Analysis of Seasonal Chilled Water Thermal Quantity Consumption for HVAC Systems in a Commercial Building:
Study of a Method of Macroscopic Diagnosis of Energy Consumption in Buildings

Noriyasu Sagara*, Jyoji Ishida2, Hitoshi Takeda3 and Masaki Shioya4

*1 Professor, Department of Environmental Space Design, Faculty of Environmental Engineering, The University of Kitakyushu, Japan
2 Mitsubishi Logistics Corporation, Japan
3 Professor, Department of Architecture, Faculty of Science and Technology, Tokyo University of Science, Japan
4 Chief Research Engineer, Kajima Technical Research Institute, Japan

Abstract

We developed a neural network model describing the process in which disturbance conditions, such as outdoor air temperature, and activity conditions, such as indoor air temperature and humidity, affected the chilled water thermal quantity for HVAC systems in a commercial building in the city of Kitakyushu, Japan within three years after its completion. The influence of each of the disturbance conditions and the activity conditions, which changed every year, on the chilled water thermal quantity was diagnosed quantitatively by a numerical simulation using these models, and how to macroscopically evaluate the carried-out energy-saving activity was shown.

Keywords: diagnosis; energy consumption; HVAC systems; buildings

1. Introduction

A simple comparison of actual measurements over two or more years of the amount of term energy consumption for HVAC systems of the same building is not necessarily enough to diagnose the performance of the building. The effects of the carried-out energy-saving acts can be incorrectly evaluated in some cases. For example, when some energy-saving measures for HVAC systems are carried out in a certain year, the subsequent amount of energy consumption does not necessarily become less as compared with what it was before, and may even increase. This is because there are differences every year in those conditions (disturbance conditions) beyond the discretion of human beings, such as the outdoor air temperature, and in those conditions (activity conditions) within the discretion of the human beings in the buildings, such as indoor air setting temperature and operation time of the HVAC system. A further cause is that the thermal properties of both the HVAC systems and the building change every year.

While the analysis of the actual conditions of energy consumption over a long period of time has progressed in recent years, there are a few reports which have studied quantitatively the relation between the amount of energy consumption and the disturbance conditions and the activity conditions stated above. In such circumstances, it is first required to quantitatively separate the amount of energy consumption into what depends on changes in disturbance conditions, and what depends on changes in activity conditions.

The above procedure will possibly enable us to grasp now how much various kinds of energy-saving acts collectively contributed to energy saving in a building. Then, in order to carry out this diagnosis about thermal energy consumption for an HVAC system, we tried to develop a mathematical model, a neural network using actual measurements. This model makes disturbance conditions and activity conditions input variables, and makes chilled water thermal quantity the output variable. It is possible to solve the thermal structure of the energy consumption of HVAC systems by comparing and examining mutually the amounts of chilled water thermal quantity, which were calculated using the model for each year, with the input variables of the year different from those of years used for training. We show the results of a diagnosis of HVAC systems of a commercial building for three years after completion.

2. Outline of the Analysis
2.1 Building / HVAC system overview

The building serving as the object of analysis is a commercial institution section (total floor-area 31,000 m²) of a complex building (14 stories above ground, three stories beneath ground level, total floor-area 85,000 m²). The thermal energy for HVAC systems in this commercial institution is supplied with chilled water and
steam from a district heating and cooling plant, and steam is used which changes into warm water. The HVAC system is composed of air handling units on each floor with four pipes and fan-coil-units (FCU) installed for all 19 zones. Moreover, a BEMS (Building Energy and Environment Management System) has been introduced which acquires field data.

2.2 Implementation period and actual conditions of the HVAC system

The time period for model training and analysis was from June to September of each summer for three years from 1998 to 2000. Yearly fluctuations in chilled water thermal quantity during summers in this commercial institution are shown in Fig. 1. The chilled water thermal quantity after 1999 is decreasing sharply because of a reconsideration of practical use of HVAC systems compared to that in 1998, the first year after completion. The monthly average outdoor air temperature and outdoor air humidity are shown in Figs. 2 and 3. The outdoor air temperature in 1999 was low as compared with other years. The trends in absolute humidity of outdoor air also resembled those of outdoor air temperature. Moreover, the monthly average values of indoor air temperature and indoor humidity (the elements constituting activity conditions) are shown in Fig. 4 and Fig. 5. The room temperature is lowest in 1998 and rises with each year.

