A Study on Determining the Optimal Stop Time of a Heating System

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ABSTRACT: The purpose of this study is to present a method to determine the optimal stop time of HVAC using the Artificial Neural Network model, which is one of the learning methods. For this, the performance of determining the stop time of HVAC for unexperienced learning data was evaluated, and time interval for measurement of input data and permissible error needed for practical application of ANN model were presented using the results from daily simulation.

1. Introduction

One of the most effective means for reducing heating energy consumption is to turn off heating systems when the space being served is not in use. The heating energy can be reduced by maintaining comfortable conditions only during the times that the spaces are occupied. An optimal stop of HVAC system means that a room air temperature is in the comfort range for a while, after heating system is turned off during the occupied times, due to thermal inertia of both the building structure and its heating equipment. So, it is necessary to predict the accurate stop time in order to save energy by minimizing the operation time of heating system. However, numerous factors such as outdoor temperature, equipment efficiency affect the stop time, and these factors change constantly. Therefore, it is very difficult to employ the optimal operation conditions considering all these factors. When the stop time is prolonged, the room air temperature will be within the comfort range after the space is vacated, so the heating energy is going to be wasted.

Conversely, when HVAC system is stopped more early, the occupants may experience uncomfortable condition at the occupancy times because the room air temperature would not be within the comfort range. To solve these problems efficiently, research is necessary on methods to accurately determine the stop time of a building and to properly apply the determined stop time.

Therefore, the concept of "learning" based on previous operation data of the building must be introduced to determine the optimal stop time of systems such as the HVAC equipments.[1,2] In this research, an efficient method for determining the stop time of heating system in a building is proposed based on the Artificial Neural Network (ANN) model, which is based on the information management method of the human brain, which formulates a solution through use of previously accumulated data.

2. Concept of optimal stop of HVAC system

Figure 1 shows how the temperature varies in a conditioned space when heating is provided. To conserve energy, the temperature

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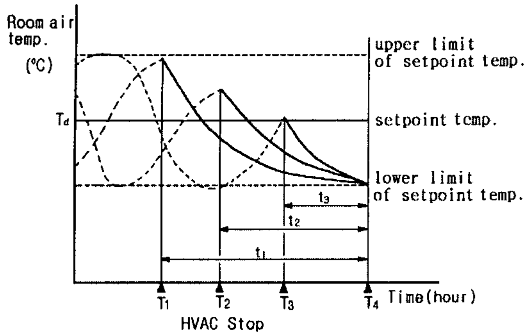


Fig. 1 Schematic diagram of the optimal stop.

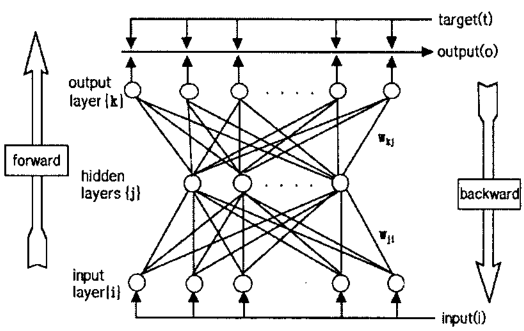


Fig. 2 Typical structure of the back-propagation learning.

should be controlled to remain within the throttling range during only the occupation times, and the heating system should be turned off, unless it needed to prevent pipes from freezing or other problems from occurring, during unoccupied times.

As shown in Fig. 1, after heating system is turned off at T_1, T_2 and T_3 during occupied times, due to thermal inertia of both the building structure and its heating equipment, a room air temperature is within the comfort range for a while. But if heating system is turned off at T_4, energy is wasted because the room air temperature is in the comfort range after the occupancy finish. So, an optimal stop means to stop the heating system before occupancy finish, keeping a room air temperature in the comfort range. An important factor is to determine the accurate T_1, T_2 and T_3.

3. Artificial neural network overview

The basic principle of the back-propagation learning,(3) chosen as the "training" algorithm in this study is shown in Fig. 2, where first, the input patterns of each node are provided at the input layer; then, this signal is converted at each node and transferred to the hidden layer; and finally, the signal generates outputs in the output layer. The output value is compared to the target value and the connection weight is adjusted toward decreasing the difference between the two values. This adjustment is back-propagated from the upper layers to the lower layers, which results in the adjustment of the connection weights in the lower layers.

