APPLICATION AND VERIFICATION OF ENERGY BASELINE ESTIMATION METHOD BY SIMULATION

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ABSTRACT

A rational method to estimate the energy baseline of a building is indispensable in performing such as retro commissioning, on going commissioning and ESCO (Energy Service Company) projects. Usually a statistical regression method is used to estimate a baseline. But the limitation of this method is that it cannot evaluate the effect of changes in operational conditions such as HVAC system and occupancy schedule, room temperatures, amount of fresh air intake in HVAC systems, weather conditions, etc. by which energy use is affected. In these cases an estimation method based on simulation would be a good option. However, few studies are found about verification of the method based on experiments using a real building. Therefore we carried out an experiment for changes of room air temperatures and the fresh air intake volume in a real building and verified the accuracy of the baseline estimation method developed in our previous study. The results show that the model can estimate the baseline change with acceptable accuracy.

KEYWORDS

energy use baseline, retro commissioning, ESCO, air-condtioning load simulation

INTRODUCTION

When we introduce energy conservation measures to estimate how much energy is reduced is a key issue. The difficulty of estimating it is on the fact that energy consumption is related to various operational conditions such as weather, occupancy, room air temperature set point, HVAC system operation, etc. which change with time and sometimes by user needs or by chance. If we can measure the reduction directly it is easy but it is not possible because post-retrofit energy usage is measurable but pre-retrofit energy use after retrofitting is not measurable. Therefore we need to estimate the pre-retrofit energy use under specific operational conditions based on a model. This is defined as an adjusted energy baseline.

The U.S. Department of Energy proposed four options to estimate the adjusted energy baseline. These are Options A, B, C and D which are explained in the International Performance Measurement and Verification Protocol (IPMVP 2002). In Japan, it is used in most ESCO projects. Option C is a method to estimate the energy baseline by statistical linear regression. Option D is a method to estimate the energy baseline by simulation. Although it requires much information and manpower, it can estimate the baseline with operational condition changes; for example, changes in weather, occupancy and equipment operation. Option D is theoretically considered more accurate than Option C. This method is important in baseline estimation because operational condition changes occur very often in usual.

We developed a method of Option D type (Miyata and Yoshida, et. al 2006). The model has two sub-modules: a heating and cooling load calculation module and an energy consumption estimation module, which consists of the models of energy consuming equipment in a building. In this study the applicability of the first sub-model is investigated by carrying out an experiment of changing room air temperatures and fresh air intake volume intentionally using a real building.

THE BASELINE ESTIMATION MODEL

Figure 1 shows an outline of the energy baseline estimation model (Miyata and Yoshida, et. al 2006). Air-conditioning load estimation is performed using ACSES developed by the authors. The load calculation is carried out by the following equations that are based on the response factor method (Yoshida, et. al 1994).

$$Q_{b,n} = Q_{T,n} - Q_{R,n} + c_a V_{oa,n}(h_{o,n} - h_{r,n}) \qquad (1)$$

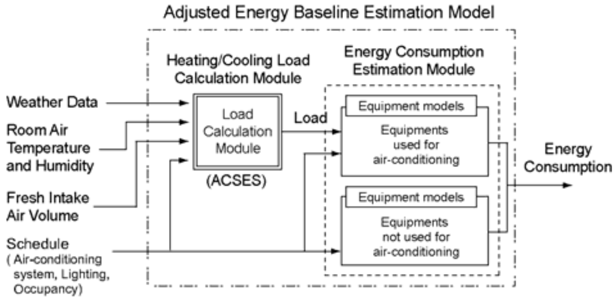

Figure 1 Adjusted energy baseline model

$$Q_{T,n} = \sum_{j=0}^{\infty}\left\{q_{t,n-j}\varphi_{t,j} + q_{g,n-j}\varphi_{g,j} + q_{r,n-j}\varphi_{r,j}\right\} \quad (2)$$

$$q_{t,n} = A_w \sum_{j=0}^{\infty}\left(\theta_{e,n-j} - \theta_{ref}\right)\phi_{T,j} \quad (3)$$

$$Q_{R,n} = \sum_{j=0}^{\infty}\left(\theta_{r,n-j} - \theta_{ref}\right)\phi_{R,j} \quad (4)$$

ACSES can calculates actual loads by inputting measured conditions such as room air temperatures and humidity, fresh intake air volume, and operation schedules of air-conditioning systems, lighting systems and occupancy.

