Energy-saving optimization of refrigeration system in a data centre based on Nelder-Mead method

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Abstract. In order to improve the cooling efficiency of the data centre HVAC (Heating Ventilation and Air Conditioning) system and save costs, this paper proposes a control strategy that combines traditional control method with Nelder and Mead method, in order to optimize equipment operating parameters. Firstly, this paper selected a data centre in Northeast China as the research object. Moreover, the central air-conditioning system, as the control object, was simulated on TRNSYS, whose result was compared with the actual operating parameters to verify the reliability of the simulation model. Finally, the optimal control strategy was applied to the simulation model to analyze the changes of energy consumption of the system before and after optimization. The results showed that in August, the optimal control strategy is able to meet the extremity of cooling load demand, and the total energy consumption of the system is 269,612kwh, which is 10% less than the energy consumption before optimization. The overall energy consumption of the system is significantly reduced, and the proportion of energy consumption of each part tends to be reasonable, which will effectively improve the cooling efficiency of HVAC.

1 Introduction

China is an energy-deficient country, which means energy conservation and emission reduction are the top priority in all fields. Among them, building energy consumption has reached 30% of the total energy consumption, and the consumption of the refrigeration system accounts for more than 40% of the entire building energy consumption [1], so that the energy saved in refrigeration system is the key to building energy saving. However, the central air-conditioning system equipped with multi-loop, non-linear, and strong coupling system characteristics [2], which causes that the traditional control strategies are not able to deal with.

In order to improve the waste of energy consumption of the air-conditioning system, many domestic and foreign engineers have made a lot of attempts. The current common energy-saving measures are mainly aimed at the cold source and transportation of chilled water and cooling water. The operation status of the chilled water pump with frequency

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conversion, the cooling water pump and the refrigeration unit is set based on experience, as well as the flow rate and the chilled water outlet temperature, to meet the extremity load. However, this lack method omits the change in the extremity load. Later on, engineers put forward a method of using frequency conversion pumps to change the flow to meet the end load. Literature [4] uses Genetic Algorithm to control parallel pumps, and changes the frequency of each pump in real time according to the load to achieve the energy saving result. Literature [5] proposes an optimal control method based on the principle of minimum, which realizes the variable control strategy on pump's and high-precised adjustment of indoor temperature. Literature [6] proposed a distributed probability estimation algorithm to configure the number of water pumps and optimize the speed ratio.

Literature [7] pointed out that variable cooling water flow would bring a positive impact on the energy consumption of the system throughout the day time. The above four methods are all with certain load adaptability, but only focus on the energy saving of the water pump or cooling tower, without considering the overall energy consumption of the refrigeration system. Literature [8, 9] controls the number and frequency of chillers, water pumps, and cooling towers according to the changes in air conditioning load, and achieves energy saving among the group, whereas the energy consumption relationship of each part is not analyzed, and the control effect is poor. The literature [10] optimized the air-conditioning system by adopting the beetle-particle swarm optimization hybrid algorithm, but does not conduct a complete verification of simulation model of the system components.

Aiming at the defects of the above method, this paper proposes a control strategy combining traditional empirical control and Nelder and Mead Method. According to the change of extremity load and the current weather conditions, the method set the value of the outlet water temperature, the temperature difference between that of water inlet and that of outlet, the frequency combination of the water pump group and the fan speed ratio of the cooling tower, which achieves the overall energy saving of the system. In view of the importance of the data centre, this paper established its dynamic central air-conditioning refrigeration system on TRNSYS for testing, and verified the reliability of the simulation model by comparing various energy consumption data of the simulation with the actual energy consumption, followed by optimal control on the most precise model. Finally, it turned out the method is practical.

2 Method of modelling and optimization

2.1 Description of buildings and refrigeration systems

The object of this research is a data centre. The first floor of the building is 6.0m high, the second floor is 5.5m high, the indoor and outdoor height difference is 1.3m, and the building height is 12.8m. The total area is 7771m2, and the total construction area is 15718m2. The appearance of the data centre is shown in Figure 1.

Fig. 1. Data centre appearance.