The back-propagation learning algorithm has the following advantages. First, it can "learn" nonlinear relationships between inputs and outputs. Second, it has been used successfully in similar applications, such as control.(4-6)

4. Simulation for the determination of daily stop time

4.1 Flow of the determination of optimal stop time

The procedure for determining stop time using ANN is as shown in Fig. 3. First, the early stages consist of collecting operation data, since the building operation data as prior experience is necessary. Data are collected from operation of HVAC equipment through scheduled or manual control. Once a certain amount of data has been collected, the stop time is determined through the learning of the optimized ANN model, and if more amount of data is collected, it would be possible to determine the stop time with greater accuracy.

For this, an ANN program based on the back-propagation learning and a program for room air temperature prediction using the finite

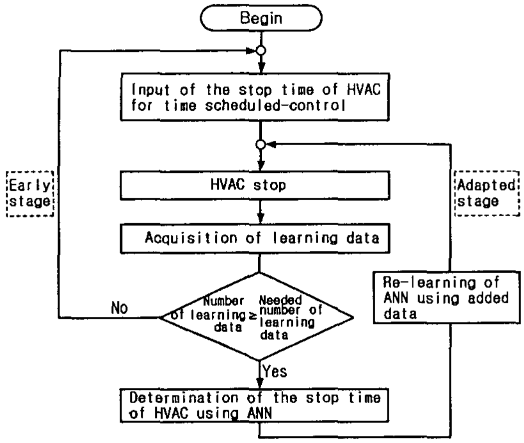


Fig. 3 Flow of determination process of stop time of HVAC using ANN.

difference method were developed. Also, through simulations using these programs, the stop time prediction performance of the ANN model is evaluated, and the optimal number of initial learning data for the prediction of stop time is presented. Furthermore, to simulate the same situations such as real buildings, simulations to predict daily stop time, using computer program which integrates the ANN program and program for room air temperature prediction, are performed to present optimal measurement intervals and acceptable error ranges of stop time.

4.2 Evaluation of determination performance of the stop time

In the determination process of the stop time using ANN model, the ANN learns operation data in the early stage, and then the stop time is determined through recall that unexperienced data is fed into the learned ANN model.

The structure and internal conditions of the simulation object space for the determination of stop time are as shown in Table 1 and Table 2.

In this research, to evaluate the performance of ANN to determine the stop time, 60 learning data were collected through simulation. 40

Table 1 Structure of wall and slab in simulation room

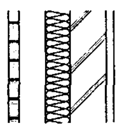
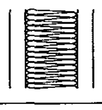
Type	Section	Composition of material			
		Material	Thick-ness (m)	Thermal conductance (W/m℃)	Thermal capacity (J/m^3℃)
Exterior wall		Stone	0.03	2.349	1,997,093
		Air	0.05	0.026	1,162
		Styrofoam	0.05	0.036	37,681
		Concrete	0.05	1.628	2,021,838
		Plaster board	0.009	0.326	1,062,614
Interior wall		Plaster board	0.009	0.326	1,062,614
		Styrofoam	0.04	0.036	37,681
		Plaster board	0.009	0.326	1,062,614
Slab		Concrete	0.10	1.628	2,021,838

Table 2 Conditions for simulation

Ambient condition	Floor area (m^2)	Ceiling height (m)	Window trans-parency ratio (%)	Indoor heat load (W/m^2)	Lower limit of setpoint temp. (℃)
 Simulation space / Outdoor	250	2.6	0.85	15	20

Table 3 Comparison between learning and recall

Number of learning pattern	Learning		Recall		
	Total error	Mean error	R^2	Mean error	Max. error
10	0.110	0.011	0.876	0.034	0.097
20	0.382	0.019	0.986	0.019	0.033
30	0.382	0.019	0.995	0.008	0.020
40	0.603	0.015	0.995	0.009	0.026
50	0.745	0.015	0.996	0.006	0.019
60	1.052	0.018	0.996	0.005	0.021

of the 60 learning data are learned by the ANN model increasing the number in intervals of 10, and the remaining 20 unlearned patterns are fed into the ANN model, so that the stop time can be calculated and the results can be evaluated.

Learning by the ANN is proceeded on the optimized ANN model[7] with 0.4 learning rate, 0.85 moment, 2 hidden layers, 4 nodes on the hidden layer, variable bias, and 5,000 iterations. The results of the determination of stop time are as follows.