The equipment are divided into two groups; equipment for air conditioning and the others. Energy consumption of the equipment used for air-conditioning is calculated based on estimated air conditioning loads. Energy consumption of the other equipment is estimated using actual operation schedules and energy use statistics for each equipment.

EXPERIMENT IN A REAL BUILDING

Experimental Building

Operation data were gathered in a mid-scale government building, with the floor area of 6,169 m^2 and the air-conditioned area of 3,942 m^2, in Osaka, Japan. Figure 2 shows the plan and the cross-section of the building. Figure 3 shows an outline of the air conditioning system of the building. The building has two gas-fired absorption chillers (R-1 and R-2), five air-handling units, and thirty-three fan-coil units.

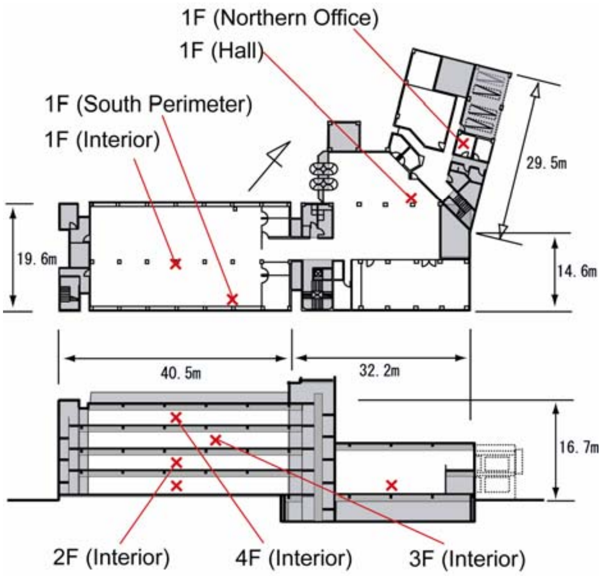

Figure 2 Plan and cross-section diagram of the experimental building (X indicates room air temperature and humidity measurement points)

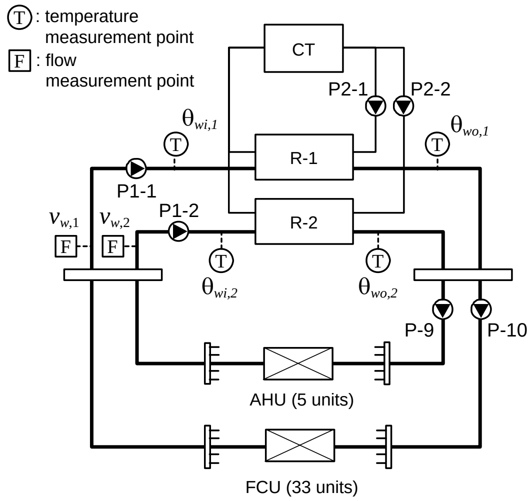

Figure 3 Air-conditioning system

It was built in 1974, and energy saving measures were retrofitted in 2003 as an ESCO project. They are installation of inverters to the fan motors of air handling units and pump motors, and replacement of fluorescent lamps with high-efficiency ones.

Measurement

The measured data are shown in Table 1. They have been accumulated for one year since the summer in 2005. Outside air temperatures and humidity and global solar radiation are measured on the roof of the building. Figure 4 shows the views of measuring instruments.

