 (11.77%)	425 (13.62%)
Extra hours (hr) (%)	3,114 (71.52%)	2,437 (55.97%)
COP_{annual}	3.13	3.05

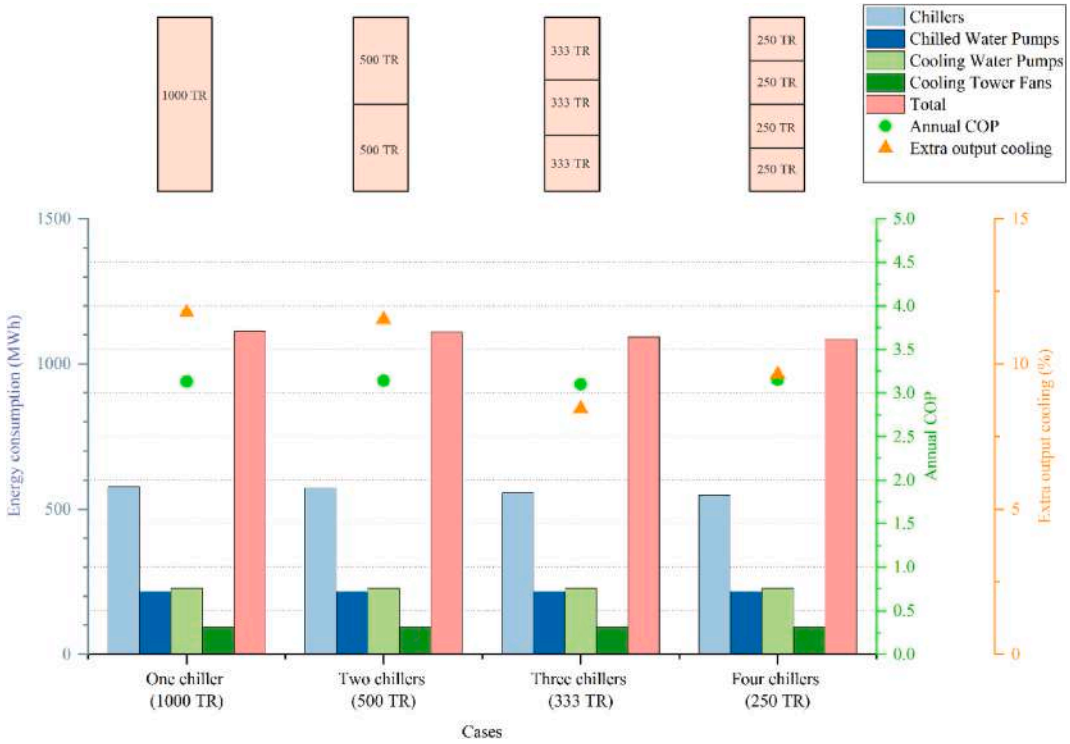


Fig. 14. Baseline strategy: effect of chiller number.

respectively. The rated power of each pump is calculated based on the rated flow rate of water and the required head. The cooling towers are selected based on the rated flow rate of cooling water and the 5 °C range temperature. The specification of the HVAC system in this case study is presented in Table 4.

To achieve the hourly energy analysis of the chiller network, it is necessary to know the hourly cooling demand and the hourly weather conditions. Hourly cooling demand, dry-bulb, and wet-bulb temperature per hour for a complete cooling season are shown in Fig. 11 a. The cooling season for the case study region is defined from April to September. The detailed information for the building specifications and cooling load calculations of the selected case study are presented in Ref. [57].

To determine the entire cooling capacity of the system, not only the maximum cooling demand, but also unmet hours, should be considered. According to the ASHRAE [58], unmet hours are any hours of operation during which the chiller plant's cooling capacity does not meet the cooling demand of the building. The maximum cooling demand for this case study is 956 TR. The chiller plant's total cooling capacity is calculated as the capacity corresponding to 50 unmet hours, which is 816 TR. To ensure reliability and safety, a safety factor of 10–15% is applied. Therefore, the chiller plant's total cooling capacity is considered 1000 TR for this case study. In Fig. 11 b, hourly cooling demand, dry-bulb, and wet-bulb temperature for a typical hot day in summer (13th august) are shown.

