Building Simulation 2003

Eighth International IBPSA Conference
Eindhoven, Netherlands
August 11-14, 2003

ENERGY SIMULATION COMBINED WITH INDOOR CLIMATE MEASUREMENT AS A BASIS FOR INDIVIDUAL ENERGY BILLING IN MULTIFAMILY HOUSES

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ABSTRACT

The present paper describes the development of a method where simulations combined with measurement of parameters for each apartment such as temperatures and relative humidity in the exhaust air and electricity consumption, are used as a basis for individual energy billing. With simulations a transfer function between total heat consumption in the building and in the measured parameters for each apartment is calculated for estimating the individual contribution to the total heating energy used in the building. Transfer functions between humidity in exhaust air from each apartment and individual domestic hot water consumption are found by process identification. The aim with this development is to establish a method for a just distribution of the energy cost at a minimum cost, i.e. with as few measurement points as possible and without having to enter the apartments for installation and service of the system.

INTRODUCTION

Most Swedish multifamily houses do not have individual measurements for heating or hot water consumption. The structure of the heating and hot water systems is also such that installation of individual meters will be very costly. Today, in general, the billing is included in the monthly rent and based on the size of apartment. Due to the relatively weak coupling between individual energy use and cost it is generally believed that the energy consumption is 10-30 percent higher than if there was a direct link between individual consumption and debiting (Berndtsson 1999).

There are mainly two different methods to form a basis for individual billing. The direct method in which the tenant is charged for the total energy supplied to each apartment or the indirect method in which parameters such as the indoor temperature, electricity consumption, moisture production etc. are used as a basis for estimating the individual contribution to the total energy consumption in the building. The direct method is what the consumers in general would consider to be fair, but the cost for installing energy meters for each apartment is overwhelmingly high since it includes the rebuilding of the pipe-networks so this is not a feasible solution for existing buildings.

Earlier projects in this field show that for buildings with good insulation of the exterior construction but no insulation between the apartments the heating energy delivered to each apartment is a rather poor indicator of the actual contribution of each apartment to the total energy consumption of the building. Heat exchange between apartments should also be observed to make them fair. Energy simulation combined with temperature measurement can improve the fairness substantially.

Fast speed internet can be used for transferring measurement data in real time from multifamily houses to the remote database server and for providing simulation result as energy information to occupants, real estate companies, and energy companies (Nord 2001).

DESCRIPTION OF BUILDINGS TREATED IN THE SIMULATION

The system targets one of the typical multi-family buildings in Sweden, but can also be used for other countries' buildings which have similar specification as shown below.

Building type:	Residential multi-family house
Heat source:	District heating system
Heating system:	Centralhydronic heating system
Common space	Basement ,attic, laundry
Ventilation:	Forced exhaust ventilation from the kitchen and/or the bathroom
Cooking:	Electrical cooking apparatus
Air conditioner:	not installed

Table1. Description of targeted building in the system

Heat for the building is provided from a district heating company which is also the most common energy source for multifamily buildings in Sweden.

APPROACH FOR ESTIMATION OF INDIVIDUAL ENERGY CONSUMPTION

For most multi-family houses in Sweden the energy consumption is at present monitored by ocular reading from installed meters regularly (every month, half year, etc.), this includes the following posts:

- Total heat consumption
- Total hot water consumption
- Total cold water consumption
- Individual electricity consumption

The method assumes continuous monitoring of the above quantities. From these values, energy consumptions below are desired to be estimated:

- Individual contribution to the total heating load
- Individual hot water consumption
- Individual cold water consumption

In order to estimate the contribution of each individual apartment to the total energy consumption, the data below is obtained by sensors and/or from official meteorological databases.

- Temperature and the relative humidity in exhaust air from each apartment
- Temperatures in common place (staircases, corridors, etc.)
- Outdoor air temperature
- Solar radiation

The above quantities are monitored continuously. The present project is mainly focused on the estimation of individual heating and hot water consumption.