3. A Method for Developing a Chilled Water Thermal Quantity Model

3.1 Outline

As compared with the conventional method using a multiple regression equation, we adopt a neural network (NN) model with features such as flexible modeling, straightforward correspondence for a nonlinear problem, excellent regression performance, and fewer trial and error attempts needed for modeling with a multi-input variable model. The input variables of the model are, as mentioned above, the daily average or integrated values of disturbance conditions and activity conditions, and the output variable is the chilled water thermal quantity per day. We use variables from the same day as both input variables and an output variable, not using a past variable.
We used variables measured on 119 days (summer 1998), 114 days (summer 1999) and 116 days (summer 2000), excluding regular holidays and other non-measuring days within a 122 day period for each year. 2/3 of the measured data was selected out at random for learning, and the remainder was used as testing data for accuracy verification of the learned NN models. The model developing procedure is shown in Fig. 8.

### 3.2 Initial input variables

An initial input variable is a variable which serves as the first candidate in the process which selects the input variables of the NN model. Judging from the scatter diagram of candidate variables and the chilled water thermal quantity, etc. (see Figs. 6 and 7), we chose the candidate variables.

A total of 45 variables were specifically selected, such as day of the week, outdoor air temperature, outdoor air absolute humidity, the indoor air temperatures of each zone, supply air temperatures of air-handling units, room temperature setting values, indoor absolute humidity, the amount of single-phase electric power of the entire commercial building, operation times of all air handling units and amount of electricity used by the #S9 air-handling unit fan.

### 3.3 The selection method for the common input variable during the three-year period

After normalizing initial input variables and an output variable for the chilled water thermal quantity, each of the correlation coefficients was computed. Moreover, when making the NN models for every summer over three years, a degree of contribution defined as Equation (2) in Appendix 1 was computed. The conditions under which the correlation coefficient between an input variable and an output variable exceeds 0.1 were set, and the input variables which fulfill either case were chosen. The correlation coefficient and the degree of contribution of input variables in each year are shown in Figs. 9, 10, and 11. The number of input variables which fulfill the above-mentioned conditions as a result was set to 26 in 1998, 35 in 1999, and 22 in 2000. There are some input variables which appear in all three years, and some input variables which appear
once or twice to affect the chilled water thermal quantity in a certain year but not to influence it in another year. All of these input variables were chosen as common input variables for each model for every year. Thereby, the number of the input variables for the models for every year was set to 43. The selection of such input variables enables us to mutually compare and evaluate the various kinds of chilled water thermal quantity as output of the models (to be discussed later).

3.4 Processing and further deletion of input variables

A portion of the input variables was processed for improvement in the correlation of the common input variables during the three years and the chilled water thermal quantity. Indoor air temperature and humidity were not used independently as an input variable but the difference in outdoor air temperature and indoor air temperature, and the difference in outdoor air humidity and indoor air humidity were used. An example is shown in Figs. 12 and 13. Furthermore, the variables which overlap as a function explaining an output variable were deleted from the input variables whenever possible.

3.5 Optimum models

A NN model which satisfies the following conditions was made into an optimum model for every year.

The number of middle-class units was determined such that AIC would serve as the minimum.

The number of training times was chosen so that the mean relative error of the model output value with testing data might serve as the minimum.

The relation between the number of times of study and the mean relative error of the optimum model for each year is shown in Figs. 14, 15, and 16.

The common input variables and the accuracy of an optimum model for each year are shown in Tables 1 and 2. The accuracy of the model with inside-and-outside temperature differences and absolute humidity differences improved more clearly compared to the model with room temperatures and indoor absolute humidity only. Therefore, its differences are used as activity conditions in this investigation.

