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MONITORING CAPABILITIES OF ENERGY MANAGEMENT SYSTEMS IN COMMERCIAL BUILDINGS

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Monitoring Capabilities of Energy Management Systems in Commercial Buildings

"Which Types of Analysis can be carried out with EMS data? An examination of the Konsolen building data."

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ABSTRACT

The Konsolen building is a high thermal mass 57-unit apartment building on the outskirts of Stockholm, Sweden. It is part of the Stockholm Project, a full-scale demonstration of energy-saving techniques. A large number of sensors were installed in the building for research purposes. However, they may not be needed for some types of analysis. It is of interest to see what could be learned if only typical EMS outputs were available. These include total electricity use, heat output from the heat pump, and heat supplied by the district heating main. It was found that the detailed sensors were essential in debugging the mechanical systems initially, but the EMS-type outputs are quite adequate to confirm that the building continues to operate normally. The building has such stable lumped parameters (average temperature, base load and thermal resistance) that detailed data are not needed to predict the average daily heat demand to within ±10%. However, neither the effect of the solar collectors nor the thermal mass of the building are visible in the EMS-type data.

INTRODUCTION

Sweden has a fairly harsh winter climate, with typical minimum temperatures of -13 F (-25 °C) and typical annual Fahrenheit heating degree-days in the range 7,000 to 9,000 to base 65 F (4000 to 5000 Celsius degree-days to base 18.3 °C). The country has no known significant sources of fossil energy: no coal, no oil, and no natural gas. In response to these constraints, Sweden has erected buildings with high levels of insulation and low levels of air leakage. The current Swedish building code (1980) requires that apartments have triple-glazed windows, insulation to a level of R-23 in walls, R-33 in roofs, and R-19 in floors (0.25, 0.17, and 0.30 $W/m^2.K$, respectively), and a maximum air leakage of 2 air changes per hour (ach) at a pressure difference of 0.20 inches of water (50 Pa). (The air leakage requirement corresponds to a maximum of approximately 0.1 ach of natural ventilation.)

However, a point of diminishing returns has been reached as far as the shell of the building is concerned, and no dramatic reductions in energy use are expected from refinements in building shell design and construction practice. In contrast, there are numerous opportunities to reduce the energy consumption of mechanical systems, both heating, ventilating, and air-conditioning (HVAC) systems and domestic hot water (DHW) systems. Strategies currently being tested involve heat pumps, heat recovery, heat storage, and the use of solar energy. Because a modern mechanical system is often controlled by an Energy Management System (EMS), it may be possible to evaluate the performance of a mechanical system design from data that the EMS collects for routine system operation. This would simplify the monitoring of new mechanical system designs.

This paper looks at EMS-type data collected at a low-energy apartment building and examines the types of analysis that may be fruitful. If EMS-type data are all that is required to perform the necessary research, it will be possible to understand the performance of a whole new class of buildings - those with EMS's installed for routine control purposes.

THE KONSOLEN BUILDING

The 57-unit Konsolen apartment building was completed in mid-1984, and consists of two almost identical wings. (Konsolen is the name of the city block on which the building is located.) Total heated area is 62,666 ft^2 (5824 m^2), and the net apartment area is 41,598 ft^2 (3866 m^2). It is one of the Stockholm Project buildings, a full-scale demonstration of energy-saving techniques. Some details of the project may be found in Hambraeus and Werner (1985). The thermal resistances of the walls, roof, and floor are R-20, R-40, and R-27, respectively (0.28, 0.15, and 0.21 $W/m^2.K$); these figures include an estimate of the effect of thermal bridges. Windows are triple glazed. The building has a massive concrete frame, and is estimated to have a time constant of 160 hours. Mechanical ventilation is supplied to the apartments at a rate of approximately 0.65 ach. Ventilation air enters through vertical solar collectors integrated into the southeastern and southwestern facades. The building is kept at approximately 0.04 inch water (10

Pa) lower than atmospheric pressure by two exhaust fans, one for each wing. Air-flow rates are controlled by individual dampers on bathroom and kitchen exhaust vents and by flap valves on air intakes. Just before air is ejected from the building, heat is removed from it by a 56 kW (thermal output) heat pump. This heat is delivered either to the hydronic radiators, which supply space heat, or to the domestic hot water system, or to 750 gallons (3000 liters) of hot water stored in tanks. Additional heat is provided by a district heating main, which delivers hot water at approximately 212 F (100 °C). The mechanical system is outlined in Figure 1.