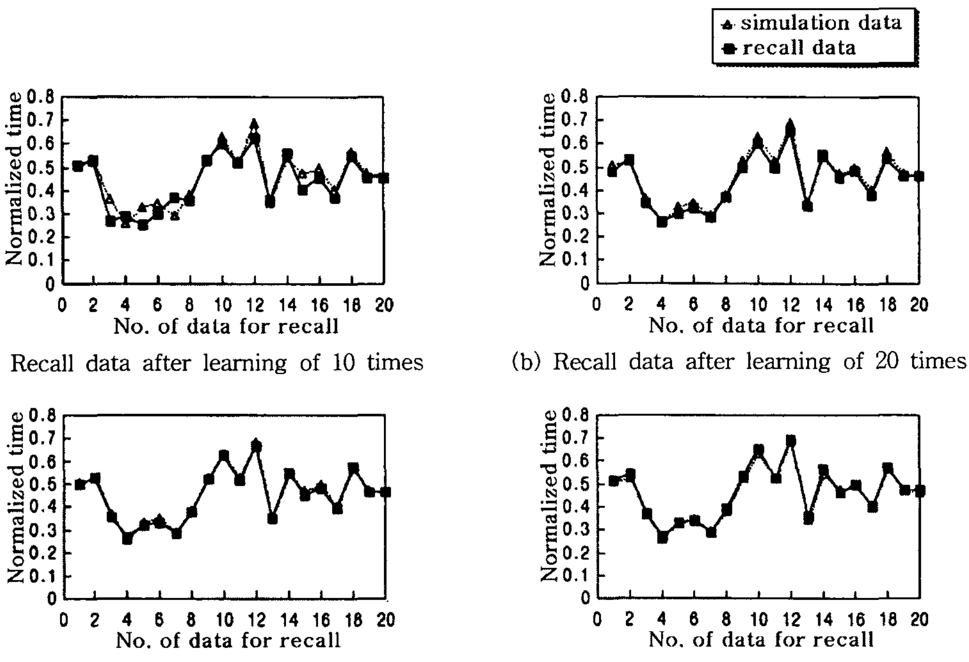
The learning results of the object space show a mean error of between 0.011 (1.2 min.) and 0.019 (2.1 min.). When the unexperienced data are fed into the learned ANN model, the ANN can determine the stop time.

As shown in Table 3 and Fig. 4, the mean error is high, with a value of 0.034 (3.8 min.) with a recall on 10 patterns learned, but decreases to 0.008 (0.9 min.) after 30 patterns have been learned. The graph shows that the calculation results from recall are almost identical to the actual values. Therefore, it can be concluded that the ANN can determine stop time accurately as long as the learning material of about 30 days is collected.

4.3 Determination of daily stop time

4.3.1 Procedure for determining daily stop time

The procedure for determining the daily stop



(a) Recall data after learning of 10 times

(b) Recall data after learning of 20 times

(c) Recall data after learning of 30 times

(d) Recall data after learning of 40 times

Fig. 4 Patterns of comparison between recall and simulations.

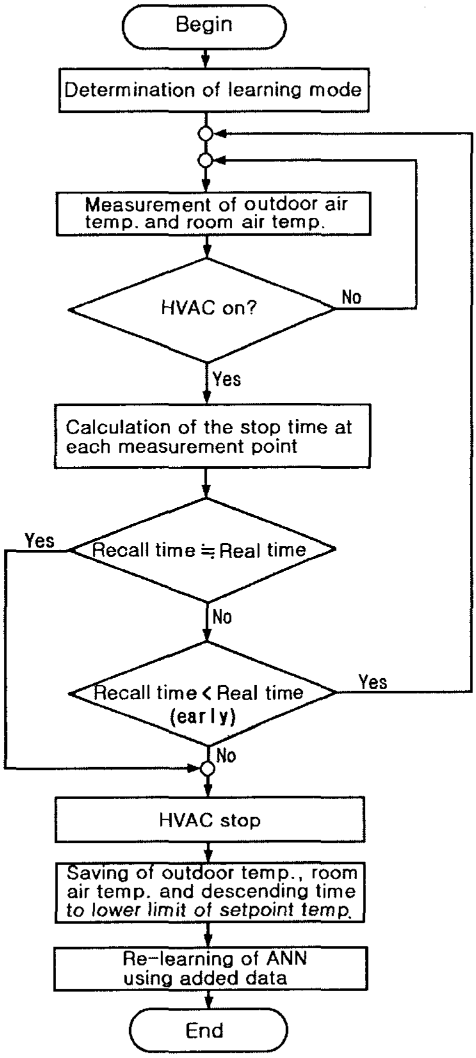


Fig. 5 Flow of daily determination of the stop time of HVAC using ANN.

time is shown in Fig. 5. The 'real time' in the figure means the time from the measurement time to the occupancy finish.