During the construction of this centre, considering it's large load characteristics, four groups of refrigeration system are established. Each group includes a chiller, a cold pump, a cooling pump and a cooling tower. Each chiller is with a cooling capacity of 4043kW and power consumption of 629kW. The cold pump flow is 640m3/h, with 28m-head and 75kW-power. The flow of cooling pump is 900 m3/h, with 36m-head, 132kW-power. The power of cooling tower motor is 22kW. Each group is equipped with the same equipment, and each group is able to operate independently. The schematic diagram of single-group refrigeration system equipment is shown in Figure 2.

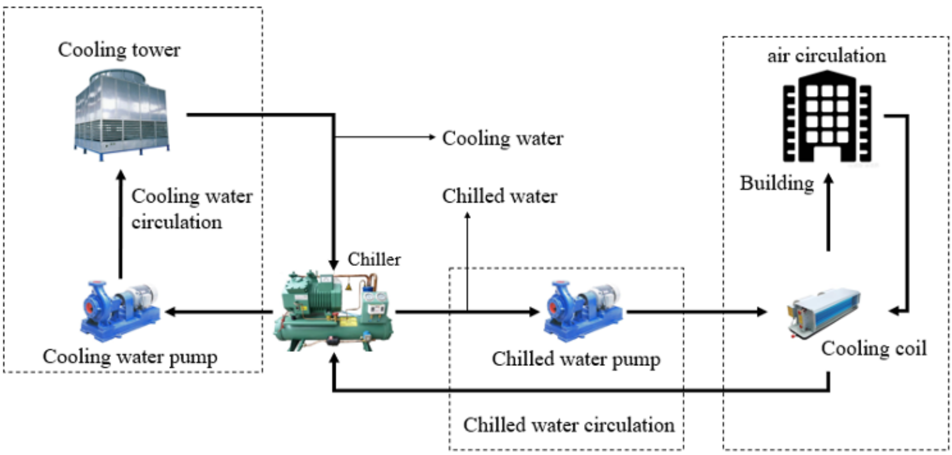


Fig. 2. Single group system.

As the computer room has not yet been completed, only one group of refrigeration systems has been put into use. In Figure 3, both the cold pump and the cooling pump operate at a fixed frequency. The outlet temperature of the chiller is set to 7°C, and the cooling tower fan is at a fixed frequency.

2.2 Simulation model establishment and verification

Since the optimization strategy is not able to be directly tested in the data centre, a simulation model of the entire refrigeration system needs to be established, and the value of each optimization parameter and equipment energy consumption can be obtained. The head, efficiency and power of pump [11] are calculated by formula(1), formula (2) and formula (3) respectively.

$$H = aQ^2 + bQ + c \tag{1}$$

$$\eta = jQ^2 + kQ + l \tag{2}$$

$$W = \frac{\rho g H Q}{\eta} \tag{3}$$

Among them, Q is the flow of pump, H is the head of pump, η is the efficiency of pump, W is the power of pump. a, b, c, j, k and l are the pump characteristic curve parameter, which is obtained by fitting the actual experimental values. The energy consumption and cooling capacity of the refrigeration unit are determined by two graphs. One is the main engine refrigeration capacity and COP curve at different difference between temperature of chilled water outlet and temperature of cooling water inlet, and the other is the main engine power curve at different load ratios. The energy consumption of the cooling tower is mainly composed of the energy consumption of the fan.

When using simulation software to simulate the refrigeration system, the verification of the model is also an indispensable part. The verification method in this paper is to compare the equipment parameters and energy consumption parameters output from the model with the actual system parameters, and through fine-tuning the parameters and adding loss coefficients to make the deviation of the simulation results and the actual values within the specified range. The specified range draws on the ASHRAE-14 calibration method [12] proposed by the ASHRAE Standards Committee. The mean bias error(MBE) and the mean square error coefficient of variation (CV) are used to evaluate the matching effect between the simulation results and the actual operating conditions. The smaller the values of the two are, the better they match.

$$MBE = \frac{A_n - S_n}{A_n} \times 100\% \tag{4}$$

$$CV = \frac{\sqrt{\frac{\sum_h (A-S)^2}{N_h}}}{N_h} \tag{5}$$

At the above formulas (4) and (5), A_n represents the actual parameter values such as energy consumption and pump frequency, S_n represents the corresponding simulation value, and N_h represents the number of time periods for verification. According to the complexity of the simulation system and the stability of the extremity load, the verification method adopted in this paper is specified as follows:

①The average deviation of the equipment parameters per hour is equal or less than 20%, and mean square error coefficient of variation is equal or less than 25%.