Although this system is quite complex, it is not controlled by an EMS. Instead, a number of off-the-shelf discrete controllers are used for local control of such variables as radiator supply temperatures and water flow rates in various heat exchangers. However, since this building is part of a research project, a dedicated microprocessor data acquisition system collects data on airflows, waterflows, temperatures, and electricity usage. The data acquisition system includes far more sensors than do the various parts of the control system. The sensors that go with the controllers are more typical of those that would be installed for a normal EMS. Table 1 compares the controllers with the research data acquisition system.

TABLE 1
Comparison of Two Systems
Controllers vs. Research Computer

Attribute	Controllers	Research Computer
Number of sensors	20	150
Weather data	Outdoor dry-bulb	Outdoor dry-bulb Solar radiation Wind speed Wind direction
Flow Sensors	1	20
Apartment Temps	0	65
Heat storage sensors	1	6
Data Stored	No	Hourly averages
Duplicate sensors	No	Yes
Valves controlled	8	0
Purpose	Control of HVAC	Data acquisition
Cost	Low	High

If the discrete controllers had been tied together into an EMS, it would have provided less data than the research system actually provides. Le Coniac et al. (1985) discuss the typical data available from an EMS. It is assumed that in a large building like this one, an EMS would provide data on outdoor dry-bulb temperature, heat supplied by the district heating and the heat pump, heat delivered to the radiators and the DHW system, electricity for all purposes except the heat pump, and an average indoor air temperature. These data are referred to as "EMS-type data" and in this paper an examination is made to see what can be extracted from such a data set.

The only flow rate that the installed control system measures continuously is that of the incoming district heating water. To calculate the energy supplied in the various water circuits, it must be assumed that spot measurements of flow were made at some time.

LUMPED PARAMETERS

On the simplest level of analysis, the building may be viewed as a black box which consumes electricity and heat. It is interesting to see if the behavior of the box can be described by a few lumped parameters, which may or may not have their bases in the physical structure of the building. The first analysis considers the heat and electricity demand as a function of outdoor temperature; the building is shell-dominated rather than internal-load dominated.

The analysis is shown graphically in Figure 2, where the components of the y-value make up the daily average heat plus electricity input to the building for January 1 to December 31, 1985. (For a small number of days, data were missing and interpolated data are shown.) The circles show the electricity use for all purposes except operation of the heat pump. Moving vertically, the next segment is heat for the DHW system. This comes from both the heat pump (from o to x) and from district heating (from x to +). The third segment is heat to the radiators. Similarly, this comes from both the heat pump (from + to Δ) and from district heating (from Δ to the diamond). Although the outdoor temperature during this period varied from almost -4 to 68 F (-20 to +20 °C), the pattern of energy use is remarkably stable. Electricity use is an almost constant 600 kWh/day, slightly more during cold periods (winter) and slightly less during warm periods (summer). Some seasonality is expected. Lighting use should be greater in winter, since there are only six hours of sunlight on January 1st but over 18 hours on July 1st. There are also more occupants at home during the winter months than during the summer holiday period. Other data show that electricity use is split almost evenly between domestic uses (apartment lighting, cooking, etc.) and common services (pumps, fans, laundry equipment, elevators, common area lighting, etc.). Energy used to heat domestic hot water (DHW) shows a greater variation than electricity; time sequence data show that there is a regular pattern to DHW use, with peaks during the weekend, and there is also a seasonal variation in use and in feedwater temperature. Although January (maximum) use was almost 700 kWh/day while July (minimum) use was just over 300 kWh/day, it can be seen from Figure 2 that DHW is fairly well approximated by a constant

600 kWh/day. The third segment is heat input to the radiators, which increases linearly with decreasing outdoor temperature from zero at about 57 F (14 °C), the balance point, to 3800 kWh/day at 0 F (-18 °C).

Thus although this building has a complex mechanical system, EMS-type data can be analyzed to extract four quite stable lumped parameters: electricity use of 25 kW, DHW use of 25 kW, a thermal resistance of 2.8 kW/F (5.0 kW/ °C) and a balance point of 57 F (14 °C).