Room air temperatures and humidity are measured at 7 points, which locations are shown in Figure 2. The average room air temperatures and humidity are calculated as an area weighted mean using measured data.

$$\bar{\theta}_r(t) = \frac{1}{S_a}\sum_{i=1}^{7}\left\{\theta_{r,i}(t)\,S_{a,i}\right\} \quad (5)$$

$$\bar{x}_r(t) = \frac{1}{S_a}\sum_{i=1}^{7}\left\{x_{r,i}(t)\,S_{a,i}\right\} \quad (6)$$

Fresh air intake volume is measured at the inlet of the air intake chamber. The fresh air intake loads are calculated using the measured outdoor air intake

Table 1 Measured data

Measured item	Interval	Instruments
Outside air temperature and humidity	10 mins	Temperature and humidity recorder
Room air temperature and humidity (7 points)	10 mins	
Global solar radiation	1 min	Pyranometer
Fresh air intake volume	10 mins	Hotwire anemometer
Inlet and outlet temperature of chilled water (R-1, 2)	10 mins	Thermister inserted in pipe
Flow rate of chilled water (R-1, 2)	10 mins	Pitot-tube flow meter

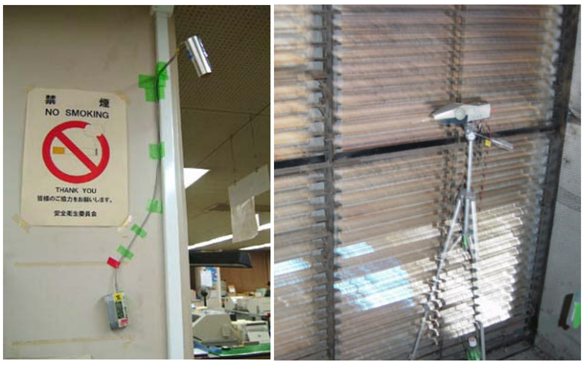

Figure 4 Photograph of measurement instruments (Left: Room air temperature and humidity, Right: Fresh air intake volume)

volume as follows.

$$Q_{oa}(t) = c_a V_{oa} \{h_{oa}(t) - h_r(t)\} \quad (7)$$

The air-conditioning loads are calculated by the equation (8).

$$Q_r(t) = c_w \sum_{k=1}^{2} \left[v_{rw,k}(t) \{\theta_{rwi,k}(t) - \theta_{rwo,k}(t)\} \right] \quad (8)$$

In this paper, Q_r is defined as the measured air-conditioning loads.

Experiment for the verification

In order to verify whether the baseline estimation model can estimate the baseline shift accurately due to the changes of operational conditions, experiments were conducted during the summer in 2006..

As the verification of the room air temperature changes, the set point of the room air temperature was changed intentionaly for four days as shown in Table 2. However, as Figure 5 shows a histogram of the average room air temperatures measured from June 22nd to September 30th, 2006, even if the set point of the room air temperature of the usual days is 27 °C, the room air temperatures are not constant, consequently, they are distributed between 26 °C and 29 °C. The room air temperatures of the experimental days fall within the distribution. Therefore not only the temperatures of the experimental days but also the temperatures under the normal operation can be used for verification.

In order to analyze the load changes by fresh air intake, the air volume was increased intentionaly in September 5, 2006 by opening the outdoor damper so that the volume becomes approximately double of the normal operation (2.46 $m^3/h{\cdot}m^2$ to 5.63 $m^3/h{\cdot}m^2$). Figure 6 shows a histgram of the fresh air intake volume from June 22nd to September 30th. Although the distribution of the volume is not so wide as room air temperature case, all the measured data are used for the verification.

LOAD ESTIMATION MODEL

The air-conditioning load estimation is carried out using a building simulation model. The building model is made using the design drawings. Table 3 and Table 4 show the wall configrations and a list of internal heat loads of the west-wing respectively as an example. The number of occupants is determined by counting the number of occupants in the building (260 persons). The calorific value of lighting and the office machines are determined by the number of devices such as lighting fixtures, personal computers, and copy machines, etc.