ESTIMATION OF THE INDIVIDUAL CONTRIBUTION TO THE HEATING LOAD

In order to estimate individual heat consumption, the heat balance in the different apartments and common places (staircase, basement floor, attic etc.) are simulated simultaneously. In the first approximation the simulations will be based on monthly means according to EN832. The main posts of the heat balance are considered. In the first approximation, steady state heat balances are used (Jóhannesson 2002). Heat balance equation in each apartment is:

$$\Phi_T + \Phi_S + \Phi_V + \sum \Phi_N + \Phi_H + \Phi_P = 0 \quad (1)$$

Φ_T: Heat transmission between outdoor and indoor ambient environments.

Φ_S: Heat generated from solar radiation through windows

Φ_V: Heat flow through ventilation and infiltration

Φ_N: Heat flow from neighbouring apartments

Φ_H: Heat flow generated from the heating system

Φ_P: Heat flow generated from household appliances, persons etc.

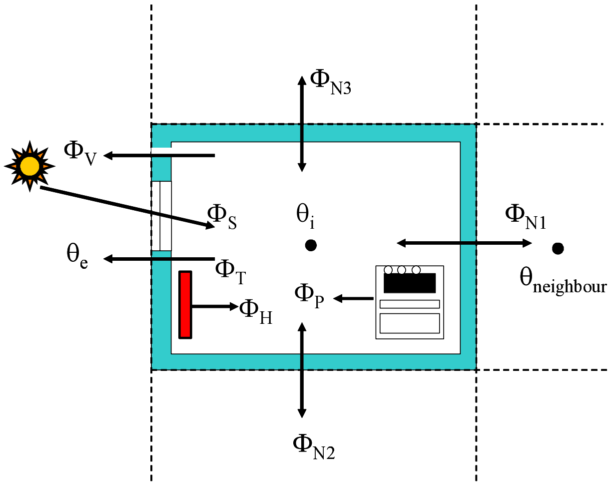

Figure 1. Heat balance model in each apartment

Among the parameters above, Φ_H and Φ_P are unknown and estimated in this system.

$$\Phi_H + \Phi_P = -(\Phi_T + \Phi_S + \Phi_V + \sum \Phi_N) \quad (2)$$

Φ_P contains generated heat from household appliances and persons. Φ_P seems to have correlation with individual electricity consumption **P**, which is measured by the meter,. Therefore the equation below is used for estimating $\mathbf{\Phi_P}$ and $\mathbf{\Phi_H}$.

$$\Phi_P \cong \eta \cdot P \quad (3)$$

Total heat consumption H_{total}, which is measured by the central meter, should be the sum total of $\mathbf{\Phi_H}$ and heat for hot water H_{hw}, which is calculated with total hot water consumption.

$$\sum_i \Phi_H = H_{total} - H_{hw} \quad (4)$$

By substituting equation (2) and (3) for (4), equation below is obtained.

$$\sum_i (\Phi m_i - \eta_i \cdot P_i) = H_{total} - H_{hw} \quad (5)$$

Where i is an ID number of an apartment and $\mathbf{\Phi m_i}$ is a right side of equation (2) and calculated with the measured data. Unknown parameters in equation (5) are η_i. By measuring data continuously, η_i can be obtained by Linear Least Squares Solutions, and therefore $\mathbf{\Phi_H}$ in each apartment can be estimated

The electrical consumption for each apartment consists of a relatively constant part for the refrigerator etc and an activity related part such as for cooking and lighting. More sophisticated relation between electricity use and free heat can be established from actual measured data, especially for the building as a whole.

The monitoring in the first multifamily house is ready to start in late winter 2003.

EXAMPLE OF THE SIMULATION

To consider the effect of heat exchange between neighbours on yearly heat demand in each apartment, simulation has been carried out by this system (Andersson 2002).Outdoor temperature and solar radiation are obtained from the monthly climate data in Stockholm.

U-values of each boundary are shown below. These data are for a typical modern Swedish building (Björk et.al 1993).

Ground:	0.20
Inner/Outer walls:	2.49 / 0.12
Window:	1.8
Attic:	0.16

Table 2. A list of boundary's U-value

The building has a balanced ventilation system and ventilation rate is 0.35 l/s, m2. Φ_p is assumed to be 5 W/ m2 (floor area), which is a recommended value in EN832.

Figure 2 shows a comparison of annual heat demand in each apartment with two different indoor temperature patterns.

