DATA ACQUISITION AND MANAGEMENT SYSTEMS FOR THE STOCKHOLM PROJECT

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ABSTRACT

A major aim of the Stockholm project is the analysis of the energy performance of five new low-energy apartment buildings. Each building is unique, and has its own energy-saving features. These include active solar heating, high thermal mass, increased insulation, and seasonal heat storage in bedrock.

All the buildings are being extensively monitored. The parameters measured include electricity use, air and water temperatures, air and water flows, relative humidity, wind speed, and solar radiation. The sensors were hardwired during building construction. Details of the sensor types used are given.

Under control of a micro-computer, sensor readings are taken every five minutes using a multiplexed high precision digital voltmeter, and hourly averages are recorded on computer tape cartridges or floppy disks. Data recorded includes both sensor readings and simple derived values such as energy flows (from a fluid flow and two temperatures). The cartridge or disk is changed every two weeks.

The amount of data being gathered in the project is rather large, approximately 10 million data points per year. The data is managed by means of a system called MUMS, written in 1980 to handle large volumes of time sequence data. The system is designed to display the data in both graphical form and tabular. It permits both the prodution of summary graphs which show the monthly performance of a building at a glance, and the detailed analysis of individual components of the building. The main features of MUMS are described, including examples of typical outputs.

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INTRODUCTION

A major aim of the Stockholm project is the analysis of the energy performance of five new low-energy apartment buildings. Each building is unique, and has its own energy-saving features whose purpose is to reduce the energy bill of buildings to less than 100 kWh/m2-year. The features include active solar heating, high thermal mass, greatly-increased insulation, and seasonal heat storage in bedrock. There are a total of 213 apartments, the smallest building having 10 and the largest 71. All the buildings are located within the city of Stockholm, Sweden. Stockholm has a 1% design heating temperature of -15 C. There is no requirement for residential cooling. The project is funded by Byggforskningsrådet (the Swedish Council for Building Research, BFR). Further details of the project may be found in Elmroth et al. (1985).

Mätcentralen för Energiforskning (the Monitoring Center for Energy Research, MCE) at the Royal Institute of Technology in Stockholm has the responsiblity of giving technical assistance to experimental building projects. MCE´s activities in the Stockholm project have included giving advice during the planning stages, designing and installating the measurement station, and operation of the measurement station and maintenance of the sensors for two to three years. MCE performs continual measurements of fluid flows and temperatures and meteorological variables. It also stores the data on a central minicomputer, and maintains data management and analysis programs.

Sweden has two energy monitoring centers (MCEs) with the same responsibilities. They were started on the initiative of the Swedish government almost ten years ago, and are funded by BFR. MCEs are designed to function as centers of expertise in data collection and management. By tapping into the MCEs´ expertise, an individual researcher can spend his time in data analysis and evaluation, leaving the task of data collection to MCE. This avoids the waste of effort that would be caused if researchers designed their own instruments and wrote their own data analysis software. Past experience showed that so much time was being spent in equipment and software design that funds were often exhausted before adequate analysis could be performed.

MEASUREMENT HARDWARE

Each project has its own measurement system consisting of sensors, connecting cables, and the measurement station. The measurement station consists of (i) a microcomputer , (ii) a pulse counter , (iii) a multiplexer and (iv) a precision multimeter. These instruments, which are predominantly off-the-shelf units, are interconnected via a GP-IB bus.

Filtered mains power is supplied via an isolation tranformer. The station does not have power back-up since it is very unusual to lose mains power. The real-time clock is battery powered, and when mains power is restored the station automatically restarts. As a safety feature, the station also automatically returns to normal operation 15 minutes after the last keyboard input.

The station is located in a locked room within the conditioned space. This usually means a small room in the basement of the building. The equipment is subjected to no extremes of temperature or humidity. There have been no problems with theft.