In order to verify the accuracy of the calculation model, the simulated loads between August 10 and September 30 are calculated and compared with the measured loads. Figure 7 shows the result comparimg daily-accumulated values of the simulated and the measuted. The relative error is approximately –1.0%, and %RMSE is approximately 11.4%. This indicates

Table 2 Details of Experiments

Date	Set point of room air temp.
Usual	27℃
8/2, 8/23	28℃
8/16, 8/30	26℃

Date	Fresh air intake volume
Usual	$2.46m^3/h{\cdot}m^2$
9/5	$5.63m^3/h{\cdot}m^2$

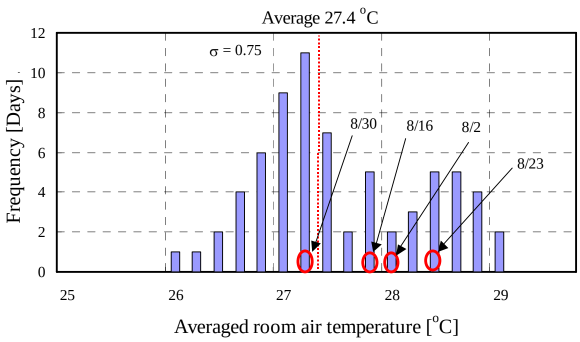

Figure 5 Histogram of room air temperature (From June 22nd to September 30th)

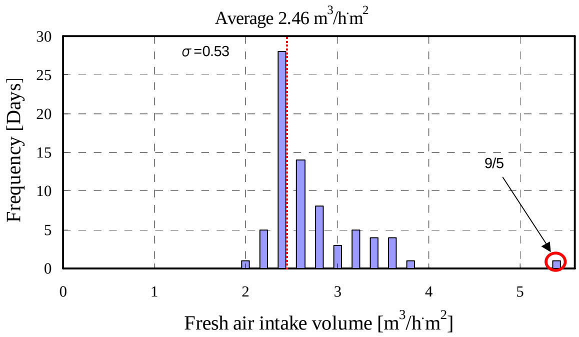

Figure 6 Histogram of fresh air intake volume (From June 22nd to September 30th)

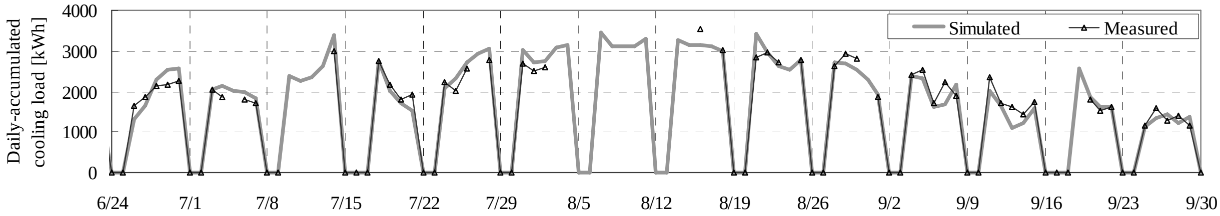

Figure 7 Comparison of simulated and measured daily-accumulated cooling loads

Table 3 Wall configuration in west-wing of the building

Exterior wall	mortar(20), normal concrete(150), light-weight concrete(20)
Interior wall	mortar(20), normal concrete(150), mortar(20)
Room divider	asbestos cement slate(6), plaster(9), still air(120), plaster(9), asbestos cement slate(6)
Ceiling	rock wool board(12), gypsum board(9), air(1160), normal concrete(130), mortar(30)
Ceiling (top)	rock wool board(12), gypsum board(9), air(960), styrene(25), light-weight concrete(150), mortar(30), light-weight concrete(100), mortar(30)
Floor	linoleum(3), mortar(30), normal concrete(130), air(1160), gypsum board(9), rock wool board(12)
Floor (bottom)	linoleum(3), mortar(30), normal concrete(120), mortar(30)

that the simulation can estimate the loads accurately.

VERIFICATION OF THE BASELINE ESTIMATION MODEL

Verification method

We examined whether cooling loads depend on values of room air temperatures and the fresh air intake volume by comparing those that are measured during experiment and simulated. The verification is performed as follows.