Internal Gains

It is tempting to go further with this analysis and extract a value of the internal gains. If the indoor air temperature is known, the balance point temperature may also be expressed as a number of degrees of free heat, and from that value the internal gains can be estimated. The average indoor air temperature for all heated space was 68 F (20 °C). Given the balance point of 57 F (14 °C) and the thermal resistance of 2.8 kW/F (5.0 kW/ °C), the 11 F (6 °C) degrees of free heat correspond to a total internal gain of 11 x 2.8 = 30.8 kW. The internal gain is made up of solar heat, metabolic heat from occupants, some heat from hot water, and heat from lights and appliances. Since essentially all the 25 kW of the electricity consumed in the building is finally delivered as heat, the other internal gains must provide 5.8 kW.

Unfortunately, it must be noted that there is a very large margin of error in this figure, as a rough sensitivity calculation shows. If the balance point temperature is taken to be 54 F (12 °C), a not unreasonable value as may be seen from Figure 2, then the thermal resistance becomes 2.9 kW/F (5.3 kW/ °C) and the other internal gain becomes 15.6 kW instead of 5.8 kW. While the four lumped parameters given above are quite stable, it can rather dangerous to use them to calculate what might be considered more meaningful variables.

Operational Data

Qualitative information on building operation is simple to obtain. The building was in a shakedown period in early 1985, and a number of minor difficulties surfaced. These are easily identified in the time-series data and can also be seen in Figure 2. The contribution of the heat pump to the radiator loop varied considerably, and there was some radiator heat usage when the outdoor temperature was almost 68 F (20 °C). The former was caused by problems with a time clock and with some heat-pump controls; the latter by mis-adjustment of radiator feedwater temperature.

BEYOND THE OBVIOUS LUMPED PARAMETERS

The building has two special design features: solar walls and high thermal mass. The solar walls pre-heat ventilation air as it enters the building; the high mass permits the heating system to be downsized, as it does not have to respond to short periods of intense cold. The EMS-type data will now be be used to evaluate the features.

Solar Walls

The solar walls provide heat that would otherwise have to come from the heating system, that is, all other inputs being constant, from the radiators. By looking at the energy delivered to the radiators on sunny days and on cloudy days, it should be possible to measure if there is any solar contribution. (It must be assumed that solar radiation data are available from a local weather station.) So as to have some chance of success, a period in March has been chosen. The sun does not shine very much in the depths of the heating season, but by March 21 there are 12 hours of daylight while the outdoor temperature is still around 32 F (0 °C). The solar walls should be expected to deliver measurable quantities of heat only in the autumn and in the spring.

Figure 3 shows the average heat delivered to the radiators in the "A" wing of the building in March 1986. The data are divided into two groups, "sunny" and "cloudy," with an arbitrary cutoff so that the groups are almost equal in size. There is no clear difference between the two types of days, except that the cloudy days tended to be colder.

Figure 3 apparently shows that there is no heat being supplied by the solar walls. However, what it really shows is that the contribution, if any, cannot be detected by these EMS-type data. That is not altogether unexpected because of the relative magnitudes of the heat inputs. At an outdoor dry bulb temperature of 32 F (0 °C), the radiator output ("A" wing only) should be about 35 kW and electricity use is expected to be about 12.5 kW for a total of 47.5 kW. The solar walls were expected to produce about 3 kW, which is on the same order as random fluctuations in domestic energy use. Such random fluctuations could be caused by the occupants opening or closing drapes, operating exhaust dampers, or just turning lights on and off; 3 kW spread over almost 30 apartments is only about 100 W per apartment. The solar contribution, if any, is lost in the noise.

Therefore, EMS-type data, as defined for this building, cannot be expected to show whether or not the solar walls are contributing any heat to the building. A special experiment, such as direct measurement of the flow and temperature difference in a solar wall, is required to determine the magnitude of the effect. This experiment is being carried out at the building, using a detailed monitoring system.