Sensors can have either digital (i.e. pulse) or analogue outputs. The signals are carried to a central junction box via twisted pairs within a screened cable. To avoid mutual interference, digital and analogue signals are carried in separate cables. Data is stored either on tape cartridges (at the older stations) or on floppy disk. Both of these media have a storage capacity of approximately 200 Kbytes. The data collection program is library-driven by a description file as explained below.

For some measurement stations, data can be dumped to the central minicomputer via the telephone, but it is more usual to collect the cartridge or floppy disk every two weeks. The complete system is shown schematically in Figure 1.

SENSORS

The main sensors employed in the Stockholm project are for temperature, liquid flow, air flow, electricity use, solar radiation, windspeed, runtime, and number of re-starts.

Temperature Measurements

In the Stockholm project Pt-100 platinum resistance sensors are used exclusively. The resistance is measured in a standard four-point configuration; this effectively eliminates any offsets that might be caused by line resistance or thermoelectric effects. Each sensor is calibrated by the manufacturer. All sensors are also checked on-site by placing them in an ice bath and reading off the temperature calculated by the measurement station. The reading is expected to be within the range -0.05 to +0.05 C. Sensors for high temperature (e.g. 50 C) applications are checked in a warm bath against a digital thermometer. By using precision calibrated sensors in a four-point configuration, temperatures can be measured to an accuracy of + 0.1 C. In measuring a temperature difference, an accuracy of 0.05 C can be achieved by selecting sensors with similar resistance/temperature characteristics.

MCE has chosen to use thermocouples in some other projects. However, in a large field project thermocouples tend to be just as expensive overall as Pt-100s, because of thermocouples´ greater maintenance requirements; they are more sensitive to mechanical and electronic interference. Also, the fine continuous thermocouple wire is rather difficult to install where there are long cable runs. Since the sensors were actually installed by sub-contractors employed by the prime building contractor, a rugged sensor and cable system were of prime importance. The most important aspect of temperature measurement is the choice of the physical design and mounting of the sensor. However, that topic is beyond the scope of this paper.

Liquid Flow Measurements

Fluid flows are measured with standard off-the-shelf units. They are bought pre-tested and according to specifications have an accuracy of 1% within the range from 5% to 100% of rated flow. As with the temperature sensors, they are installed by sub-contractors to the main building contractor. Each meter is installed between shut-off valves to allow easy replacement in the event that the meter should fail. For building commissioning, a blank section of pipe is installed in place of the meter. MCE requires that the plumbing system be in operation for at least two weeks before the meters are installed to ensure that the meters are not damaged by foreign material in the pipes.The meters usually give outputs in terms of volume flow. For some meters, these are transformed into mass flow using measurements of fluid temperature.

Air Flow Measurements

Air flow in ducts is measured with various standard commercial devices. These produce a pressure difference either by means of an orifice plate in the duct or by means of the Pitot-tube effect. Care must be taken that there is the specified length of straight duct before and after the measurement plate or tube. The pressure difference that results from a properly-installed plate or tube corresponds to the air flow with an uncertainty of less than 5%.

The pressures are carried to a multiplexer by means of rigid-wall plastic piping, and thence to a pressure transducer, as illustrated in Figure 2. The maximum length of the tubes is 20 m. The pairs of tubes are connected sequentially to the transducer. In one position, no tubes are connected. This allows the transducer zero to be checked routinely by the program; any zero drift - often a large source of error - is automatically adjusted for.

As for fluids, the meters usually give outputs in terms of volume flow. For some meters, these are transformed into mass flow using measurements of local air temperature. The total uncertainty in air flow is less than 10%.

Other Sensors. Electricity is measured by a standard pulse count meter, calibrated by the manufacturer. The uncertainty is less than 1%. Solar radiation is measured as total radiation with a pyranometer. Windspeed is measured by a pulse count anemometer. Relative humidity is measured with a capacitance sensor.

SOFTWARE

The data collection program is library-driven. The core of the program is very general, and has been used for a number of measurement projects over the years. The library file, called a B-FIL, contains all the site-specific data: the number of sensors, the time interval between readings and all the data on the individual sensors. The same B-FIL is used in three different parts of the data collection process, and ensures consistency among the core programs. First the B-FIL is used to run the measurement station; then it is used to pack data from the cassette into the minicomputer disk; and finally it is used to control the unpacking of the data.