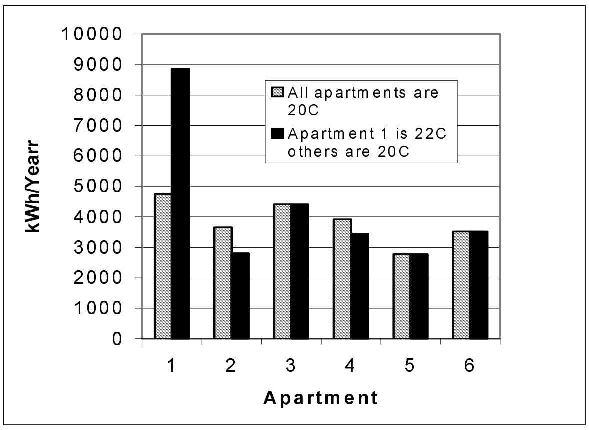

Figure 2. A comparison of annual energy demand for space heating in each apartment

This result indicates that heat demand in each apartment is much affected by the neighbour's temperature.

Another example of the simulation result is shown below. Indoor temperature in each apartment is shown below. These temperature are based on the statistic indoor climate data in Sweden (Andersson 1993).

1	2	3	4	5	6
21C	22C	20C	21C	23C	21C

Table 3. Temperature in each apartment

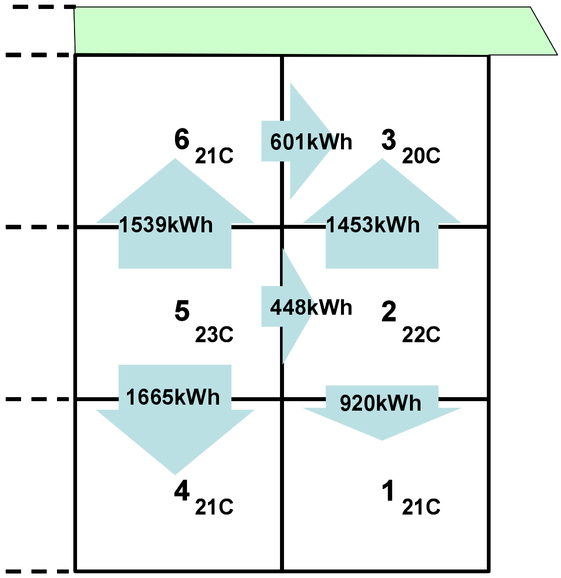

Figure 3. Yearly heat flow between the apartments

Figure 3 shows a result of the simulation. The system can calculate hourly, daily, monthly and yearly heat flow between apartments and occupants. Assuming that each tenant has the right to maintain 21C the extra heat loss or the savings due to a difference in mean temperature can be estimated from the heat balance as described above and used as a basis for the billing. The information gained can at the same time be used to continuously inform the tenant about his energy consumption and give information to the real estate company on the operation and possible energy savings in the building.

ESTIMATION OF INDIVIDUAL HOT WATER CONSUMPTION

In order to estimate individual hot water consumption, relative humidity data of exhaust air from the apartment is monitored.

In each apartment hot water is generally used for:

Bathroom
- shower
- bathtub
- wash at a basin

Kitchen
- wash at a sink
- dishwashing machine

Among these usages, the large part of hot water consumption is bathroom and dishwashing. Therefore, in this paper, other usages are neglected.

If hot water is used at a bathroom, relative humidity of exhaust air from a bathroom is expected to increase. By measuring total hot water consumption for the building and relative humidity in the individual apartments at the same time, it seems to be possible to detect the apartments in which hot water is used and from this information over time build up a transfer function between measured humidity and hot water consumption for each apartment.