4. Analysis of the Chilled Water Thermal Quantity Consumption

Fig.17 shows the output relation between the actual measurements and estimated values of chilled-water thermal quantity when input variables act on a real building and on a model respectively. We adopted a method (Fig.18) that mutually compares the values of...
Table 1. Common input variable table covering three years

| System name | All | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | S10 | S11 | S12 | #n4 |
|-------------|-----|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|
| Place       | B1Fwest | B1Feast | 1Fwest | 1Feast | 2:west | 2:Feast | 3Fwest | 3Feast | 4F | 5F | 6Fwest | 6Feast |
| $W$ | $\odot$ (1) |
| $\theta_0$ | $\odot$ (4) |
| $X_0$ | $\odot$ (5) |
| $\Delta \theta_r$ | $\bullet$ (6) | $\bullet$ (9) | $\bullet$ (12) | $\bullet$ (15) | $\bullet$ (18) | $\bullet$ (21) | $\bullet$ (24) | $\bullet$ (27) | $\bullet$ (32) | $\bullet$ (38) | $\bullet$ (41) |
| $\Delta Xr$ | $\bullet$ (8) | $\bullet$ (11) | $\bullet$ (14) | $\bullet$ (17) | $\bullet$ (23) | $\bullet$ (26) | $\bullet$ (29) | $\bullet$ (34) | $\bullet$ (37) | $\bullet$ (40) | $\bullet$ (43) |
| $\phi_1$ | $\bullet$ (44) |
| $\phi_3$ | $\bullet$ (45) |
| $T$ | $\bullet$ (3) |

$W$: day of the week, $\theta_0$: outdoor air temperature (daily average value), $X_0$: outdoor air absolute humidity (daily average value), $\Delta \theta_r$: difference between average outdoor air temperature and average room air temperature during air-conditioning time, $\Delta Xr$: difference between outdoor air humidity and room air humidity when A/C is being used, $\phi_1$: single-phase electric power, $\phi_3$: 3-phase electric power (daily addition value), and $T$: each AHU operation time (daily addition value)

The numerical values in Table 1 express an input variable number, and correspond to the numbers in Fig.9, 10, 11.

Table 2. Accuracy evaluation of models

| Year | Model Name | Model Designation | Correlation Coefficient$^{*1}$ [-] | ARE$^{*2}$ [%] | EEP$^{*3}$ [%] | MBE$^{*2}$ [%] |
|------|------------|-------------------|-----------------------------------|----------------|----------------|----------------|
| 1998 | Model 1998 | SC8113_5_63.1k    | 0.98555                           | 2.727          | 2.6            | 0.3            |
| 1999 | Model 1999 | SC9110_5_41.6k    | 0.89678                           | 6.714          | 6.97           | 0.35           |
| 2000 | Model 2000 | SC018_5_130.5k    | 0.99001                           | 2.891          | 2.56           | 0.28           |

*1) is correlation coefficient between measured values and model-presumed values.
*2) is explained in Appendix 2.
*3) shows values from the testing process.

Fig.17. Relationship chart for input variables and output variables of the actual building and the model
thermal quantity computed by entering the input conditions for various years in the optimal model for each year shown in Chapter 3. The horizontal axis in Fig. 18 is a set of input conditions for an NN model. The A in the designation (A, B) is disturbance conditions and the B is activity conditions, which are the elements of input conditions. For example, Id98 is the measured disturbance conditions in 1998, and Ia98 is the measured activity conditions in 1998. The value of the vertical axis of point [1] in the figure is computed by entering the input conditions into Model 1998, and is expressed as M98 (Id98, Ia98). [2], [3] and [4] have analogous interpretations in Figs. 18 and 19. Since [1] is quite close to an actual measurement, it is subsequently called an actual measurement for 1998. Each point is connected in a straight line for convenience. Moreover, the output values ([1’], [4’]) of Model 1999 are also written together using a symbol ∆. [4’] is called an actual measurement for 1999 for the same reason as [1] is. The difference ΔE of the measured thermal quantity for every year is considered to be almost equal to ∆Q expressed as the sum of three thermal quantity differences (∆Ia, ∆Id, ∆M)(Eq.2). Namely,

\[ \Delta E = \Delta Q \]  

\[ \Delta Q = \Delta Ia + \Delta Id + \Delta M \]  

Here, ΔIa represents the difference between two output variables computed by entering a pair of input variables (A, B) and (A, C) into a Model Mi. Among the input variables, A represents disturbance conditions, and B and C represent different activity conditions (Eq.3).  

\[ \Delta Ia(Mi, A, B,C) = Mi(A, B) - Mi(A, C) \]  

where i=98, 99, 00,
A = Id98, Id99, Id00,
B and C = Ia98, Ia99, Ia00,
B is not equal to C.