A typical B-FIL entry includes the sensor code number, its channel number (the connector it is attached to in the multiplexer input), its name, a short commentary, the sensor type, any calibration constants, the maximimum and minimum (used in a data checking routine), the resolution and the conditional requirements (if any). The file contains data on both the sensor outputs and the compound parameters calculated from two or more sensors´ data (such as energy flows).

Each measurement station takes readings every five minutes from between 100 and 300 sensors. Hourly averages or totals, as appropriate, are stored on cartridge or floppy disk. The signals are converted into engineering units, such as degrees Celcius or kilowatthours, before storage on cassette or disk. Both these simple parameters and a number of compound parameters such as energy flow are calculated every five minutes and sums or averages stored each hour. For some parameters the hourly average is not meaningful. For example, the temperature of the cold water supply slowly rises to ambient temperature when the flow is zero. For such cases, a "conditional" average is calculated, i.e. the average value when the flow is above a specified minimum.

The most important energy flows in fluids and air are calculated directly by the measurement station and stored on cassette or disk. The calculation for water takes account of the variation of density and specific heat with temperature. A correction for the density and specific heat of the glycol brine in a heat-pump, whose concentration varies with time, is made when the data is unpacked for analysis. The calculation for air takes account of the variation of density with temperature, but assumes a constant pressure and specific heat. This assumption is estimated to increase the uncertainty of the long-term values by less than 1%.

DATA MANAGEMENT AND ANALYSIS SYSTEM

The Stockholm Project buildings include systems and design features that are being tested for the first time on a large scale. This experimental nature of the buildings has made it necessary to install an extensive array of sensors. Some of these sensors were used to help in commissioning the building. There are also arrays of sensors whose data will be used in the detailed examination of the performance of experimental components, such as the solar wall. Other sensors are for routine collection of data on the energy consumption of certain areas of a building, such as the electricity consumption of the apartments or the laundry room.

Naturally, this array of sensors has produced a large volume of data. This data is managed by means of a system called MUMS, written about five years ago by the Monitoring Center for Energy Research (MCE) at the Royal Institute of Technology in Stockholm. The program is also used at the MCE at Chalmers Technical Institute in Gothenburg and at the Luleå and Lund Institutes of Technology. It was designed to function as a general tool for the management of time series data. The program has now been in use for a number of years, and has demonstrated itself to be user-friendly (on-line help is available), easy to use, and almost totally immune to user abuse (it does not crash). Although the program is in general use in Sweden, it is not commercially available. However, the features of the system should be of general interest to those designing experiments which will produce large amounts of time-series data.

Data from the measurement site cassette is stored in a packed form on either tape or disk at the minicomputer. It is usual to keep the two previous months´ data on disk at any time. This avoids mounting tapes, which is impossible from a modem hookup. Before any form of analysis, the data must be unpacked. This is performed either by keyboard commands, or, more usually, by command files. A rudimentary command file would instruct which sensors´ data should be unpacked for a certain period. More sophisticated command files can include routines for the automatic correction of data for known sensor re-calibrations, for the production of multi-colour plots, or for tabular output.

Unpacked data is stored in data areas in a dayfile. This file is too large for long-term storage, and it is very unusual to retain such a file. The normal procedure is as follows: (i) write a command file (ii) use the file to unpack the desired data into a dayfile (iii) carry out any data adjustment for known sensor errors (iv) perform analysis, produce graphs, plots, or tables, and then (v) delete the dayfile. If necessary, the dayfile can be stored temporarily on disk. The data can always be reconstructed from the packed data and the command file, which is usually small and thus easy to store. The command file is a convenient record of the precise analysis performed.