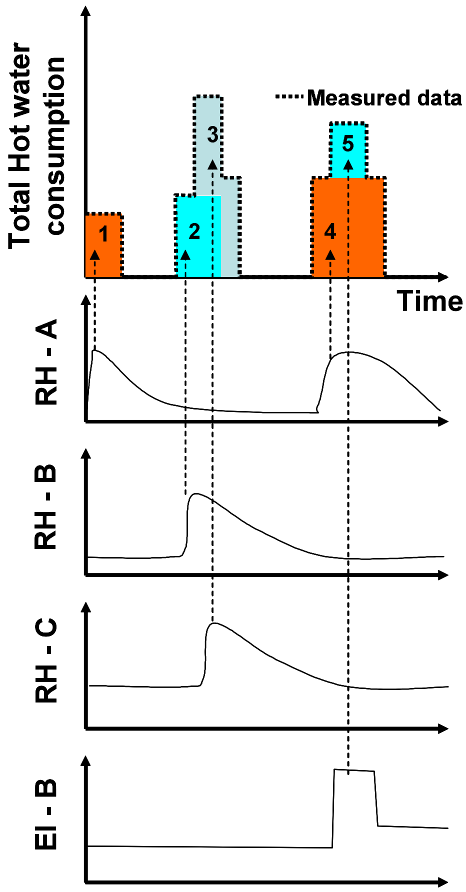

Figure 4. Overview of hot water consumption estimation method:
RH-A, RH-B and RH-C shows relative humidity of apartment A, B, C respectively.
El-B shows electricity consumption in apartment B

The usage of dishwashing machine or a washing machine in the apartment is detected by a time-series data of individual electricity consumption. Generally, dishwashing machine is controlled by simple timer and a sequential process, it seems easy to detect its usage by observing individual electricity consumption. From the simultaneous measurement of the total hot water consumption it can be detected if the machines have a hot water inlet.

Once the usage of bathroom or dishwashing machine is detected in an apartment when total hot water consumption increases, the amount of increasing hot water is supposed to be used in the apartment.

The basic estimation strategy can be explained by the equation below.

$$HW_{\text{total}}(t) = \sum_i f_{\text{HW}_i}(\Delta V_i(t)) \quad (6)$$

$HW_{\text{total}}(t)$: Total hot water consumption

f_{HW_i} :Transfer function between relative humidity in the exhaust air and hot water consumption in apartment *i*.

$\Delta V_i(t)$: Time-domain differential humidity in the exhaust air in each apartment.

f_{HW_i} is not a linear function and the transfer properties have to be established from real consumption data and corresponding variations in indoor humidity for the individual apartments over a longer time in the manner suggested below.

Overview of the practical estimation strategy is shown in figure 4 and explained as follows:

Hot water consumption shown as region 1 and 4 is considered to be taking place in apartment since it matches a sharp increase in humidity with time. In order to detect a significant increase of the humidity, threshold levels for each apartment are set based on the standard deviation of time differential of humidity while occupants are not active, i.e. in the middle of the night.

Region 2 and 3 are considered to be used in apartment B and C respectively by detecting the increase of the humidity at the same time.

Region 5 is considered to be used in the apartment B by detecting a certain amount of increase in electricity consumption of apartment B.

In this example, only 3 apartments are considered, but the estimation method can be applied for larger number of apartments.

To examine the possibility of this estimation method, the relative humidity of exhaust air from a bathroom was measured for 2 days at an apartment. Relative humidity was measured by the sensor installed at the entry of the exhaust duct in the bathroom.

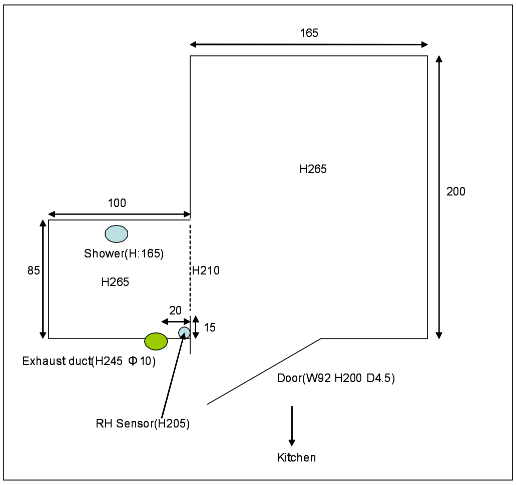

Figure 5. A plan of the bathroom

During the experiment, relative humidity in the exhaust duct in the bathroom, as well as the time of shower use and door open/close were recorded at the same time. 2days trend of relative humidity is shown in figure 6.