② Daily mean deviation of unit energy consumption and water system energy consumption is equal or less than 20%.

2.3 Selection of optimization variables

The purpose of the optimization in this paper is to make the energy consumption of the entire refrigeration system as low as possible in the condition of meeting the demand of the extremity cooling load. Firstly, it is necessary to determine the optimization variables. The energy consumption formula of the refrigeration system is shown in equation (6):

$$E_{total} = E_{chiller} + E_{cold\_pump} + E_{cooling\_pump} + E_{tower} \tag{6}$$

Among them, E_{total} is the total energy consumption, $E_{chiller}$ is the energy consumption of the chiller, E_{cold_pump} is the energy consumption of the cold pump, $E_{cooling\_pump}$ is the energy consumption of the cooling pump, and E_{tower} is the energy consumption of the cooling tower.

$E_{chiller}$ accounts for the largest proportion of the total energy consumption, which is mainly determined by the temperature of outflow chilled water, inflow chilled water, outflow cooling water and inflow cooling water, as well as the flow rate of chilled water and cooling water. For the chilled water side, the flow rate of the cold pump is mainly determined by the extremity load and the temperature difference between the outlet chilled water and the inlet chilled water, whose pressure is controlled by the traditional method in a fixed level. Therefore, by optimizing the difference between the outlet temperature of chilled water and the temperature different between outlet chilled water and inlet chilled water can significantly reduce $E_{chiller}$ and E_{cold_pump}.

For the cooling water side, there also exist a energy-saving space by changing the flow of the cooling pump, but it is necessary to maintain a certain proportional relationship between it and the flow of the chilled water to ensure the normal operation of the host. E_{tower} is mainly determined by the frequency of its own fan. Therefore, through optimizing the flow rate of the cooling pump and the frequency of the cooling tower fan can significantly reduce $E_{cooling\_pump}$ and $E_{cooling\_pump}$. Therefore, there exists four optimization variables in this paper, namely, the temperature of chilled water, the temperature difference between the outlet chilled water and the inlet chilled water, the flow ratio of cooling water to chilled water and fan speed ratio.

2.4 Selection of intelligent optimization algorithm

Intelligent optimization algorithm is by changing the value of each optimization variable according to the established mode, in order to get a better solution. The Nelder and Mead method[13] is a derivative-free optimization algorithm. It generates other n points $(x_2 \dots x_{n+1})$ in the n dimension space according to the number n and the initial point x_1 of optimization variable to construct a simplex in n dimension. Each vertex of the simplex represents a solution, and the corresponding objective function value can be obtained, followed by sorting the function values of these vertices from small to large, for example, $f(x_1) \le f(x_2) \le \cdots \le f(x_{n+1})$, and average position of the vertices except the maximum function value point is calculated according to formula (7):

$$x_m = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{7}$$

After that, the following three operations are performed alternately to replace the vertex with the largest objective function value:

① Reflecting Operation:

$$x_r = x_m + \alpha(x_m - x_{n+1}), \alpha > 0 \tag{8}$$

② Extension Operation: to tackle the result after Reflecting Operation further.

$$x_e = x_m + \gamma(x_r - x_m), \gamma > 1 \tag{9}$$

③ Compression Operation:

$$x_c = x_m + \beta(x_{n+1} - x_m), 0 < \beta < 1 \tag{10}$$

The specific steps are as follows:

Step 1: Function values of all points are sorted, of which the average value is calculated, and x_r is obtained by performing Reflection Operation on the point x_{n+1} with the largest function value.

Step 2: the result of the reflection Operation is checked, if only $f(x_r) < f(x_1)$, x_e is obtained by using Extension Operation on x_r, because there may be a further improvement. Once $f(x_e) < f(x_r)$, x_e is used to replace x_{n+1}. Otherwise, x_r is used to replace x_{n+1}, and the procedure goes back to step 1.

Step 3: If the situation $f(x_r) \ge f(x_1)$ is in Step 2, the function value of x_r and x_{n+1} are compared. If $f(x_r) \le f(x_n)$, x_{n+1} is replaced by x_r and the procedure goes back to step 1, otherwise, the procedure goes forward to step 4 to try Compression Operation.