A data area is characterized by a start time and by a time step. Each area has a label (a 24-character description of the sensor), and an associated axis (used for plots). The basic data operations which can be carried out, either within one area or between areas, are (i) averaging or summing over time, for example to form daily, monthly, or yearly averages; (ii) plotting against time; (iii) plotting two areas against each other (x-y plot); (iv) tabulating on screen or to a file; (v) simple arithmetic or logical operations or (vi) transferring data to or from other programs. As well as permitting access to standard program packages such as editors, this last feature also allows analysts to write their own FORTRAN programs for any specialized purpose. The output from such a program can be transferred back into MUMS for plotting, tabulation, or further computation.

MISSING DATA AND CORRECTING DATA

A full year is a long time over which to maintain a monitoring system in operation. During such a period sensors drift and must be recalibrated, so their data must be adjusted to reflect this. Sensors inevitably fail, and often their data has to be reconstituted in some fashion. This tends not to be particularly important in detailed analysis; one chooses a period for which the data set is complete. However, in energy monitoring projects the energy consumption over a full year is often of interest. Therefore missing or incorrect data must be dealt with in some way.

MUMS includes two simple methods to solve the missing data problem. Missing data can be replaced with the arithmetic mean of surrounding points. Or, when calculating averages, missing points can be ignored. More detailed adjustment of the data can be carried out with programs external to MUMS. One of the authors has written a simple Fourier series program to fill in cyclic data, a linear least-squares program for cases where the missing data point is linearly dependent on another data point, and a "fudge" program which inserts missing points by interpolating between points on an x-y plot.

Data is cleaned up after unpacking by the use of a command file which includes all the known corrections. The packed data - the data written to storage by the measurement station - is not touched, even if it is known to contain errors. (Periodically the control program of the data collection computer is corrected, so as to reduce the amount of post-processing of data.) The correction command file becomes a log of the necessary corrections. This file can make use of the logical operators in MUMS. For example, a correction might be "A should be ((2.01*A) + B) when C > 1.2 ". The correction can also be temporal, such as "A should be (1.03*A - 0.37) after June 30 and before August 24".

TYPICAL OUTPUT FROM MUMS

Figure 3 shows typical MUMS outputs. The first shows a plot of a variable against time. The second shows an x-y plot, one variable plotted against another. The third plot shows a cumulative frequency distribution, the percentage of time a variable is greater than a certain value. The final plot shows one variable plotted against the rank of another variable. This is used to produce a power-duration diagram in which the power to a heating system is plotted against the number of hours ranked by the temperature.

These output capabilities can be used in various ways. In the next section we discuss how they are used routinely to produce summary plots to check system operation. In the Stockholm project we use MUMS to produce an extensive series of plots for each month's data as it comes in. In this way we check both the building and the monitoring system. The MUMS outputs are also available for more detailed analysis.

EXPERIENCES IN THE STOCKHOLM PROJECT

The Stockholm project buildings all contain experimental features being tested for the first time. To ensure that both the buildings and the monitoring system were functioning correctly, the project included a year-long shakedown period. There are five buildings: Konsolen, Kejsaren, Sjuksköterskan, Bodbetjänten, and Höstvetet. The first three have been occupied since the summer of 1984, and have thus completed the shakedown. Experiences from this period are detailed in Cleary, Elmroth and Hambraeus (1986). The last two have only been occupied since September 1985 and February, 1986, respectively.

In calendar year 1985, over 95% of the desired data was collected in Konsolen, Kejsaren and Sjuksköterskan. The data was processed in a similar way in all buildings. Konsolen will be treated as an example to show how the data is routinely checked for sensor errors and building system errors.

As soon as possible after a full month of data has been loaded into the minicomputer, about 20 multi-colour summary graphs are produced. Most of these show both a monthly total for a variable (produced by a graphics program from MUMS tabular output) and the variation with time (produced directly from MUMS). In order to write the command files that prepare the monthly graphs, the outline of the energy analysis method must already be known. Systems under investigation include those for space heating, ventilation, and domestic hot water (DHW). The following are calculated:

District heat: total input; heat exchangers´ output to radiators, to DHW, to DHW pumped loop losses.