To create different possible options for chiller network configurations, it is helpful to know the number of hours that each cooling load is required. For this purpose, the cooling demand histogram and accumulation are shown in Fig. 12. To express this issue in a more general way, the ratio of cooling load to total capacity has been used to divide the horizontal axis intervals.

4.2. Results of energy analysis

The results of energy, economic, and environmental analysis are presented in this section for the selected case study. To enable a proper comparison, first, the energy results related to the baseline strategy are stated, then the energy results related to the optimal

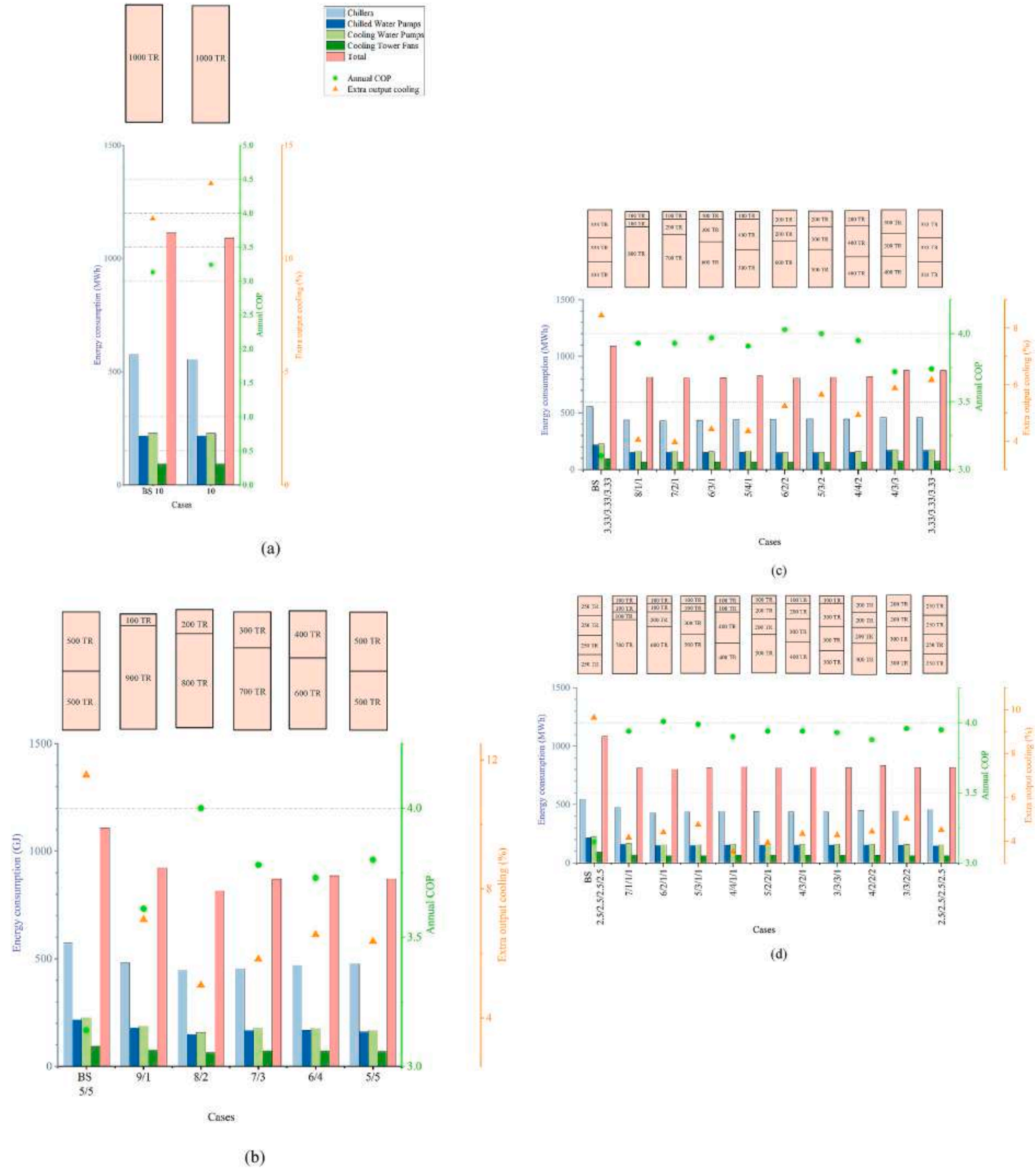


Fig. 15. Energy consumption for different chiller plants (a) One-chiller plant (b) Two-chillers plant (c) Three-chillers plant (d) Four-chillers plant.

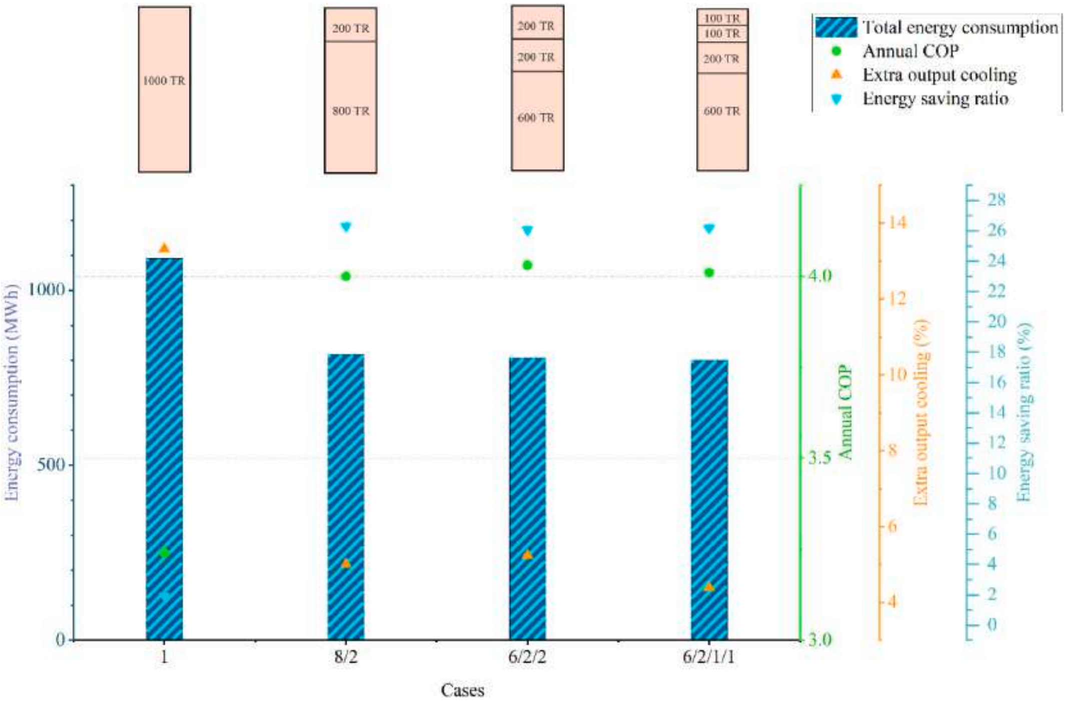


Fig. 16. Optimal configurations of each network from energy point of view.

strategy (PSO) are presented and compared. Then, the results of economic analysis are presented. Finally, the sensitivity analysis to electricity price is performed and the selection of the optimal configuration is discussed.