Time Constant

Another special feature of the building is its high thermal mass. According to design calculations, the time constant of the building is 160 hours. The time constant is defined as the length of time that it takes (after all heat input to a building suddenly ceases) for the indoor-outdoor temperature difference to fall to 1/2.72 (37%) of its original value. The advantage of a long time constant is that the building cools down very slowly during periods when the heating system cannot meet the heating load. Thus, the heating system can be downsized - it can be sized to meet heating loads that last for a long period and need not meet loads caused by short-lived periods of intense cold. The downsizing permitted depends on the amount of temperature droop permitted.

According to the design calculations, the building has one time constant. In terms of a thermal circuit analogy, it is assumed that the building performs like a single resistance-capacitance combination. The equivalent circuit is shown in Figure 4(a). The resistance corresponds to the thermal resistance of the shell and the ventilation/infiltration; its value is found from the overall slope of a plot like Figure 2. The current source corresponds to the heat source, heat from the radiators plus electricity plus all other heat sources. The capacitance is unknown and corresponds to the thermal mass. Data for indoor temperature, outdoor temperature, and heat input from the radiators and from electricity can be used to calculate the value of the time constant, which is the product of the resistance and the capacitance.

The calculation was carried out with hourly data for the "A" wing for March 1986. The resistance was found to be 0.80 F/kW (0.44 °C/kW). Using hourly data and the solution to the circuit of Figure 4,

$$T_{in} = (T_{out} + IR)\,(1 - e^{\frac{-t}{CR}}) + T_{in}^{*}\, e^{\frac{-t}{CR}}$$

where

T_{in} = indoor temperature, F (°C)
T_{out} = outdoor temperature, F (°C)
I = heat from radiators, electricity, etc., Btu/h (kW)
C = thermal capacitance of building, Btu/F (kWh/°C)
R = thermal resistance of shell, F.h/Btu (°C/kW)
t = time, h (h)
T_{in}^{*} = indoor temperature at time t = 0, F (°C)

it was found that the time constant was almost exactly 0 hours. That is clearly incorrect. The time constant of the air is 1.5 hours, the inverse of the ventilation rate (which is 0.65 ach). The calculated mass time constant is close to the air time constant.

The main reason why the calculation gives an incorrect result is that the temperature that should be used in the equation is the temperature of the thermal mass; the calculation actually used the average temperature of the air being exhausted from the building. The air has a much lower thermal mass than the concrete frame, and its temperature can vary quite rapidly. The air is coupled to the mass by an effective film coefficient. The temperature of the mass is not being measured, and it would not be measured by any conventional EMS. Thus, EMS data from normal building operation will not be able to provide information about the thermal mass.

To get a first approximation of the value of the time constant, the temperature of the mass should be used. Even then, it is unlikely that a good estimate could be obtained, since the temperature of the mass is very constant during normal operation. Given the resistance of 0.80 F/kW (0.44 °C/kW), if the time constant of the mass is 160 hours as designed, then a change in mass temperature of 0.4 F (0.2 °C), would release approximately 75 kWh of heat. That is the kind of day-to-day variation seen in Figure 2.

If we imagine that all of this variation is caused by thermal storage effects (and not by the solar wall or other unquantified systems), then to obtain an estimate of the mass accurate to 25% would require that the temperature of the mass be measured to better than 25% of 0.4 F (0.2 °C), that is, 0.1 F (0.06 °C). Such accuracy is unlikely to be possible in a large building.

As mentioned above, EMS data from normal building operation will not give accurate thermal mass information. However, EMS data from abnormal operation could be used, for example, if the heating system were to be turned off for perhaps 24 hours. The indoor air temperature would be expected to drop rapidly as first the radiator water temperature dropped to air temperature, and then the air and the mass would begin to cool more slowly. After 24 hours the air temperature might have dropped by 4 degrees F (2 degrees C), so it would probably be necessary to heat the building above its normal setpoint before this experiment began, so as to avoid uncomfortable conditions for the tenants. With EMS-type data from such an experiment, a model that included the air mass, such as that shown in Figure 4(b), could be solved to find the thermal mass of the building frame.

A time-clock problem actually turned off the radiator system for approximately eight hours a day for several days, but that was not long enough to get beyond the radiator and ventilation time constants. If the time constants of the three components taken separately are quite different from each other, it may be possible to identify each time constant by simple analytical methods. If the time constants of the radiator system and the ventilation system are similar in magnitude, it may not be possible to extract any well-defined time constants from whole-building data, even by detailed analytical means.