Step 4:, if $f(x_r) > f(x_n)$, x_{n+1} is dealt with Compression Operation.Otherwise, x_r is used to replace x_{n+1}, followed by using Compression Operation on x_r.

Step 5: The effect of the point after Compression Operation. If $f(x_c) \geq f(x_{n+1})^3$, each $x_i$is replaced by $\frac{x_i+x_1}{2}$ and the average value is obtained again, followed by Compression Operation. Otherwise, x_c is used to replace x_{n+1} and the procedure goes back to step 2.

The process of sorting the vertex function values and replacing vertices is repeated continuously. After each vertex is replaced, the variance of the function value at the vertex is calculated. If the equation (11) is satisfied or the iteration threshold is reached, the optimization algorithm is judged to end, and the current x_1 is taken as the optimal solution. $f(x_1)$ is the optimal value of the objective function.

$$\frac{1}{n}\left(\sum_{i=1}^{n+1}\left(f(x_i)\right)^2 - \frac{1}{n+1}\left(\sum_{i=1}^{n+1} f(x_i)\right)^2\right) < \varepsilon^2 \tag{11}$$

Since the energy consumption of the entire refrigeration system is complex and cannot be derived. HVAC engineers can usually set a reliable initial value for each optimization variable based on experience, it is expected that the Nelder and Mead Method is able to achieve better results.

3 Analysis on simulation and energy consumption

3.1 Analysis on simulation model verification results

According to the specific actual equipment situation, a simulation model of the refrigeration system was established on the TRNSYS platform. Since the actual data is from Jilin Chemical Data Center in August, the local weather files and building load files in August were imported from the outside to restore the actual working conditions as much as possible, and multiple modules is set up to record and output important parameters of system, which is used for subsequent analysis and verification. The simulation architecture is shown in Figure 3.

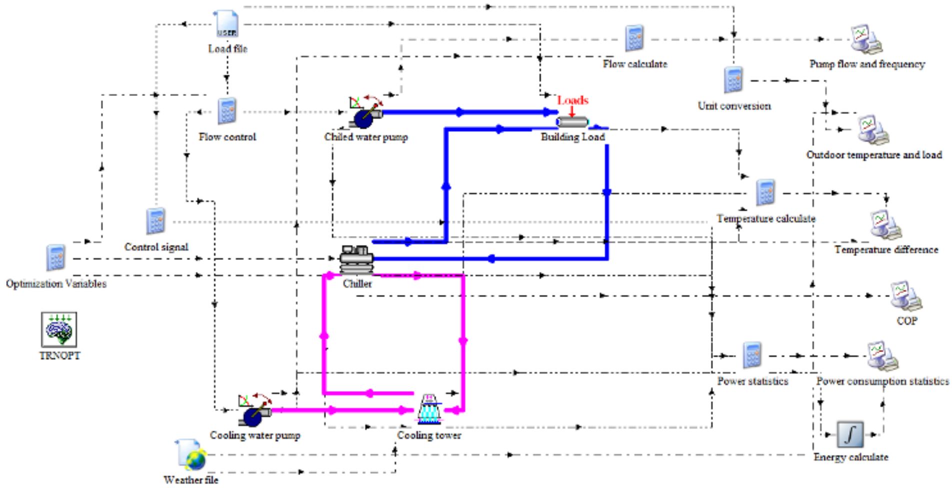
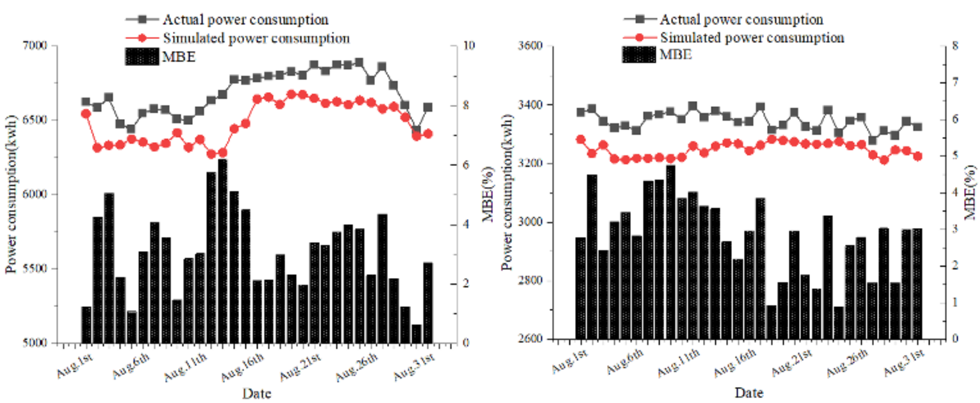


Fig. 3. TRNSYS refrigeration system model.