4.2.1. *Baseline strategy*

In the baseline strategy, the set-point temperature for chilled water is considered to be constant. The range that this set-point can vary is assumed to be between 5 and 10 °C for all chillers in the present study. The question raised here is what should be this temperature? The higher the value of this set-point, the greater the COP and available capacity of the chiller. However, according to the assumption of a maximum temperature of 14 °C for the return chilled water temperature, if this temperature is set to the maximum allowed value (10°C), the chiller cannot work at its maximum capacity. So there is a contradiction between the thermal comfort conditions inside the building and the efficiency of the system. Two cases 1 and 2 are defined with set-point temperatures of 5 and 10 °C. The hourly results for these two different set-point temperatures for a sample week are presented in Fig. 13. The overall results for a cooling season are compared in Table 5. The case1 (set-point 5°C) leads to an acceptable supply of the cooling demand and higher COP_{annual}, in contrast, the case2 (set-point 10 °C) is unable to fully supply the cooling demand of the building in 15.64% of the time (due to the limitation of the difference of supply and return temperature to provide thermal comfort conditions). As a result, in this strategy, the lowest allowed set-point temperature (5 °C) is considered to provide thermal comfort conditions.

Fig. 14 shows energy consumption, annual COP, and extra output cooling for chiller plants with different chiller numbers under the baseline control strategy. It should be noted that the baseline strategy can only be applied to the network of chillers with the same chillers. As the number of chillers increases, the chillers energy consumption decreases, and due to the almost constant energy consumption of other equipment, the total energy consumption decreases. The annual COP for four different configurations is almost the same and has a slight difference of about 1%, but the extra output cooling for three-chillers plant is less than other options.

4.2.2. *Optimal strategy*

The energy consumption for different chiller plants under PSO strategy is shown in Fig. 15. In order to be able to compare with the baseline strategy, the results related to this strategy are presented along with the results of the PSO strategy.

In order to achieve a comprehensive comparison between different configurations, the total annual energy consumption is shown in Fig. 16. For all plant options (one, two, three, and four-chillers), applying the PSO strategy leads to a decrease in the total energy consumption compared to the baseline strategy by 1.92, 26.3, 26.06, and 26.18%, respectively. So, with the increase in the number of chillers, the plant performance in terms of energy is improved, and the annual COP also increases. Also, extra output cooling for all options (except one-chiller plant) is reduced compared to the baseline strategy.

Table 6
Details values for LCC analysis for a sample case “8/2”

	Item	Cost (1000 USD)
Investment costs	Chillers	283
	Cooling towers	19.21
	Pumps	20.57
Operation cost	Maintenance	8.40
	Electricity	233.57
	Environmental	36.79
LCC		2,519.42

&lev1;4.3Economic evaluationIn the current research, the LCC criterion is used for the economic evaluation of different configurations. Based on the LCC equation, the LCC depends on the investment cost and the annual operating cost.The details of values for different terms in the LCC analysis for the case “8/2” as a sample case are presented in Table 6 (considering the world average electricity price of 160 USD/MWh).The investment cost, annual operating cost, and LCC for different configurations are shown in Fig. 17. The investment cost related to different configurations is different due to the various sizes of chillers. The smaller a chiller, the higher the investment cost required. The annual operating cost is dependent on the electricity tariff, which is considered to be the world average price of 160 USD/MWh in this graph. For different configurations, with the number of one, two, three, and four chillers, the annual operating cost in the optimal case is reduced by 2.75, 19.64, 19.48, and 20.55%, respectively, by applying the PSO strategy compared to the baseline strategy. For different configurations, with the number of two, three, and four chillers, the optimal configuration in terms of LCC are the cases 4.3. Economic evaluation

In the current research, the LCC criterion is used for the economic evaluation of different configurations. Based on the LCC equation, the LCC depends on the investment cost and the annual operating cost.

The details of values for different terms in the LCC analysis for the case “8/2” as a sample case are presented in Table 6 (considering the world average electricity price of 160 USD/MWh).