1) Defining three variables Q_r , $Q_{s,r}$ and $Q_{s,c}$, where Q_r is the daily average of measured hourly load, $Q_{s,r}$ is the simulated by adopting recorded operational conditions and $Q_{s,c}$ is the simulated by adopting a constant value for room air temperature or fresh air intake volume as the seasonal average.

2) Taking the differences of Q_r and $Q_{s,r}$, and of Q_r and $Q_{s,c}$, and defining those as $d_r = Q_r - Q_{s,r}$ and $d_c = Q_r - Q_{s,c}$ respectively. Taking the deference ($u_t = \theta_r - \overline{\theta_r}$) of room air temperature θ_r and $\overline{\theta_r}$,

Table 4 Internal cooling loads in west-wing of the building

Occupants			0.066 person/m^2
Calorific value of lighting			25 W/m^2
Calorific value of office apparatus	Sensible heat	4F	5.49 W/m^2
		2,3F	8.45 W/m^2
		1F	15.19 W/m^2
	Latent heat		0 W/m^2

where $\overline{\theta_r}$ is the seasonal average of room temperatures (27.4 °C), and the difference ($u_s = Q_{oa} - \overline{Q_{oa}}$) of Q_{oa} and $\overline{Q_{oa}}$, where $\overline{Q_{oa}}$ is the seasonal average of the fresh air intake load (22.5 kJ/h).

3) Taking seasonal average of Q_r , $Q_{s,r}$ and $Q_{s,c}$ as $\overline{Q_r}$, $\overline{Q_{s,r}}$ and $\overline{Q_{s,c}}$ respectively. The difference of $\overline{Q_r}$ and $\overline{Q_{s,r}}$ gives simulation accuracy (Figures 8 and 9).

4) Applying linear regression analysis to d_r and u_t . If the gradient of the regression line becomes zero or the regression line holds horizontal position it tells that the simulated loads depend on room temperatures or simulation can physically account for the condition changes. In addition when applying linear regression analysis to d_c and u_t , and if the gradient of the regression line becomes positive or the regression line holds upward slope, we reach to the same conclusion. Therefore we applied both approaches to make the conclusion confident (Figures 8 and 9).

5) Checking the linearity of the relationship between d_r and u_t , and of d_c and u_t . Based on the physical

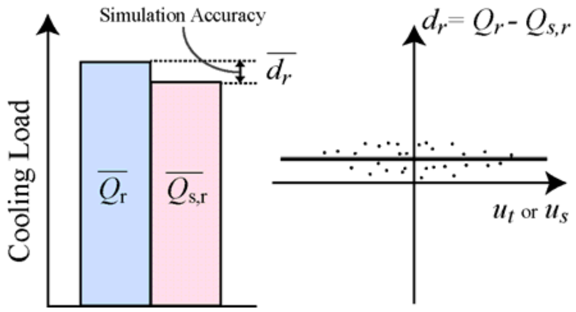

Figure 8 Comparison of measured cooling load Q_r with simulated cooling load $Q_{s,r}$

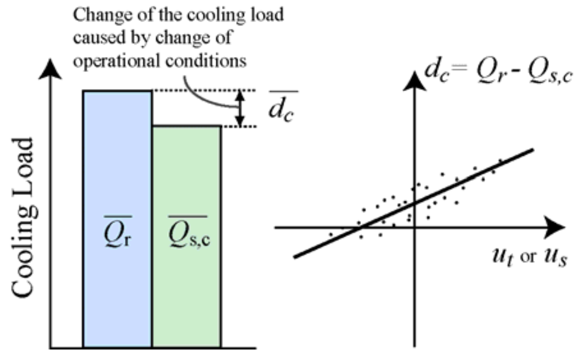

Figure 9 Comparison of measured cooling load Q_r with simulated cooling load $Q_{s,c}$

theory the relationship of the two variables is linear but we need to check it by the following method. We divide operational conditions into three ranges so as to make the number of points same in each range and calculate the average of both variables and check the linearity. This test is used as additional proof to the above verification if the value of R^2 of liner regression is too small to prove the existence of correlation.