The condition of operation of the refrigeration system in August is simulated on the simulation platform. The energy consumption of each component is simulated every hour, and the daily simulated energy consumption is calculated to be compared with the actual energy consumption. As shown in Figure 4, the error between the simulated consumption of chiller and the actual consumption of chilled water is within 8%, and the error of simulated consumption of water pump and actual consumption of water pump is within 5%, so as to cooling tower. This illustrates that the model reaches a high fitting degree with the actual condition, which verifies the correct of the simulation method and can be used on optimization algorithm later.

Since the setting value of the chilled water temperature of the on-site chiller is fixed, the energy consumption of the chiller is mainly related to the building load; While the variable frequency pumps are used at a fixed frequency, which causes the basically constant energy consumption of the water pump. The change of the energy consumption of the water system is mainly decided by the cooling tower. Although the changes in the actual conditions are limited, the simulation result still verified the correct of the model to a certain extent.



(a)Power consumption of Chiller (b)Power consumption of pump and cooling tower

Fig. 4. Comparison of power consumption between simulation and reality.

Due to the large amount of equipment parameter information, the calculated MBE and CV are applied to be analyzed. As shown in Table 1, it can be seen that the parameters of the cooling water pump, chilled water pump, and chiller are close to the actual data, and the simulation model is high accuracy.

Table 1. Coefficient of variation (CV) of main parameters.

Evaluation index	**Temperature of inlet chilled water (%)**	**Temperature of outlet cooling water (%)**	**Temperature of inlet cooling water (%)**	**Chiller load rate (%)**	**Cold pump flow (%)**	**Cooling pump flow(%)**
CV	9.2	12.5	16.8	5.5	1.2	1.7

3.2 Analysis of optimization results of Nelder-Mead method

On the GenOpt optimization platform, the four optimization parameters of the refrigeration system were optimized by the Nelder and Mead Method. It can be seen from Figure 5 that as the number of iterations increased, the overall power consumption of the refrigeration system was with a downtrend. After 30 iterations, the target value basically reached the optimal value, and the entire energy consumption decreased by about 10%.

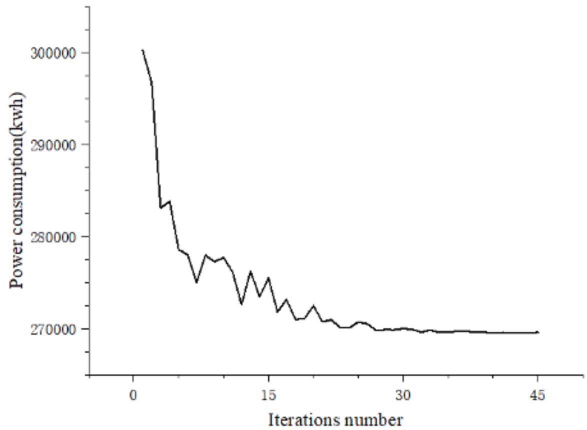


Fig. 5. Change of power consumption during optimization.

The specific energy consumption of each part of the refrigeration system before and after optimization is analyzed as follow. It can be seen from Figure 6 that the energy consumption of the chiller is significantly improved by optimizing the set temperature of chilled water and the temperature difference between the outlet chilled water inlet chilled water. The energy consumption of the cooling pump is optimized by improving the flow ratio, and the energy consumption of the cooling tower is optimized by the fan speed ratio. The energy consumption of the cold pump increases due to the decrease in efficiency, but the overall system is still at an optimal operating point to save energy.