Heat pump: heat and electric input; total output to radiators, to DHW, to pumped loop losses.

Water circuit: total domestic hot water, pumped loop losses, heat stored in water tanks, grey water.

Figure 4 shows the monthly totals for district heating energy use in December, 1985. Three bars are shown. The left one gives, from the bottom, energy flow to the radiators in the A and B sections of the building, then domestic hot water use, then pumped loop losses. The next bar gives the district heating energy input as measured by the heating company´s meter, and the third bar gives the same input as measured by a duplicate flow meter and temperature sensors. This diagram allows a quick check to be made on a number of temperature sensors and flow meters. Further details of the monthly plots may be found in Hambraeus and Werner (1985)

If the bars are not equal in height, then something unexpected is happening. In this case, the heat use is greater than the heat input because of the waste heat from approximately 2 kW of circulation pumps. In other instances, unequal inputs and outputs were caused by water flowing the wrong way in pipes, and unexpected air leakage in ducts. In Konsolen, graphs are prepared for district heating, electricity, heat pump inputs and outputs, ventilation air flows and temperatures, domestic hot water use and storage, total water inputs and outputs, and apartment temperatures.

DETAILED ANALYSIS

Using the stored variables, it is not difficult to produce energy signatures or power-duration diagrams or most other tools of the energy analyst. New variables can be created by means of the arithmetical and logical operators. All data can be used in hourly form, or averaged by any time interval, including calendar month or year.

The way the B-FIL and the command files are set up makes it easier for an analyst to manage the mounds of data that a large-scale long-term project produces. The B-FIL can be written so as to include all the important energy flows in the building. By means of command files, the relationships between these flows can then be plotted each month. This can all occur more or less automatically. If the researcher has a clear idea of what he or she is trying to demonstrate, then it is not difficult to set up computer routines in advance which will produce the plots and tables needed for the final report. By arranging for the data to be managed in this way, the researcher is left free to follow up the interesting and unexpected problems as they arise.

CONCLUSION

A major aim of the Stockholm project is the analysis of the energy performance of five new low-energy apartment buildings. Each has been hardwired with an extensive array of sensors. These sensors have proved invaluable in detecting design and operation flaws during the shakedown year, the first year of operation of the buildings.

The Monitoring Centre for Energy Research at the Royal Institute of Technology has the responsibility of designing and operating the energy monitoring equipment, and also storing the data collected. MCE has almost ten years of experience in this area. A very high system reliability has been achieved, and over 95% of data has been collected during the shakedown year for three buildings in the Stockholm project.

The MUMS program is employed for data management. It makes use of packed data, which is unpacked for analysis by means of command files. Data can be corrected automatically for known sensor problems. Command files can produce monthly summary plots and tables to check building system operation. MUMS can also be used for detailed analysis of the performance of individual components. The complete system of sensors, hardware and software has proved to be quite effective at monitoring the energy performance of these modern low-energy buildings.