Here, ∆Id indicates the difference between two output variables computed by entering a pair of input variables; (A, C) and (B, C) into a model Mi. Among the input variables, A and B represent different disturbance conditions and C represents the activity conditions (Eq.4).

\[ \Delta Id(Mi, A-B, C) = Mi(A, C) - Mi(B, C) \]  

\[ \Delta M(i-j, A, B) = Mi(A, B) - Mj(A, B) \]  

where i and j=98, 99 and 00,
A and B=Id98, Id99 and Id00,
A is not equal to B,
C=Ia98, Ia99 and Ia00

Moreover, ΔM(i-j, A, B) indicates the difference between two output variables computed by entering the same set of input variables (A, B) into two mutually different models Mi and Mj (Eq.5).

5. Considerations

The chilled-water thermal quantity computed using a model for each year and the various input conditions is shown in Table 3.

| Model 1998 | Activity Condition |
|------------|--------------------|
| 1998       | 14,969             | 13,117 | 12,174 |
| 1999       | 14,152             | 12,310 | —      |
| 2000       | 14,139             | —      | 11,346 |

| Model 1999 | Activity Condition |
|------------|--------------------|
| 1998       | 12,837             | 12,106 | —      |
| 1999       | 12,368             | 11,566 | 10,798 |
| 2000       | —                  | 11,672 | 10,786 |

| Model 2000 | Activity Condition |
|------------|--------------------|
| 1998       | 12,105             | —      | 11,863 |
| 1999       | —                  | 11,081 | 11,437 |
| 2000       | 11,624             | 11,034 | 11,349 |
The four sorts of calculation results using Model 1998 and Model 1999 show the following considerations (Fig. 19).

\[ \Delta Q(M98, Ia98, Ia99) = 14969 - 13117 = 1852 \]
\[ \Delta Ia(M98, Ia98-Id99, Ia99) = 13117 - 12310 = 807 \]
\[ \Delta Ia(M98, Ia98, Ia99-Ia99) + \Delta Id(M98, Ia98-Id99, Ia99) = 2659 \]

Therefore, supposing the building and HVAC systems with the same heat characteristics in 1998 are operated on the input conditions for 1999, about a 2659 GJ/term decrease is seen in the process from [1] to [2] to [4].

This corresponds to 78% of difference \( \Delta Q(3403 \text{GJ/term}) \) for the thermal quantity between 1998 and 1999 (from [1] to [4'] in the figure). Furthermore, the analysis of the details shows that the change of activity conditions enables the realization of the amount 1852 GJ/term in energy saving, 54% of \( \Delta Q \), which is considerably larger than 807, 24% of \( \Delta Q \), reduced by the change in disturbance conditions.

On the other hand, \( \Delta M(98-99, Ia99, Ia99) = M98(Id99, Ia99) - M99(Id99, Ia99) = 3403 - 2659 = 744 \) is the amount of reduction of the thermal quantity with the change from Model 1998 to Model 1999 under the input conditions for 1999.

This is equivalent to the amount of energy saving, 22% of \( \Delta Q \), obtained by the means which cause the change in the thermal characteristics of the building among energy-saving means adopted in 1999. Therefore, the thermal quantity is reduced to 76% of \( \Delta Q \), as a result of the improvement of both the activity conditions and heat characteristics of the building decided by the discretion of people, but excluding other disturbance conditions.

Next, each output of Model 1999 for four kinds of input conditions is smaller than for Model 1998, which shows that Model 1999 has an energy-saving thermal structure as compared with Model 1998. Moreover, the fluctuation of the outputs of Model 1999 with the change in the input conditions is also smaller than for Model 1998. This shows that Model 1999 has thermal structures which are not easily influenced by both disturbance conditions and activity conditions.

Fig. 20 shows the following. Model 2000 resembles Model 1999 with thermal characteristics less influenced by both disturbance conditions and activity conditions, as compared to Model 1998 (Fig. 20).