The investment cost, annual operating cost, and LCC for different configurations are shown in Fig. 17. The investment cost related to different configurations is different due to the various sizes of chillers. The smaller a chiller, the higher the investment cost required. The annual operating cost is dependent on the electricity tariff, which is considered to be the world average price of 160 USD/MWh in this graph. For different configurations, with the number of one, two, three, and four chillers, the annual operating cost in the optimal

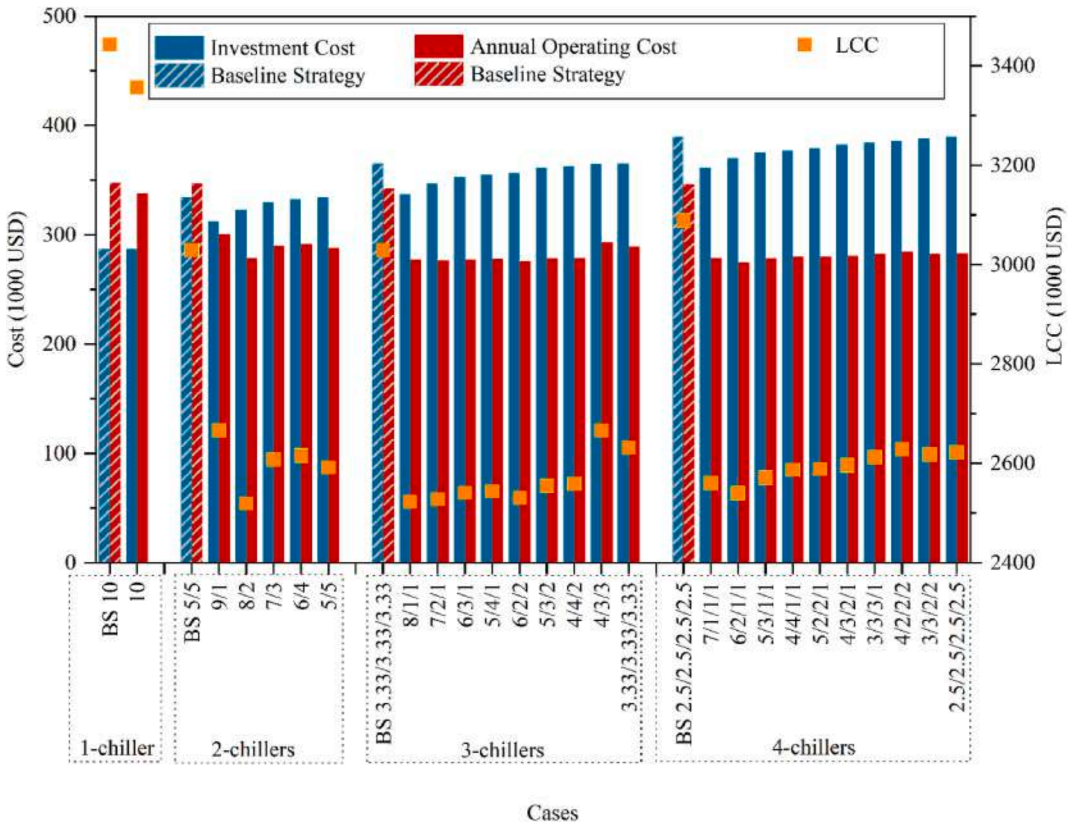


Fig. 17. Investment cost, annual operating cost, and LCC.

case is reduced by 2.75, 19.64, 19.48, and 20.55%, respectively, by applying the PSO strategy compared to the baseline strategy. For different configurations, with the number of two, three, and four chillers, the optimal configuration in terms of LCC are the cases "8/2", "8/1/1", and "6/2/1/1", with LCC of 2519.4, 2522.6, and 2540 (1000 USD), respectively. By comparing these values with a base configuration (where the network has two symmetrical chillers under the baseline strategy), these LCC values are reduced by 16.84, 16.73, and 16.15%, respectively. As a result, if the amount of LCC is considered in deciding the optimal chiller network arrangement, for the electricity price of 160 USD/MWh, the optimal selection is the case "8/2". If, for any other reason, such as facility room space limitation or purchase restrictions in the market, the decision is made to use a three or four-chillers network instead of a two-chillers network, the optimal case for these networks is also identified.