ACKNOWLEDGEMENTS

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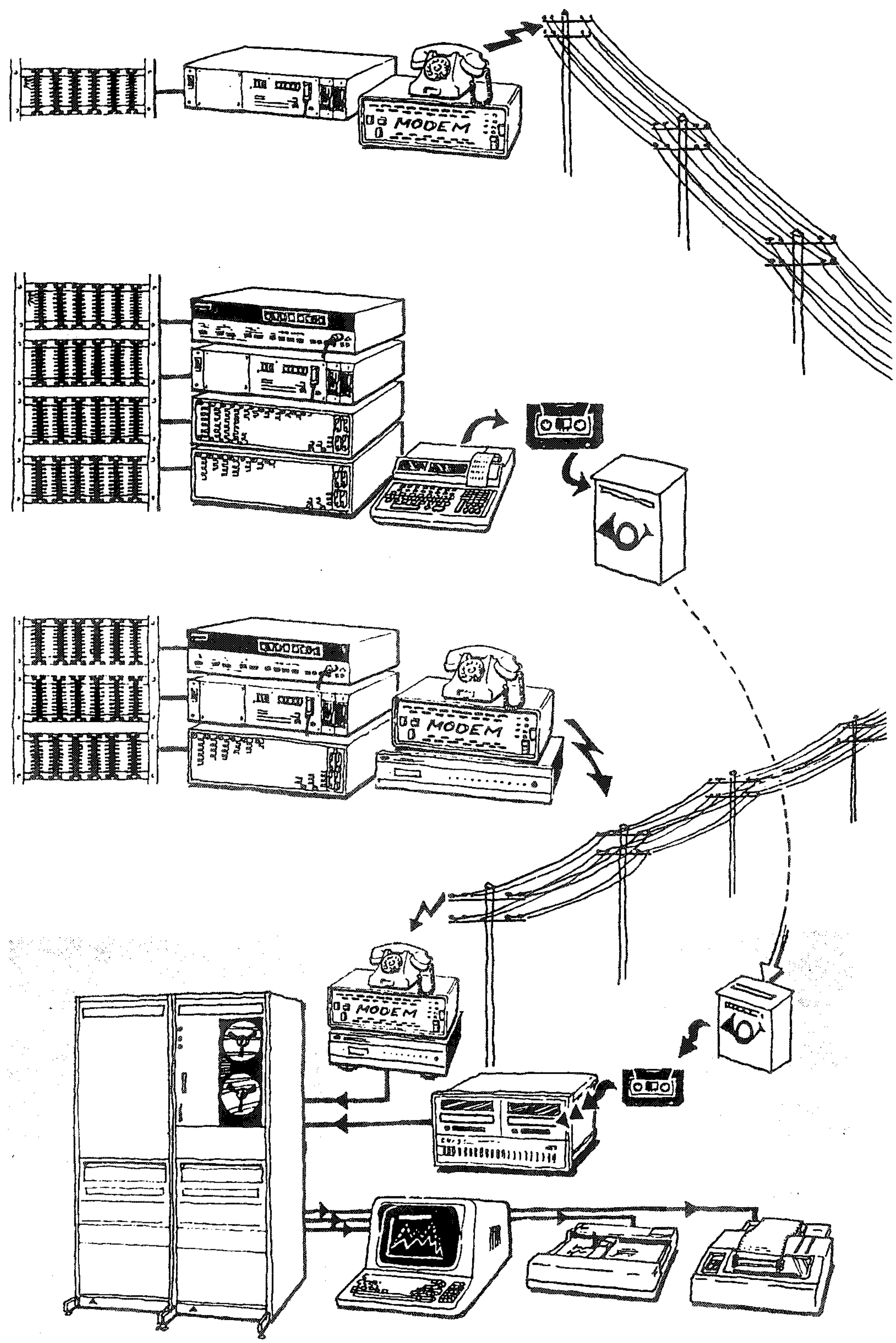


Figure 1. Overall design of typical MCE measurement stations. For details, see text.