First, when the measurement begins, the outdoor air temperature and room air temperature are measured and saved at each measurement time interval, and after 1 hour, the varying rates of the outdoor air temperature and room air temperature are calculated from the measured temperatures of the current time and those of an hour before.

Using these values, the stop time for each measurement time can be calculated by ANN recall. If the error, which is the difference between the calculated stop time and the real time, is within the acceptable error range, the HVAC equipment is turned off, and if not, the measurement is continued. Also, if the error is made to drop within the acceptable error range, the equipment is turned off, and if the calculated time exceeds the pre-set time which is the limited time for unexpected error, the equipment is turned off immediately.

After the HVAC equipment is turned off in accordance with one of the conditions described above, the outdoor and room air temperatures and the varying rates of the outdoor and room air temperatures are saved, and when the room air temperature reaches the desirable temperature, the time from when equipment stops to when it reaches the desirable temperature is saved. These learning data are added to the ANN through the ANN re-learning, a more accurate stop time of the following day can be determined.

4.3.2 Measurement time interval of the input data

Since the values measured and calculated at certain time intervals are fed to the ANN model as input data, and the stop time is calculated at each time interval using these data, optimal time interval for measurement must be set.

In previous studies, the measurement time intervals were 5,[1] 15[1] and 30[8] minutes. However, if the interval is too short, instantaneous local changes in the input variables could cause high error, on the other hand if the interval is too long, the accuracy will be less accurate, so, it is important to set on the appropriate measurement interval.

4.3.3 Acceptable error range

When the stop time is determined using the ANN model, the HVAC equipment is turned

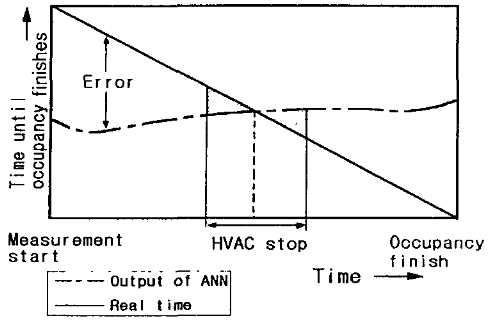


Fig. 6 Determination of the stop time using ANN model.

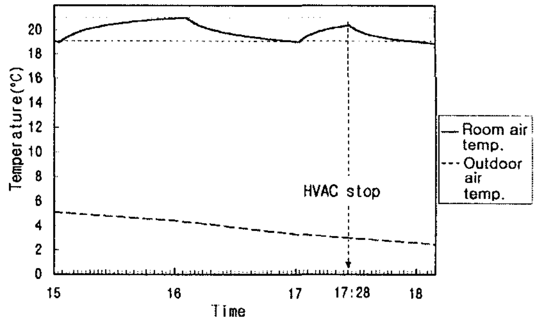


Fig. 7 Patterns of outdoor air and room air temperature.

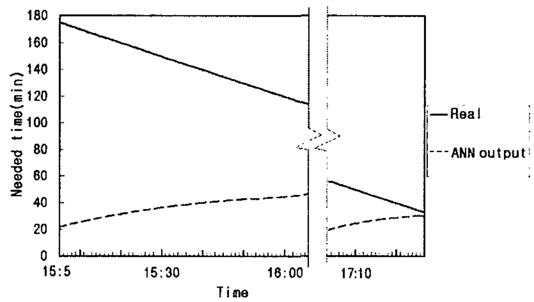


Fig. 8 Determination of the stop time using ANN recall.

off as in an actual building if the stop time calculated at measurement time equals the time remaining until the occupancy finish.

As described in Fig. 5, HVAC equipment is turned off at the point where the solid line, which represents the time remaining until the stop of the occupancy, meets the dotted line, which represents the stop time determined by the ANN model.

However, the outputs of the ANN model may vary, such that it may be too short on one day or too long on another day. Furthermore, although the line in the figure is continuous line, in reality, there exist intervals in measurement time intervals, this implies that two lines may not intersect from interval to interval.

Therefore, in practice, it may be very difficult to always determine the stop time as intersected point of two lines, thus an acceptable error range should be set.