DISCUSSION

Data from the Konsolen building have been examined to determine how data from an EMS could be employed to determine physical parameters of a building. The energy signature plot, showing heat and electricity supplied as a function of outdoor temperature, shows that there are some robust lumped parameters that describe the behavior of the building. They are: an effective thermal resistance, an effective balance point, DHW energy use, and electricity use. These parameters remain quite stable for a complete year, over a wide range of outdoor temperatures. Their variation over the course of a year can be guessed by looking at the deviation of the data from straight lines. Linear least squares analysis can give a more precise estimate of the variation.

However, care must be taken when trying to extract further information from these parameters; for this building, a small error in the effective balance point temperature, perhaps 3.6 F (2.0 °C), can result in the estimated internal gain being in error by 100% or more. Thus attempts to "back out" the solar gain from EMS data are unlikely to be successful. In any particular case, sensitivity studies should be made to determine the magnitude of possible errors. In some cases, experiments must be made if the value of the parameter is to be determined to an acceptable level of accuracy.

When the area of interest concerns small variations in the data, even greater care must be taken. Uncontrolled day-to day and hour-to-hour variations in electricity use, ventilation habits, window-shade habits, water consumption, and a host of other unmeasured variables produce noise: quasi-random unexplained variations in a parameter's value. Some effects are simply too small to be extracted from the noise. An example of this is the solar wall output. This cannot be determined from EMS data; the airflows and temperature rises must be measured directly.

CONCLUSION

Data from a 57-unit low-energy apartment building have been examined to determine what can be extracted from EMS-type data. Four lumped parameters have been found, which together give a good estimate of the heat demand of the building.

The building has two main features, solar walls to pre-heat incoming ventilation air and a high thermal mass to even out space heating demand. EMS-type data were used to estimate the heat output of the solar walls and to estimate the time constant of the building. The apparent heat output of the solar walls was zero, and the apparent time constant of the building was zero. However, closer analysis showed that random variations in the data were sufficient to mask the expected solar wall output. The erroneous time-constant result was caused by the use of a simple model that required the temperature of the thermal mass as an input; this is not measured by the system.

In summary, there are some kind of parameters that EMS-type data can deliver, but great care must be taken to ensure that noise in the data, caused by numerous uncontrolled variables, does not invalidate any analytical method employed.