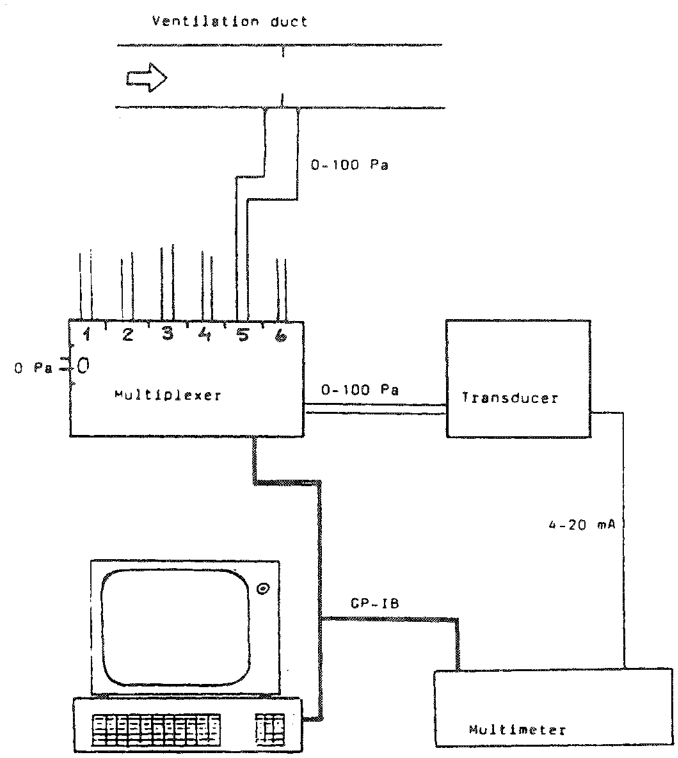


Figure 2. Set-up for the air flow multiplexer. This system allows any zero drift in the transducer to be corrected.