As shown in Fig. 6, the equipment can be turned off as long as the error is within the acceptable range. The stop time determined in this manner may be slightly short or slightly long, so that the optimal acceptable error range must be determined.

4.3.4 Simulation for determination of daily stop time

In this section, simulations were performed to obtain the optimal measurement time interval and acceptable error for determining the daily stop time by varying the measurement time interval and acceptable error range as in Fig. 5.

The occupancy finish is set to 6 p.m., and the simulation was performed for the period from Dec. 1st to Mar. 10th, using the weather data of Seoul. For the first 10 days, 10 learning data were collected with the equipment turned off at a certain time, and after the 10 days, the stop time for 90 days were determined through the learning of the collected learning data.

Figure 7 shows the room air temperature and the outdoor air temperature during the occupied times, and after HVAC system is stopped. The room air temperature is in the comfort range called throttling range (i. e., between the lower and upper set-point temperatures) during the occupied times. In the figure, ANN determines twice the stop time because HVAC system is stopped within only the range during which time heat is supplied. In Fig. 8, the difference

Table 4 Calculated days according to measurement interval and permissible error

Measurement interval (min)	Permissible error (min)						
	1	2	3	4	5	6	7
1	51	51	51	51	51	51	51
2	24	51	51	51	51	51	51
4	28	38	41	44	51	51	51
5	17	39	49	48	51	51	51

between the real time to occupancy finish and the time recalled by the ANN is getting narrower as the time elapses, and if the conditions such as acceptable error range are not satisfied, the stop time can not be determined. In this figure, HVAC system is stopped at 17 : 28, from this time, the room air temperature continues to descend, and the room air temperature reaches the lower set-point temperature (19℃) at 17 : 58, showing an error of 2 minutes.

Table 4 shows the number of days during the simulation period when the stop time is calculated with varying measurement time interval and acceptable error. As shown in Fig. 6, there are instances where the ANN fails to determine the stop time at all, due to failure to meet the convergence conditions such as the measurement intervals and acceptable error ranges. Therefore, to obtain the stop time for all of the days in the simulation period, the acceptable error range must be set to be longer than the measurement interval.

(1) Stop time according to variation of measurement time interval

To select the optimal measurement time interval in determining stop time using the ANN model, simulations were performed by varying the measurement time interval, with a maximum of 5 minutes, and values of 1 min., 2 min., 4 min. and 5 min. Figure 9 shows the results of the stop time calculation according to the variation of the measurement time interval. The mean error of the results range

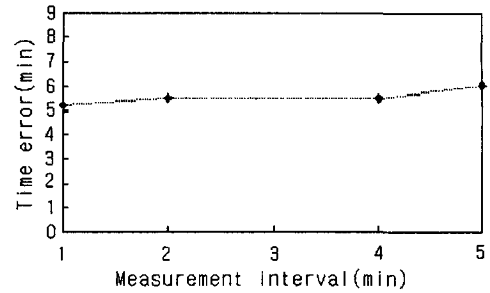


Fig. 9 Patterns of time error according to measurement interval.

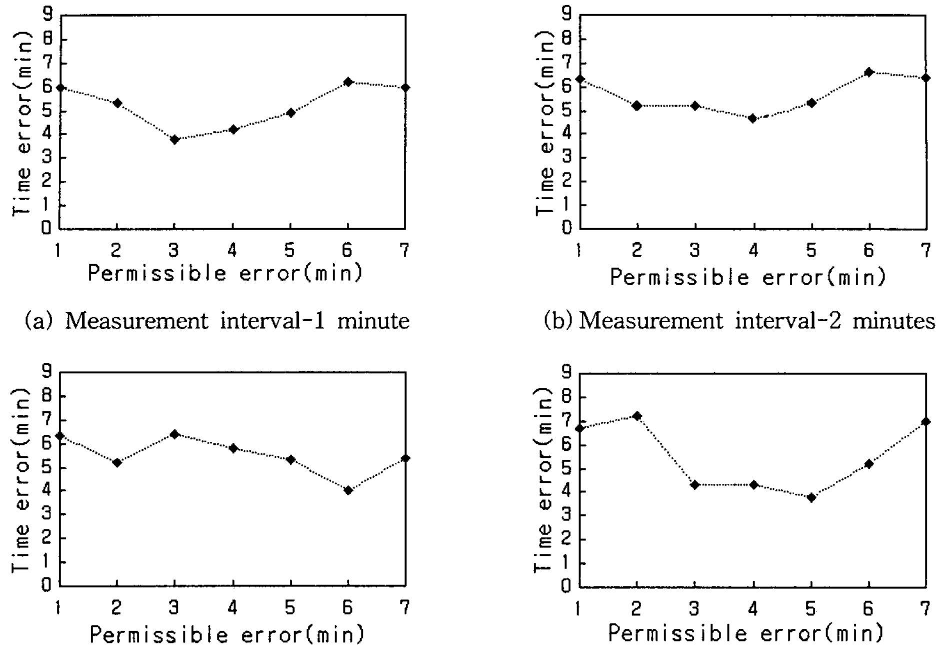
between 5.2 min. and 6.0 min. Also, mean error is 5.2 min., when the measurement time interval is 1 min. and much higher when the measurement time interval is beyond these values. Therefore, to keep the acceptable error low and still be able to obtain solutions for all cases, the measurement time interval must be set as 1 minute.