Room air temperature change

Figure 10 and Figure 12 shows the relationship between d_r and u_t, and d_c and u_t respectively. We found that the linear regression line holds almost horizontally compared to the Figure 12. This indicates that the simulated loads account for the room air temperature changes, however the R^2 value is too small (0.09) to prove it statistically. The reason why the relationship is not so definite could be due to that the load change caused by the room air temperature fluctuation is not substantial. According to the simulation results it is known that the effect is only about 6 % of the total load. However Figure 11 shows the averaged values of the three ranges align mostly on a horizontal line that shows the existence of the linear relationship.

From Figure 12 it can be seen that the gradient of the linear regression line has a large negative value. This assists the above conclusion. However still the R^2 value is not so large (0.42). In Figure 13 the averaged values of the three ranges are shown that shows the linear relationship very clearly.

Fresh air intake volume change

Figure 14 and Figure 16 shows the relationship between d_r and u_s, and d_c and u_s respectively. The point isolated in the right hand side corresponds to the experiment of fresh air intake volume change on Sept. 5, 2006. In this case the gradient of the regression line of Figure 14 is smaller than that of Fig 16. This modestly shows that the volume change can account for the load change but the proof

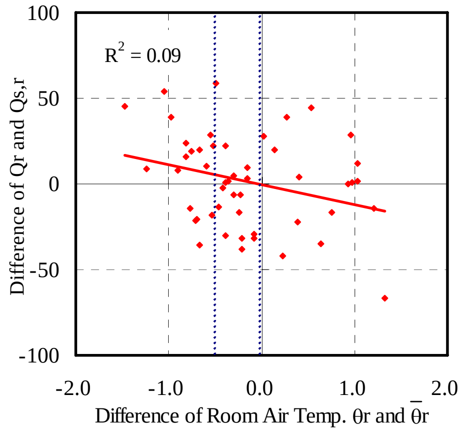

Figure 10 Relation between room air temperature and difference between Q_r and $Q_{s,r}$

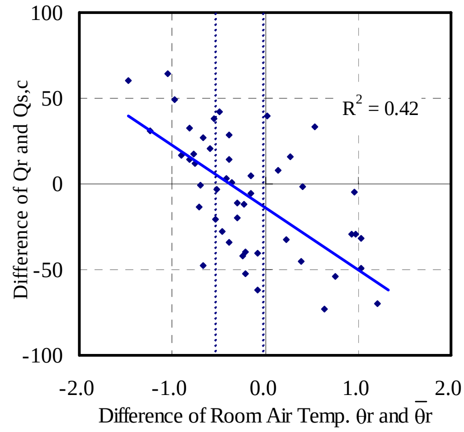

Figure 12 Relation between room air temperature and difference between Q_r and $Q_{s,c}$

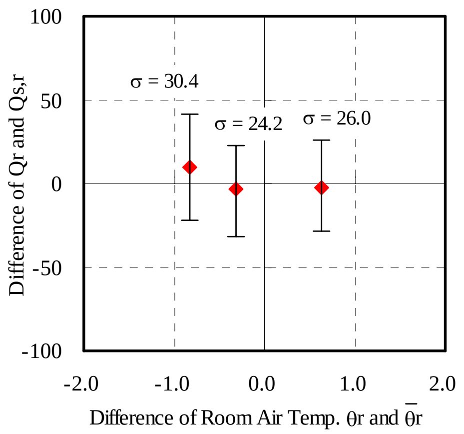

Figure 11 Relation between room air temperature and grouped difference between Q_r and $Q_{s,r}$ (σ : Standard deviation of the each group)

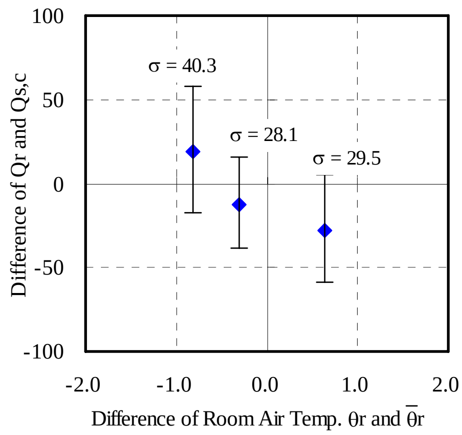

Figure 13 Relation between room air temperature and grouped difference between Q_r and $Q_{s,c}$ (σ : Standard deviation of the each group)

is not confident. The other method of using the averaged points of three ranges cannot also prove the fact. In conclusion the evidences are consistent physically but they cannot be proved in statistical manner.