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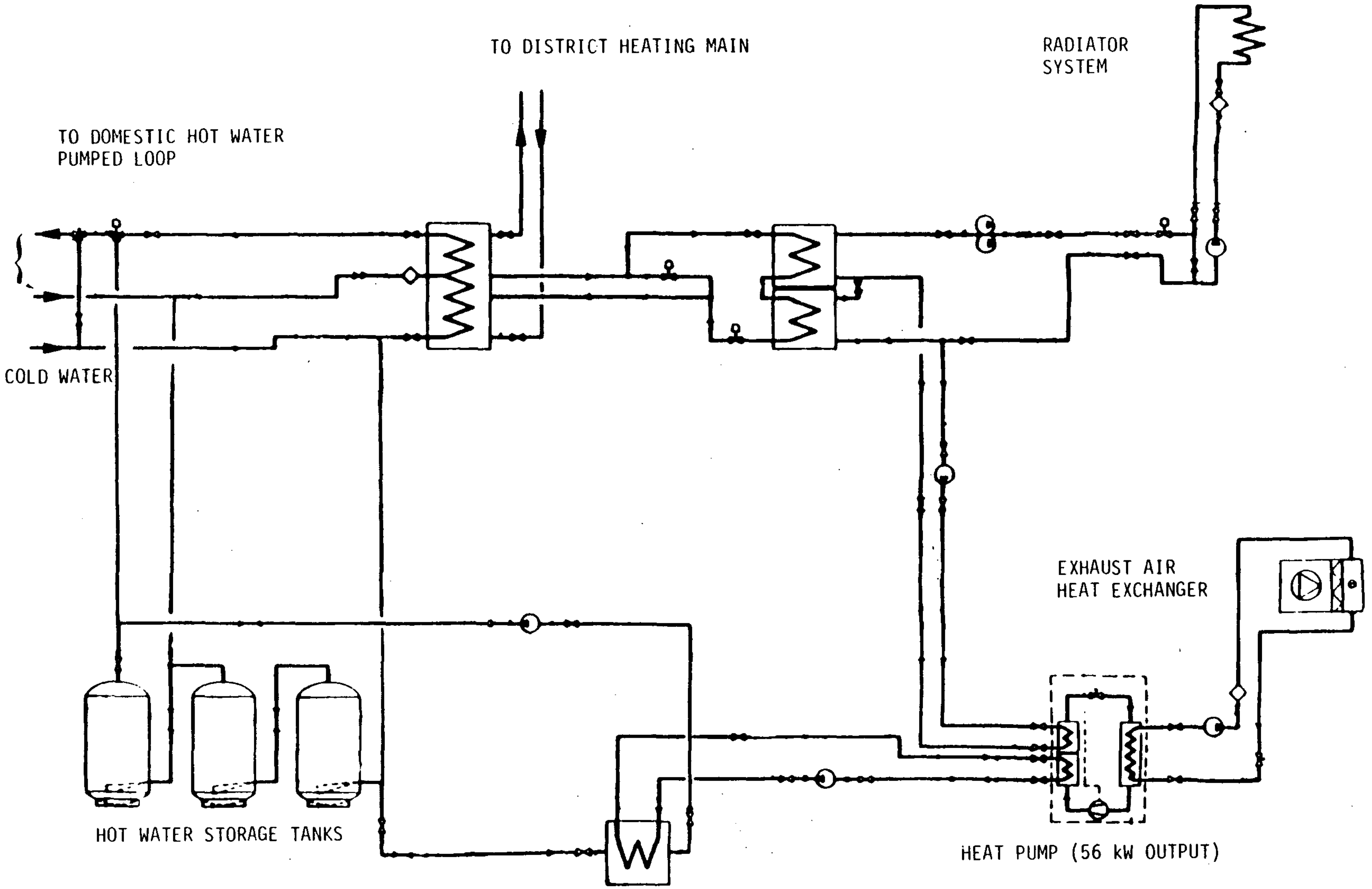

XBL 872-459

Figure 1. The space heating and domestic hot water system for the Konsolen building. For clarity a number of components have been omitted.