(2) Stop time according to variation of acceptable error

Figure 10 shows the results of the stop time calculation according to the acceptable error range to 1 min., 2 min., 3 min., 4 min., 5 min., 6 min. and 7 min. When the measurement time interval was 1 min., 2 min. and 4 min., the each mean errors were found to be between 3.8 min. and 6.0 min., between 4.0 min. and 6.4 min. and between 4.8 min. and 6.3 min respectively. The case with the lowest mean error was the one with an acceptable error range of 3 min. when the measurement time interval was 1 min. Here, the mean error was 3.8 minute. From this, we can conclude that measurement interval of 1 min. yields the most accurate stop time when the ANN model is used.

(3) Simulation results using optimized values

Figure 11 shows the determined stop time, and the error between the finish time of the occupation and the actual time until the temperature reaches the desired level, at which



(a) Measurement interval-1 minute
(b) Measurement interval-2 minutes
(c) Measurement interval-4 minutes
(d) Measurement interval-5 minutes

Fig. 10 Patterns of time error according to permissible error.

point simulations are performed using the 1 minutes measurement time interval and 3 minutes acceptable error range obtained through the procedures described in Fig. 4.

The (+) sign in Fig. 10 means that the desired temperature is reached before the occupancy finish, and the (−) means that the desired temperature is reached after the occupancy finish. The average error in the simulation period is 4.2 min., so the ANN can determine the stop time with relative accuracy.

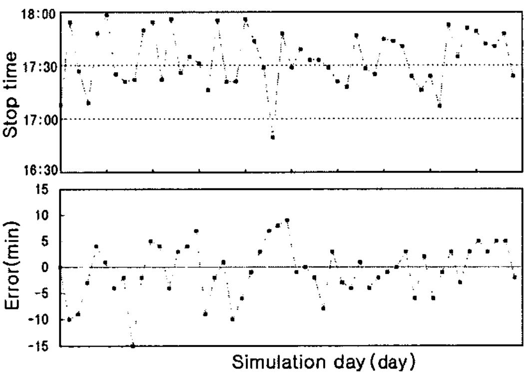


Fig. 11 Result of daily simulation.

5. Conclusions

The purpose of this study is to present the method for determining the optimal stop time of building using Artificial Neural Network Model, one of the learning methods. To this end, the ANN performance evaluation and simulations for the determination of daily stop time are performed to present optimal measurement time intervals and acceptable error ranges. The results of this research are as follow:

(1) The stop time was determined through ANN recall after unexperienced data were fed into the ANN. The learning data were fed to the ANN as the number by increments of 10 was increased. When there are more than 30 learning data, the multiple correlation coefficient (R^2) of the recall results was above 0.94

with the average error of below 1.6 min., but as the number of learning data was increased, the error was significantly decreased. This shows that the ANN model is able to accurately determine the stop time.

(2) The average error of 5.2 min. is given when the measurement time interval is 1 min. Thus, in order to minimize the error, and at the same time obtain solutions for all cases, the measurement time interval should set to be as 1 minutes.

(3) The average error of 3.8 min. was given when the acceptable error was 3 min., showing that the ANN can determine the stop time with relative accuracy.

To apply ANN effectively, future research will need to be carried out. Also, since the ANN model suggested in this study has not been tested in real building situations, they will need to be tested on real buildings. With the results of such research, ANN will play a useful role in the optimal operation of HVAC equipments, such as the optimal control and predictive control.

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