Since LCC is dependent on electricity price, the sensitivity of LCC value to electricity price is shown in Fig. 18. In this figure, the lowest LCC value for base configuration, two, three, and four-chillers networks are displayed, for different electricity prices from 10 to 800 USD/MWh. Also, the percentage of LCC reduction for these configurations compared to the base configuration is displayed. The two-chillers network has the lowest LCC for the electricity tariff up to 255 USD/MWh, while for tariffs greater than 255 USD/MWh, the four-chillers network has the lowest LCC. By increasing the electricity tariff up to 255 USD/MWh, the LCC reduction for all configurations increases significantly. By increasing the electricity tariff to more than 255 USD/MWh, this reduction will be fixed at 17–19%.

4.4. *CO_2 emissions*

As mentioned in section 3, the CO_2 emissions and environmental cost is directly related to the electricity consumption. In Fig. 19, the CO_2 emissions for different cases is displayed. For the baseline strategy, this value decreases slightly as the number of chillers increases. Applying the PSO strategy in all cases leads to a reduction in the CO_2 emissions compared to the baseline strategy. For the PSO strategy, the lowest CO_2 emissions for the one, two, three, and four-chillers network corresponds to the configurations of “10”, “8/2”, “6/2/2”, and “6/2/1/1”, is equal to 982.26, 735.78, 726.72, and 720.54 tones, respectively. For the chiller plant with two, three, and four chillers, choosing the optimal configuration under the optimal control strategy compared to the baseline configuration and strategy leads to an annual reduction of 26.30, 26.06, and 26.18% of CO_2 emissions, respectively, which is equivalent to 262, 256, and 255 tons of CO_2.

5. Conclusion

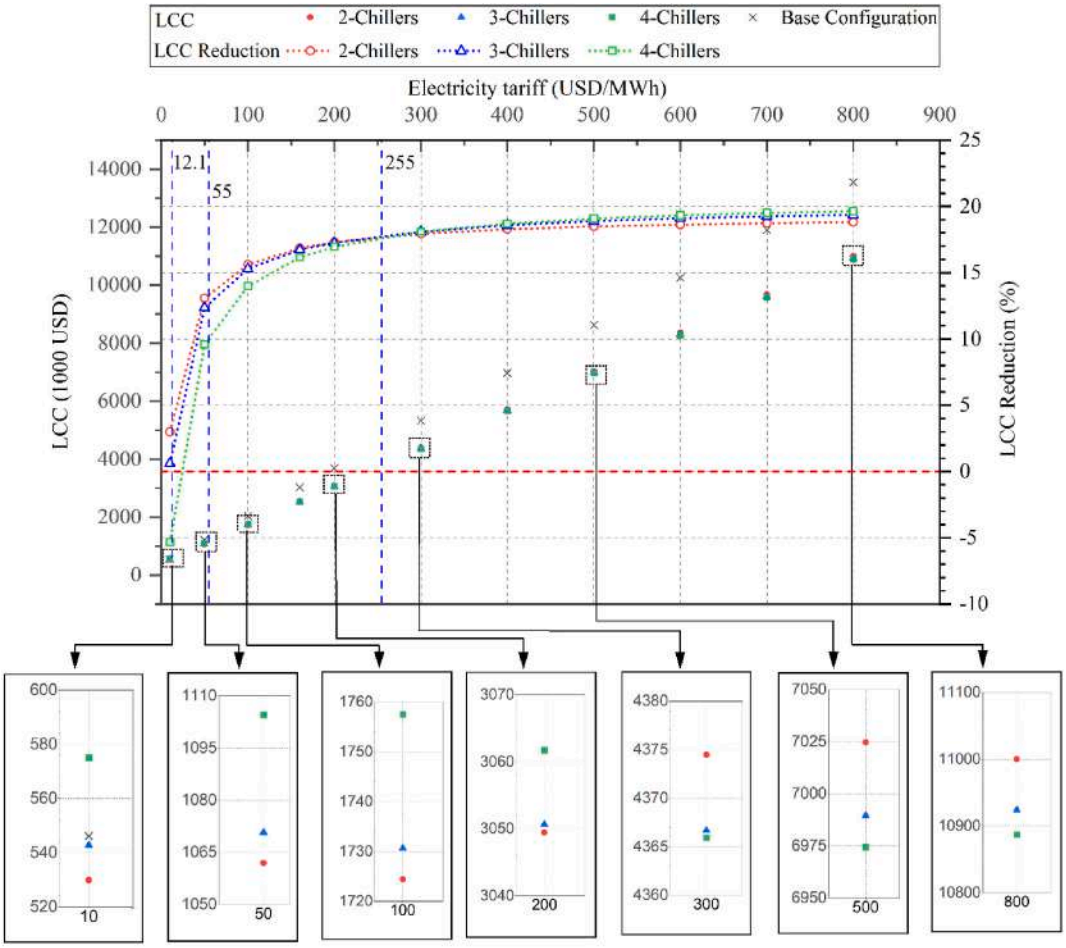
In this study, a general procedure for designing a compression chiller network is presented. The investigated procedure is based on ANN model and PSO search algorithm. The performance of chillers, which includes COP and actual capacity, was considered dependent on nominal capacity, chilled water temperature, cooling water temperature, and PLR. The performance curve of the chiller with arbitrary capacities were determined by applying an ANN model to the performance curve data of the available commercial chillers on the market. The PSO control strategy is applied on the chiller network to solve the OCL problem and minimize the hourly energy consumption of the chiller plant.