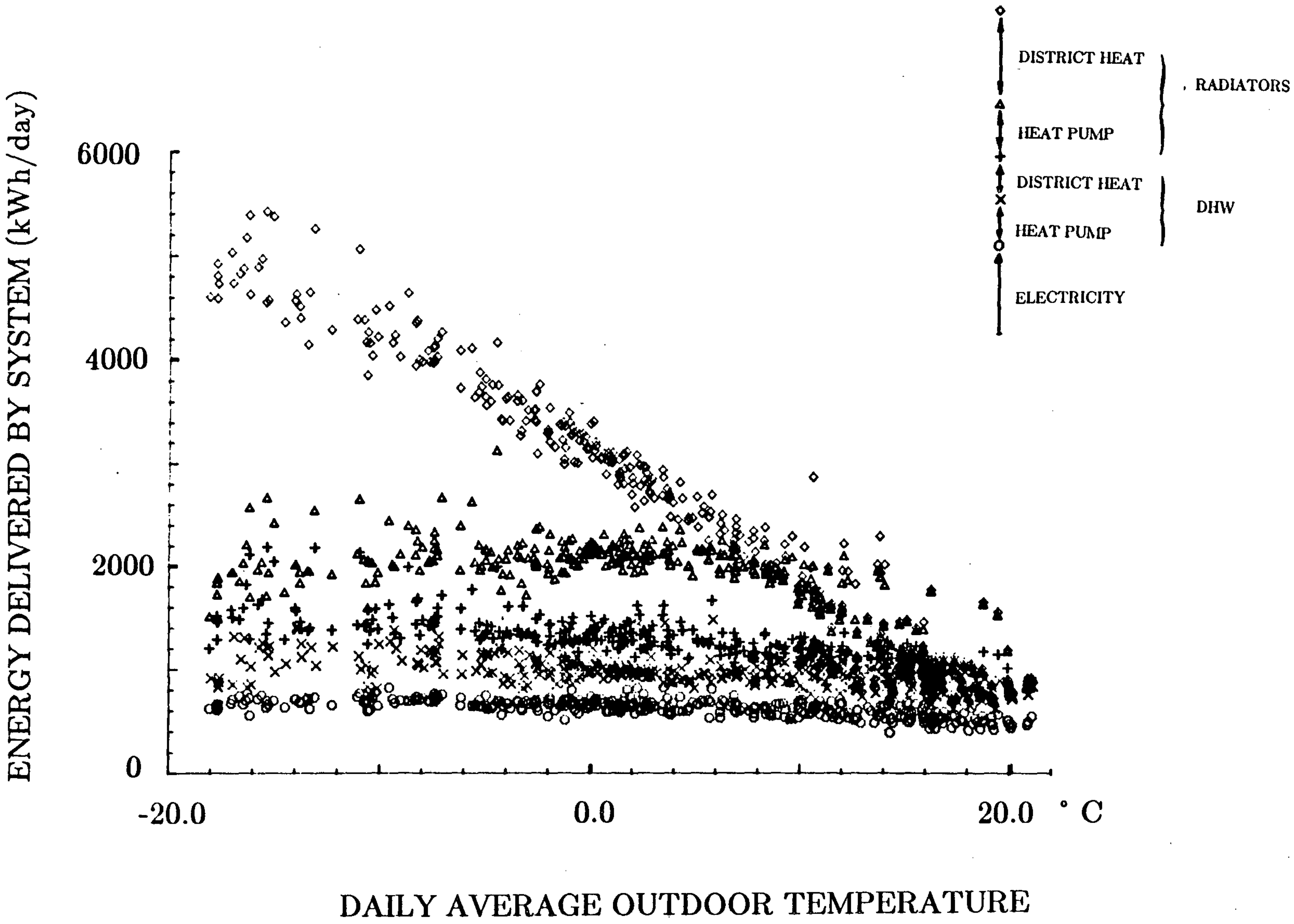

Figure 2. Heat and electricity inputs to the Konsolen building as a function of outdoor temperature. Each point represents a 24-hour sum. (For a small number of days, data were missing and interpolated data are shown.)