The shower was used 6 times in 2 days. It is obvious that relative humidity rapidly increased when the shower was used. Figure 7 shows a detail profile during a shower time. Shower was used twice during a shower time as shown between 2 broken lines.

Relative humidity started increasing when shower was started and started gradually decreasing when shower was stopped.

These results indicate that there is a high possibility to detect the beginning of using hot water. If shower is not used and bathtub is filled with hot water, relative humidity seems to increase as the result above therefore a threshold for detecting an exact start should be carefully considered in future.

To evaluate the estimation method for multiple apartments, a continuous 2 days monitoring was carried out in a multifamily house, in which there are 15 apartments for both singles and families. Hot water consumption in each apartment was estimated using the practical strategy described above. Electricity consumption in each apartment has still not been taken into consideration since simultaneous reliable data has not been gained for all the 15 apartments.

Relative humidity of exhaust air from each apartment was measured together with the total hot water consumption in the building. A 48 h series of measured data and estimation result of hot water consumption in each apartment is shown in figure 8 and figure 9 respectively. “Other” in figure 9 shows the part of consumption which can not be allocated to a certain apartment based on variations in the exhaust air humidity.

The relationship between total hot water consumption and the percentage error by detection chance is shown in figure 10. The result shows that the error percentage is relatively high when hot water consumption is low. Total percentage error by consumption is 9.9%.

One of the causes of error that can be considered is that there is a laundry and a shop in the building and some part of hot water flow, which was also measured by the same water meter, could be consumed by them. In this case, the hot water user cannot be detected.

The error percentage in high consumption is low. The results indicate that the biggest energy consumers, can be detected.

The estimation error in the case when hot water is consumed in more than 2 apartments at the same time should be considered in future work and how the errors can be reduced when the consumption is also related to the electricity consumption which also is a measure of human activity.