The different configurations of the chiller network are generated in terms of the quantity and ratio of the nominal capacity of the chillers. In order to achieve a comprehensive energy, economic, and environmental analysis, the hourly energy consumption of the chiller plant was evaluated for a cooling season for each generated configuration.

The proposed method was applied on a large building with specific cooling demand as a case study. The results obtained from the analysis of this case study demonstrated that:

- **In the perspective of energy analysis**, the optimal configuration for chiller plant with two, three, and four chillers is case “8/2”, “6/2/2”, and “6/2/1/1”, respectively.
- The annual total energy consumption for cases “8/2”, “6/2/2”, and “6/2/1/1” is 817.53, 807.47, and 800.60 MWh, respectively.
- For the optimal configurations, applying the PSO control strategy compared to the baseline strategy led to a decrease of about 26% in annual energy consumption.
- **In the perspective of economic analysis**, considering the world average electricity price of 160 USD/MWh, the optimal configuration for chiller plant with two, three, and four chillers is case “8/2”, “8/1/1”, and “6/2/1/1”, respectively.
- The LCC for cases “8/2”, “8/1/1”, and “6/2/1/1” is 2519.4, 2522.6, and 2540 (1000 USD), respectively.
- The sensitivity analysis of LCC to electricity price showed that for the electricity price up to 255 USD/MWh, the two-chillers network has the lowest LCC; while for prices greater than 255 USD/MWh, the four-chillers network has the lowest LCC.
- By increasing the electricity price from 10 to 255 USD/MWh, the LCC reduction for all configurations increases significantly. By increasing the electricity price to more than 255 USD/MWh, this reduction will be fixed at 17–19%.
- **In the perspective of environmental analysis**, for the chiller plant with two, three, and four chillers, choosing the optimal configuration under the optimal control strategy compared to the baseline configuration and strategy leads to an annual reduction of 26.30, 26.06, and 26.18% of CO_2 emissions, respectively, which is equivalent to 262, 256.15, and 255.49 tons of CO_2.

As a summary, the correct selection of the chiller network configuration in terms of the number and capacity ratio in the initial



	EP<12.1	12.1<EP<55	55<EP<255	255<EP
2-Chillers	9/1	8/2	8/2	8/2
3-Chillers	8/1/1	8/1/1	8/1/1	6/2/2
4-Chillers	7/1/1/1	7/1/1/1	6/2/1/1	6/2/1/1

1st choice

2nd choice

3rd choice

Fig. 18. Sensitivity analysis of electricity price on LCC.