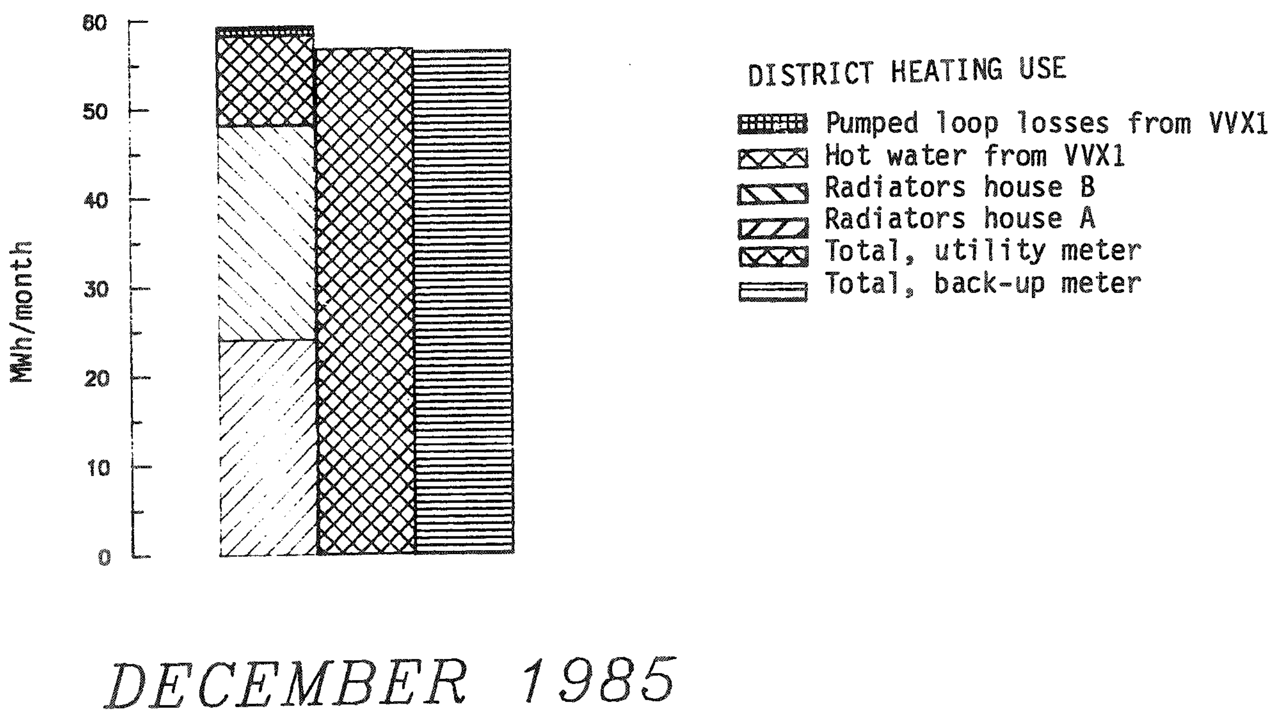
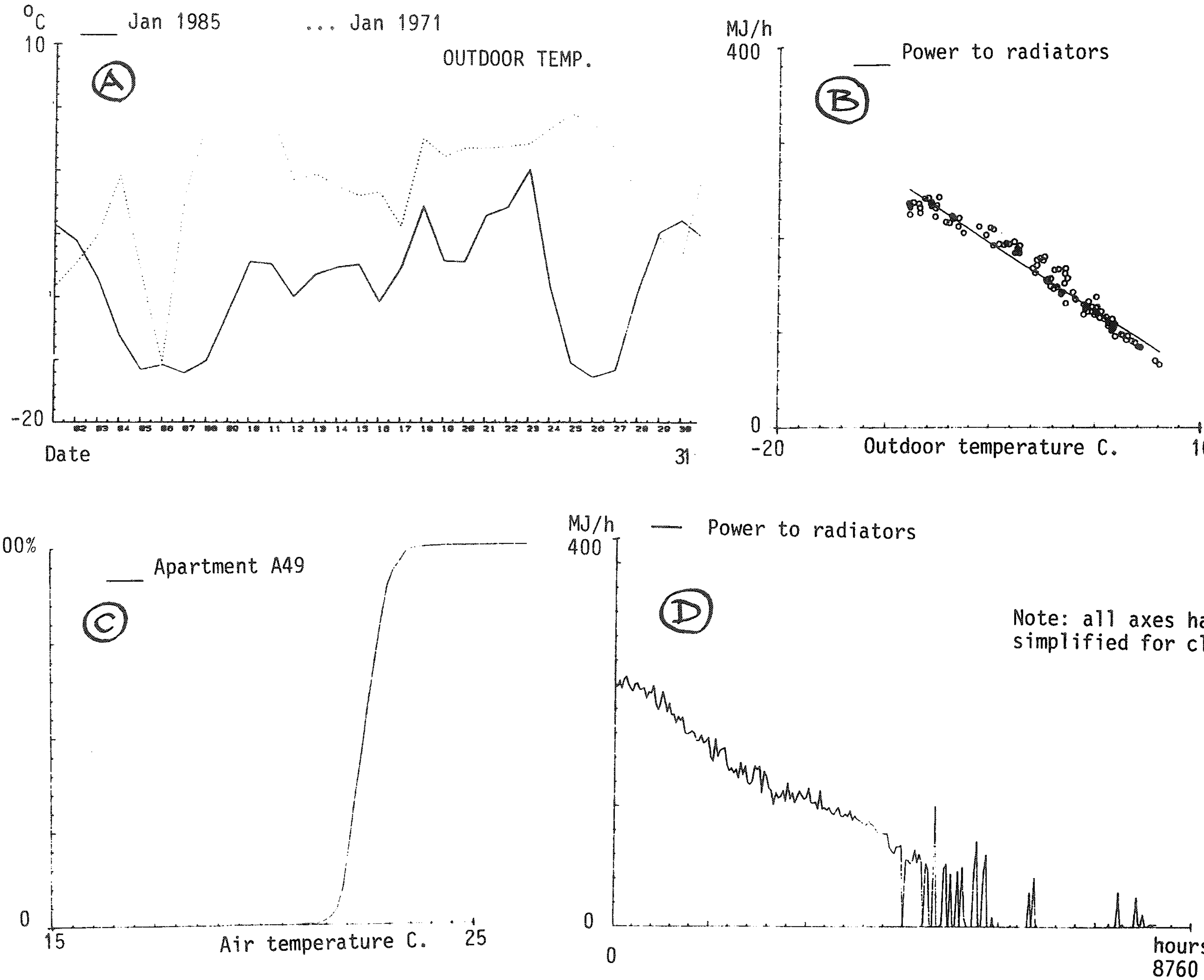


Figure 4. A typical monthly summary plot used to check building system operation in the Stockholm project. For details, see text.



Note: all axes have been simplified for clarity.

Figure 3. Typical graphics outputs from MUMS: (a) Time plot; (b) x-y plot; (c) Frequency plot; and (d) Power-duration plot.