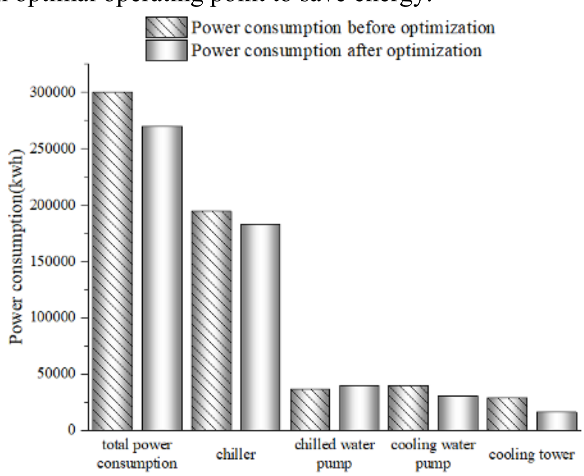
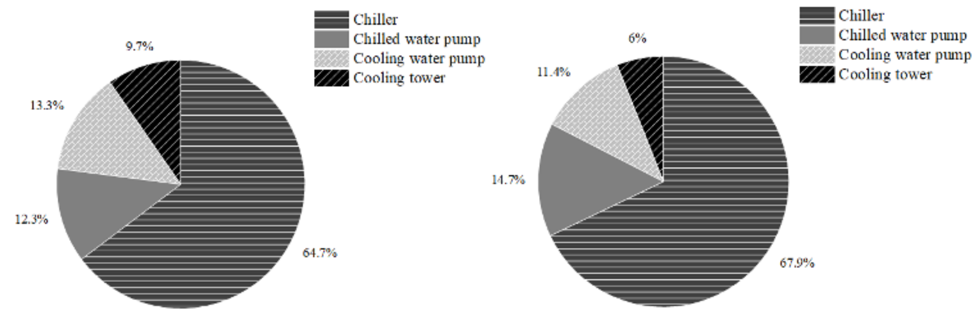


Fig. 6. Comparison of power consumption before and after optimization.

Meanwhile, the proportion of energy consumption in each part is also optimized. It can be concluded from Figure 7 that after using the optimized algorithm, the energy consumption ratio of cooling pumps and cooling towers significantly decrease, and the energy consumption ratio of chiller slightly increase. The energy consumption ratio of cold pumps significantly increase. It can be seen from the equipment selection that the cooling pump flow and head of Jilin Chemical Data Center are higher than the that of cold pump, but the actual cold pump requires a higher head than the cooling pump. Therefore, in the energy consumption ratio chart before optimization, the cooling pump and cooling tower account for a large proportion, so there is a considerable room for parameter adjusting to save energy. The optimization algorithm improves the cooling water flow and the speed ratio of the fan in cooling tower fan, and optimizes the energy consumption ratio of each part.



(a) before optimization (b) after optimization

Fig. 7. Comparison of power consumption ratio before and after optimization.

The comparison of the optimization variables before and after optimization is shown in Table 2. The optimization algorithm achieves the effect of large temperature difference and small flow by raising the set temperature of chilled water, increasing the temperature difference between outlet chilled water and inlet chilled water, and matching the relevant parameters of the cooling water pump and the cooling tower. , Under the condition of meeting the load, energy saving of the whole system is carried out.

Table 2. Comparison of each variable before and after optimization

	The set temperature of chilled water (℃)	**Temperature difference between outlet chilled water and inlet chilled water (℃)**	**Flow ratio of chilled water to cooling water**	**Speed ratio of fan in cooling tower**
Before optimization	8	4	1.24	0.8
After optimization	9.9	5.9	1.1	0.7

4 Conclusions

This paper establishes a simulation model of a refrigeration system in a data center through TRNSYS, and proposes Nelder and Mead Method for optimizing equipment parameters. Though the comparison of simulation data and the actual data. The results shows that the simulation model has reached a high degree level of fit with the real refrigeration system and meets the testing requirements of the optimization algorithm.

After using the optimization algorithm to optimize the pump flow and chiller outlet temperature, the entire energy consumption of the refrigeration system has been reduced by 10% compared to before, and the energy consumption of the cold pump slightly increases. The energy consumption of the chiller, cooling pump and cooling tower has been significantly reduced. This solution is able to save considerable power consumption costs, which will alleviate the high energy consumption of the HVAC system in the building.

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