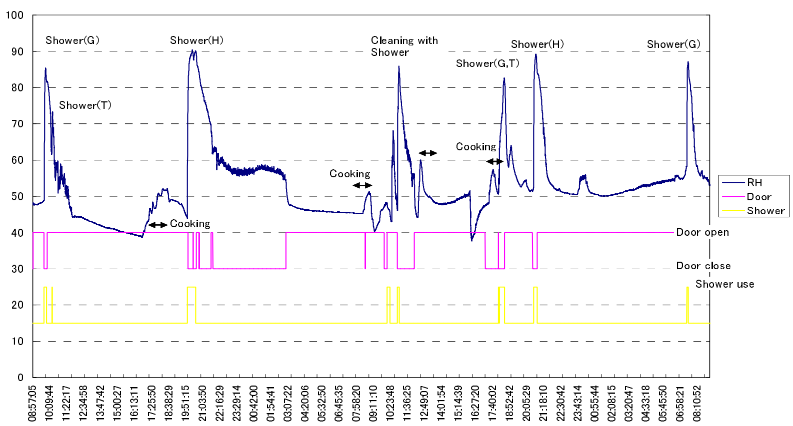

Figure 6. 2 days profile of relative humidity in exhaust air

Figure 7. Detailed profile of relative humidity during shower time

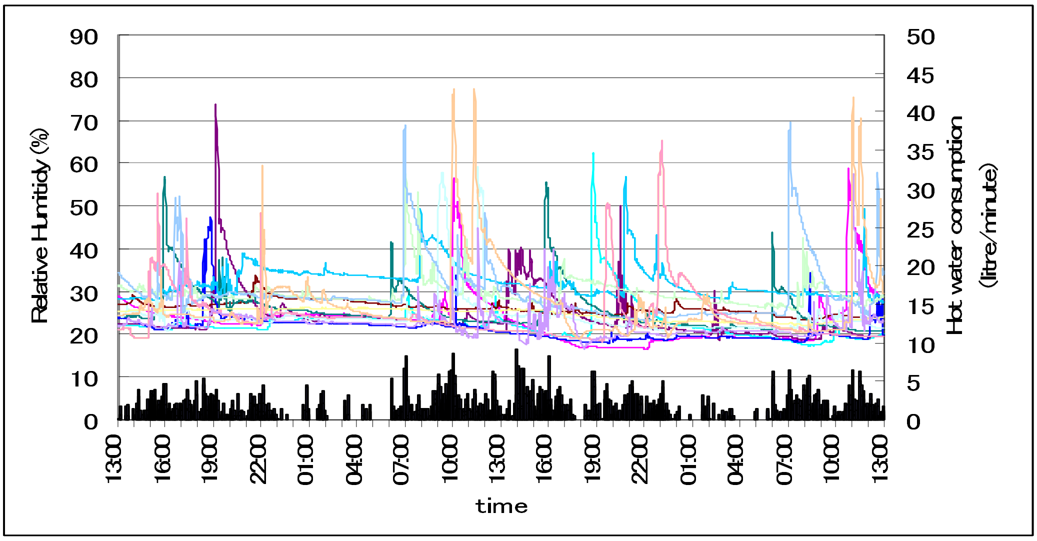

Figure 8. 48 h series of relative humidity in each apartment and the total hot water consumption

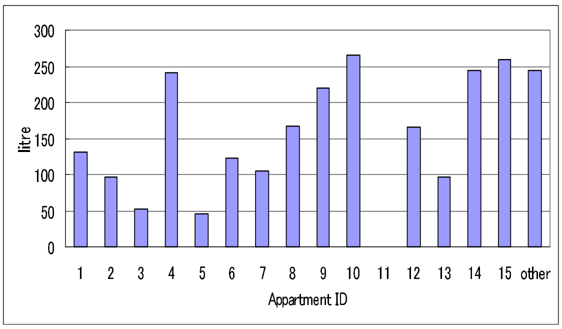

Figure 9. Estimation result of hot water consumption

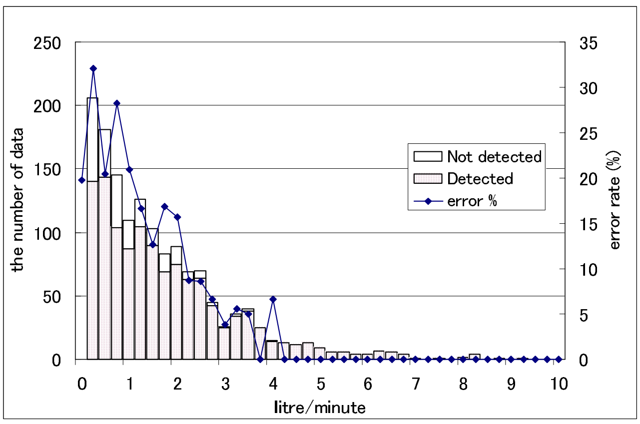

Figure 10. Hot water consumption and estimated error by detection chance

ESTIMATION OF INDIVIDUAL COLD WATER USAGE

When a user of hot water is detected, cold water seems to be used at the same time by the same user as shown in figure 11.

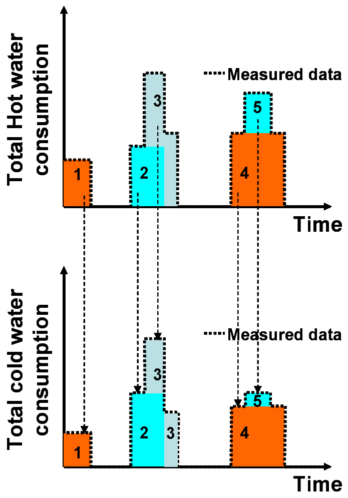

Figure 11. An example of estimation of individual cold water consumption

If only cold water is used, the user of the cold water is not detected by the system. But generally, in such cases as used at basin or kitchen for washing face, hand or food, the water consumption is much less than that when cold water is used with hot water for shower, bathtub water, or dishwashing. Therefore these cases are not considered in the system.

ENERGY INFORMATION SYSTEM

The purpose of developing the simulation described in this paper is to provide the estimation results as energy information to occupants, real estate companies and energy suppliers. In this section, the whole system including measurement system is described.

Total consumption of heat, hot water, cold water, and individual electricity consumption are measured by meters, which are generally installed by energy companies. Most of these meters output "pulse signal" when a certain amount of energy is consumed. Energy consumption in a fixed period is obtained by pulse-count sensors coupled with the meters.