CONCLUSIONS

Estimating the energy baseline of a building is essential in performing retro commissioning, on going commissioning and ESCO (Energy Service Company) projects. In this study whether air-conditioning load can be estimated by simulation accurately is verified based on experimentation in a real building. The followings are the results obtained.

1) It was verified that room air temperature affects air-conditioning loads and the quantity of the load change can be estimated by simulation.

2) It is not statistically verified that the load is affected by fresh air intake volume. But at least no negative indication was found against the relation.

3) The relationship between load and operational conditions change is identified as linear.

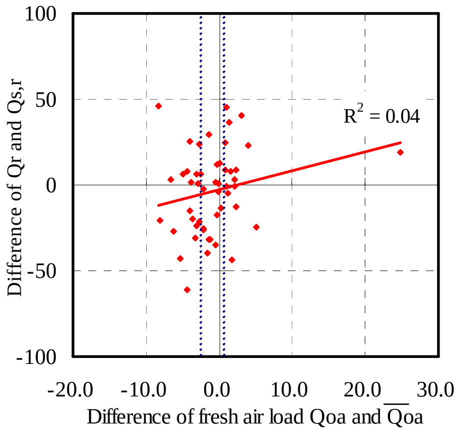

Figure 14 Relation between fresh air load and difference between Q_r and $Q_{s,r}$

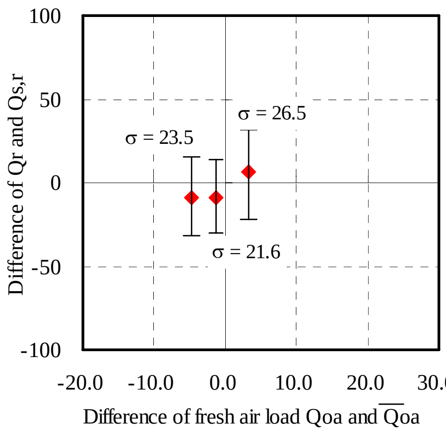

Figure 15 Relation between fresh air load and grouped difference between Q_r and $Q_{s,r}$ (σ : Standard deviation of the each group)

NOMENCLATURE

A_w : Area of external wall [m²]
c_a : Specific heat of dry air [J/g·K]
c_w : Specific heat of water vapor [J/g·K]
$h_{o,n}$: Enthalpy of outdoor air [J/kg]
$h_{r,n}$: Enthalpy of room air [J/kg]
$q_{g,n}$: Heat load by light through glass [W]
$q_{t,n}$: Transmitting heat load through external wall [W]
$q_{r,n}$: Heat load by internal heat emission [J]
$Q_{b,n}$: Total thermal load [W]
Q_r : Measured thermal load [W]
$Q_{s,c}$: Simulated thermal load with constant operational condition [W]
Q : Simulated thermal load with measured

[W]
[m²]
[m²]

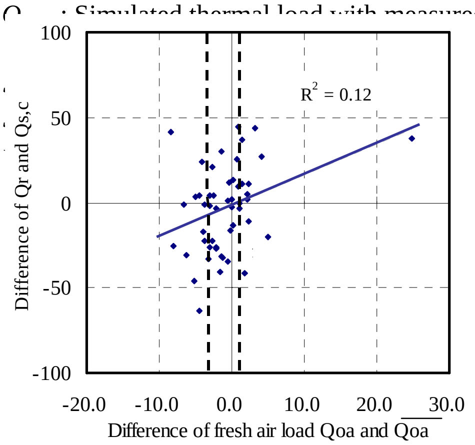

Figure 16 Relation between fresh air load and difference between Q_r and $Q_{s,c}$