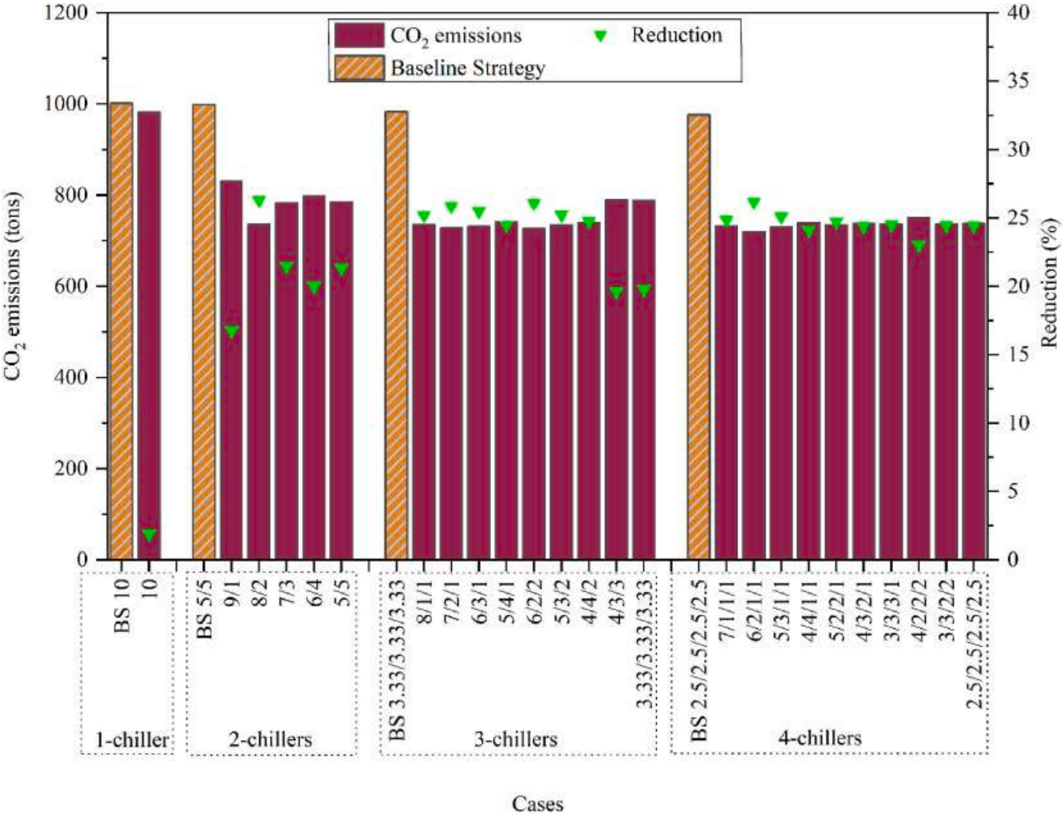


Fig. 19. CO_2 emissions.

design stage can lead to a significant reduction in energy consumption, investment and operation costs, as well as a reduction in the emission of environmental pollutants. By applying the proposed approach to the selected case study, it was found that if there is a need to re-design the cooling system for this building, the selection of chillers based on the results of this study compared to the conventional design method leads to a 26% reduction in annual energy consumption and a 18% reduction of life cycle cost. The proposed approach is a comprehensive method that for any other building with different cooling demand distribution and in different weather conditions can lead to the suggestion of optimal design of chiller network in terms of energy and economy.

CRediT author statement

Navid Moghaddas-Zadeh: Writing - Original Draft, Writing - Review & Editing, Visualization, Methodology, Validation, Software, Investigation.

Mahmood Farzaneh-Gord: Supervision, Project administration, Formal analysis, Visualization, Methodology, Validation, Software, Investigation.

Amir Ebrahimi-Moghadam: Writing - Review & Editing,

William P.Bahnfleth: Supervision.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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