Fig. 21 shows the following. The 563 GJ/term thermal quantity at point [9"] is larger than that at point [9']. This shows that it is reduced, supposing the building with the heat characteristics for 1999 is operated under the input conditions for 2000. Therefore, since [9"] is a measured value in 2000, the thermal structure in 2000 increased the thermal quantity from [9’] to [9’']. That is, with the input conditions for 2000, the thermal structure in 2000 has a characteristic that causes a higher thermal quantity compared to the structure in 1999. However, the change of activity conditions may act to increase or decrease the output of each model, and its influence is complicated ([4’] to [7’] and [4”’] to [7”’]). This is one of the reasons that the differences of the outputs in 1999 and 2000 are smaller than in the other cases.

6. Conclusions

We proposed a model in which the chilled water thermal quantity was caused by the three factors (disturbance conditions, activity conditions, and the thermal structure of the whole building with HVAC systems).

While energy saving is being realized after completion, the amount caused by the three factors changing for every year can be shown separately and quantitatively.

Consequently, it is possible to presume the true amount of energy saving, except for the influence of disturbance conditions or activity conditions, and to evaluate the energy-saving activities based on the result.

Endnotes

1. The #S9 air-handling unit has the maximum capacity in the commercial building, and its chilled water thermal quantity has a close relation with that of the entire commercial building.
Appendix 1

The relation between input variables and output variables of the neural network model is as follows.

\[
\begin{bmatrix}
 x_{m1} \\
 \vdots \\
 x_{mi} \\
 \vdots \\
 x_{mn}
\end{bmatrix}
\rightarrow [NN] \rightarrow O_m
\]

where \(x_{mi}\) is an element of the input vector, \(i\) is an element number, \(m\) is a pattern number \((m=1\text{ to } n)\), \([NN]\) is a neural network model as \(F(x_{m1}, \ldots, x_{mi}, \ldots, x_{mn})\), and \(O_m\) is an output.

\[
A_m = \frac{\partial O_m}{\partial f_m} = \frac{F(x_{m1}, \ldots, x_{mi} + \Delta x_{mi}, \ldots, x_{mn}) - F(x_{m1}, \ldots, x_{mi}, \ldots, x_{mn})}{\Delta x_{mi}}
\]

\[
\eta_i = \frac{1}{n} \sum_{m=1}^{n} \left| A_{mi} \right| (x_{mi} - \bar{x})
\]

where \(A_{mi}\) is a sensitivity of an output to an input with the pattern \(m\), and \(\eta_i\) is the degree of contribution with an input element \(i\). The degree of contribution is the average value of the product of the sensitivity to the output variable of an input variable, and the difference between an input variable and its average value, as shown in Equation (2). Thus, this measure can evaluate the degree of influence of an input variable on an output variable, which cannot be evaluated only by sensitivity. Moreover, this serves as a different valuation basis from the correlation coefficient, which evaluates linearity.

Appendix 2

\[
ARE = \frac{1}{n} \sum_{m=1}^{n} \left| \frac{\hat{y}_m - y_m}{y_m} \right| \cdot 100
\]

where \(ARE\) is Average Rate of Relative Error, \(y_m\) is a measured value and \(\hat{y}_m\) is an estimated value.

\[
EEP = \frac{1}{\max\{y_m\}} \sqrt{\frac{\sum_{m=1}^{n} (\hat{y}_m - y_m)^2}{n}} \cdot 100
\]

where \(EEP\) is Expected Error Percentage.

\[
MBE = \frac{\sum_{m=1}^{n} (\hat{y}_m - y_m)}{n |\bar{y}|} \cdot 100
\]

where \(MBE\) is Mean Bias Error and \(|\bar{y}|\) is the average of \(y_m\).

References

1) Matsuda, A., The INSPIRE User Manual, Version 6.0, 1996.
2) Ishida, J., Sagara, N., Shioya, M. and Takeda, H., Research on predictive diagnostic techniques for energy-consuming structures, #1 (in Japanese), Collection I of Academic Papers of the Society of Heating, Air-conditioning & Sanitary Engineers of Japan, 2001-9.
3) Ishida, J., Sagara, N., Shioya, M. and Takeda, H., Research on predictive diagnostic techniques of energy-consuming structures #2 (in Japanese), Collection III of Academic Papers of the Society of Heating, Air-conditioning & Sanitary Engineers of Japan, 2002-9.