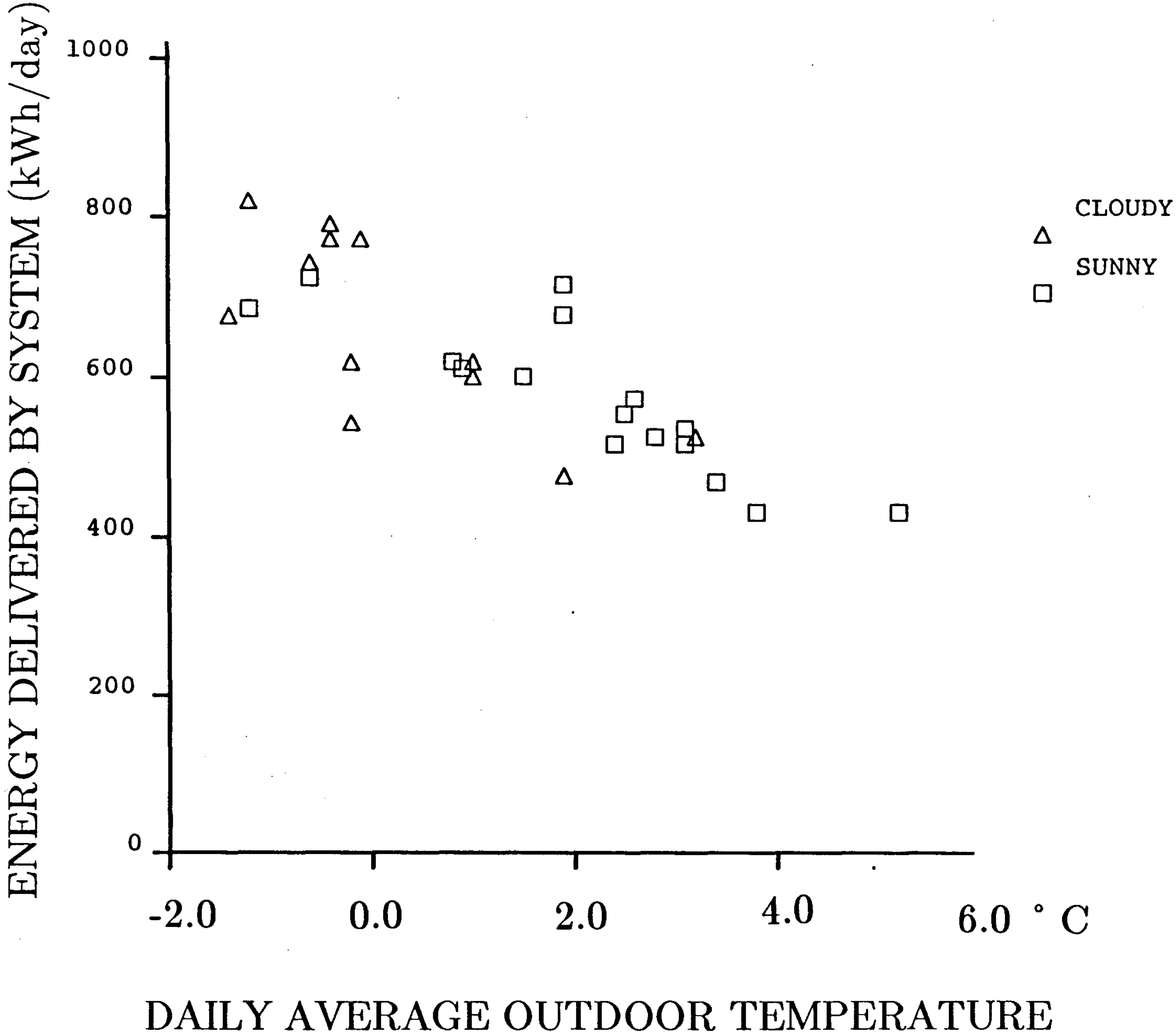

Figure 3. Heat input to the radiators in the Konsolen building for March 1 to 31, 1986. Each point represents the total heat delivered in a 24-hour period. Days have been divided into "sunny" and "cloudy" according to measured total daily solar radiation.

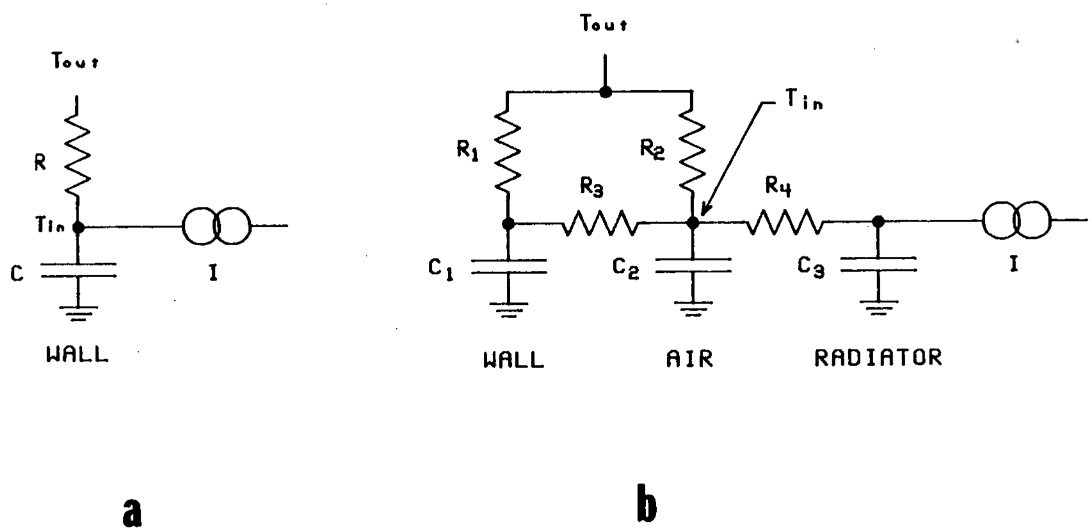

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Figure 4. Lumped parameter equivalent circuit diagrams for heat flows in a building. The total heat input to the building is represented by I. (a) one time-constant only (C,R) for the building shell; (b) time constants for the radiator circuit (mass C), the air (mass C_2 and ventilation rate R_2), and the building shell (mass C_1 and effective thermal resistance R_1). R_4 and R_3 are effective film coefficients between the radiator circuit and the air, and the air and the mass, respectively.

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