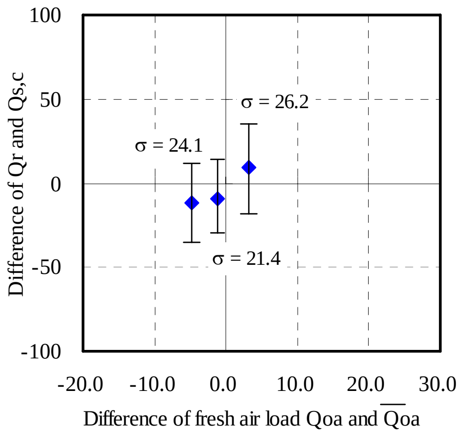

Figure 17 Relation between fresh air load and grouped difference between Q_r and $Q_{s,c}$ (σ : Standard deviation of the each group)

(k =1:R-1, k =2:R-2) [m^3/h]

$V_{oa,n}$: Fresh air intake volume [kg/s]

$\underline{x_{r,i}}$: Measured humidity of room i [g/gDA]

$\overline{x_r}$: Area weighted average room air humidity [°C]

$\underline{\theta_{e,n}}$: Sol-air temperature [°C]

$\overline{\theta_r}$: Area weighted average room temperature [°C]

$\theta_{r,i}$: Measured temperature of room i [°C]

θ_{ref} : Reference temperature [°C]

$\theta_{r,n}$: Room air temperature [°C]

$\theta_{rwi,k}$: Inlet child water temperature (k =1:R-1, k =2:R-2) [°C]

$\theta_{rwo,k}$: Child water temperature at outlet (k =1:R-1, k =2:R-2) [°C]

$\varphi_{g,n}$: Weighting factor of heat gain of light [-]

$\varphi_{r,n}$: Weighting factor of internal heat gain [-]

$\varphi_{t,n}$: Weighting factor of external wall [-]

$\phi_{R,n}$: Heat absorption response factor of room [-]

$\phi_{T,n}$: Heat transfer response factor of external wall [-]

Subscript

n : Time step

REFERENCES

Adam C., Andre P., *et al*: Commissioning Oriented Building Loads Calculations. Application to the CA-MET Building in Namur, International Conference For Enhanced Building Operations, 2004

Giebler, T., M. Liu, and D. E. Claridge: Evaluation of Energy Conservation Measures by Model Simulation, The Eleventh Symposium on Improving Building Systems in Hot and Humid Climates Proceedings, 1998.1

Harunori Yoshida, Toshio Terai, Hiroaki Sueyoshi: Transient Analysis of Air-Conditioning Load and Room Conditions Considering Simultaneous Heat and Moisture Transport of Multi-Layered Constructions , Building and Environment, Special Issue 29.3, pp.337-343, 1994

IPMVP New Construction Subcommittee: Concepts and Options for Determining Energy and Water Savings Volume I, International Performance Measurement & Verification Protocol, 2002.3

Kreider, J.F. and Haberl, J.S.: Predicting Hourly Building Energy Usage: The Great Predictor Shootout -- Overview and Discussion of Results, ASHRAE Transactions Vol. 100, pp.1104-1118, 1994.1

Liu M., Zhu Y., *et al*: Airflow Reduction to Improve Building Comfort and Reduce Building Energy Comsumption – A Case Study, ASHRAE Transactions Research, Vol. 105 Part1, P.384-390,1999

Masato Miyata, Harunori Yoshida, *et al*: Estimation of Excessive HVAC Energy Consumption due to faulty VAV units, Building Simulation, 9th International Conference, pp.777-786, Canada, 2005.8

Masato Miyata, Harunori Yoshida, *et al*: Estimation of Energy Baseline by Simulation for On-going Commissioning and Energy Saving Retrofit, International Conference of Enhanced Building Operation, Shenzhen, Vol.6-6-2, 2006.11