Temperatures in each apartment and relative humidity in the bathroom are obtained by sensors inserted in the exhaust ducts at the roof. Entering into each apartment and disturbing occupants for installing sensors can be a substantive cost, therefore this indirect measurement is chosen. Normally there are separate exhaust air ducts from each apartment to the roofs. The possible heat loss from the duct between the apartment and the roof will be considered.

Data above are monitored continuously as a basis for the simulation and process identification. Measured data are sent from the internet gateway server through the internet to the Service Centre where data is processed and analyzed.

Figure 12. Internet gateway server (Ericsson eB103)

The results from the measurements together with the analysis results can be accessed by the occupants, the real estate company and the energy company in appropriate formats through the internet.

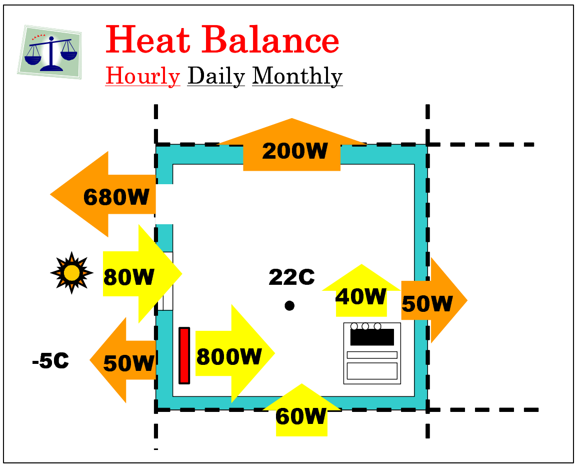

Figure 13. An example of energy information for occupants

The system was installed in February 2003 at a multi-family house in Gävle, 180km north from Stockholm, Sweden. Monitoring and transfer of data started in March 2003.

Figure 14. An experimental multi-family house in Gävle

Figure 15. Exhaust ducts for relative humidity measurement

CONCLUSIONS

In this paper a method for energy billing using energy simulations of multifamily houses combined with measurement of temperature, electricity and relative humidity is treated. Estimation methods of individual heat consumption, hot water consumption, and cold water consumption are shown with examples.

Estimation of individual hot water consumption using relative humidity in the exhaust air and individual electricity consumption seems to be a new approach. Preliminary experiments with comparison of shower use time and relative humidity indicates that with a proper signal processing a reliable data on individual hot water consumption could be established. The example with estimation result from actual data measured in the multifamily house also shows the high potential of this estimation method.

Measurement system for simulations can be installed with low-cost by adding few sensors to existing buildings. In this paper, residential multifamily houses are treated as a target of the simulation, but it can be apply for other types of existing multizone buildings.

Though a validity of each estimation method is not sufficiently studied, examples show a high potential of providing them as energy information for occupants, real estate companies and energy suppliers. Further studies will be carried out with actual data.

ACKNOWLEDGEMENTS

The research project is done within the Smart Homes Project in the European Commission Fifth Framework Program.

REFERENCES

Andersson D., "Individual debiting of space heat in Swedish multi-family buildings-Fair or not?", Diploma thesis, KTH - The Royal Institute of Technology, Stockholm 2002

Berndtsson L., "Utredning angående erfarenheter av individuell mätning av värme och varmvatten i svenska flerbostadshus." ER 24:1999. Energimyndigheten, Eskilstuna, Sweden, 1999.

Björk, C., Kallstenius, P., Reppen, L., "Så byggdes husen 1880-1980" - Arkitektur, konstruktion och material i våra flerbostadshus under 100 år. T1:1984-Fjärde upplagan, Stockholms stadsbyggnadskontor och Statens råd för byggforskning, Stockholm, 1984

Jóhannesson G., "Lectures on Building Physics", KTH - The Royal Institute of Technology, Stockholm, 2002

Nord N., "Smart residences. A study of services, network systems and future trends from an energy perspective", Master of Science Thesis no.313. Department of Building Science KTH- The Royal Institute of Technology, Stockholm, 2001

Norlén U., Andersson K., "The indoor climate in the Swedish housing stock", Document D10:1993. Swedish Council for building research, Stockholm 1993

prEN832, "Thermal performance of buildings-Calculation of energy use for heating-Residential buildings", CEN/TC 89 N 476E, 1995