ANALYSIS BY MEASUREMENTS OF ENERGY CONSUMPTION IN FULL-SCALE MODEL HOMES

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Summary

If measurements of energy consumption in buildings are to be of general value, a large number of factors affecting the energy consumption must be studied. These factors refer to the outdoor climate, the building and its installations and to the use and operation of the building. An analysis of the measurement conditions prevailing in uninhabited and inhabited buildings indicates that considerable difficulties will be encountered in any attempt to study the change in energy consumption resulting from a change in the building, its installations or its use and operation. Detailed measurements are presented for two blocks of flats. These measurements were taken partly during 1971/72 and partly during the oil crisis of 1973/74. In one of these two projects, major savings were achieved by adjusting the heating system, reducing the room temperature and reducing the mechanical ventilation. About half of the savings made in the energy used for heating and ventilation (approx. 40%) resulted from reduced airing of rooms.

Résumé

Pour que les mesures de consommation d'énergie dans les bâtiments aient une valeur plus générale, il est nécessaire d'étudier un grand nombre de facteurs qui ont une influence sur la consommation d'énergie. Ces facteurs se rapportent au climat extérieur, au bâtiment et à ses installations ainsi qu'à son utilisation et à son exploitation. Une analyse des mesures dans les bâtiments habités et non habités montre que l'on se heurte à d'importantes difficultés si l'on veut étudier la modification de la consommation lors de la transformation du bâtiment, de ses installations, de son utilisation ou de son exploitation. Un compte rendu est donné des mesures minutieuses effectuées dans deux maisons pour plusieurs familles. Ces mesures ont été exécutées d'une part en 1971/72 et d'autre part pendant la crise pétrolière en 1973/74. Pour une de ces maisons, de grandes économies ont été réalisées par le réglage du système de chauffage et par la réduction de la température intérieure et de la ventilation mécanique. Sur l'économie d'énergie réalisée sur le chauffage et la ventilation (env. 40%) environ la moitié est à porter au compte d'une diminution de l'aération.

Introduction

Several motives can be provided for studying energy supply and energy consumption in entire buildings. One such motive can be the desire to examine how new building components such as walls, roofs, windows etc, and new installation components function when they are included in the complicated system which an inhabited building comprises. Another motive may be to study an ordinary building of completely normal design, construction or use, which does not contain any form of conscious experimentation. The study may aim at establishing whether the building functions in the manner intended during the design stage. Deviations can, as Fig.1 illustrates, be the result of errors and shortcomings in the design (1), in the construction (2) or in the operational maintenance (3).

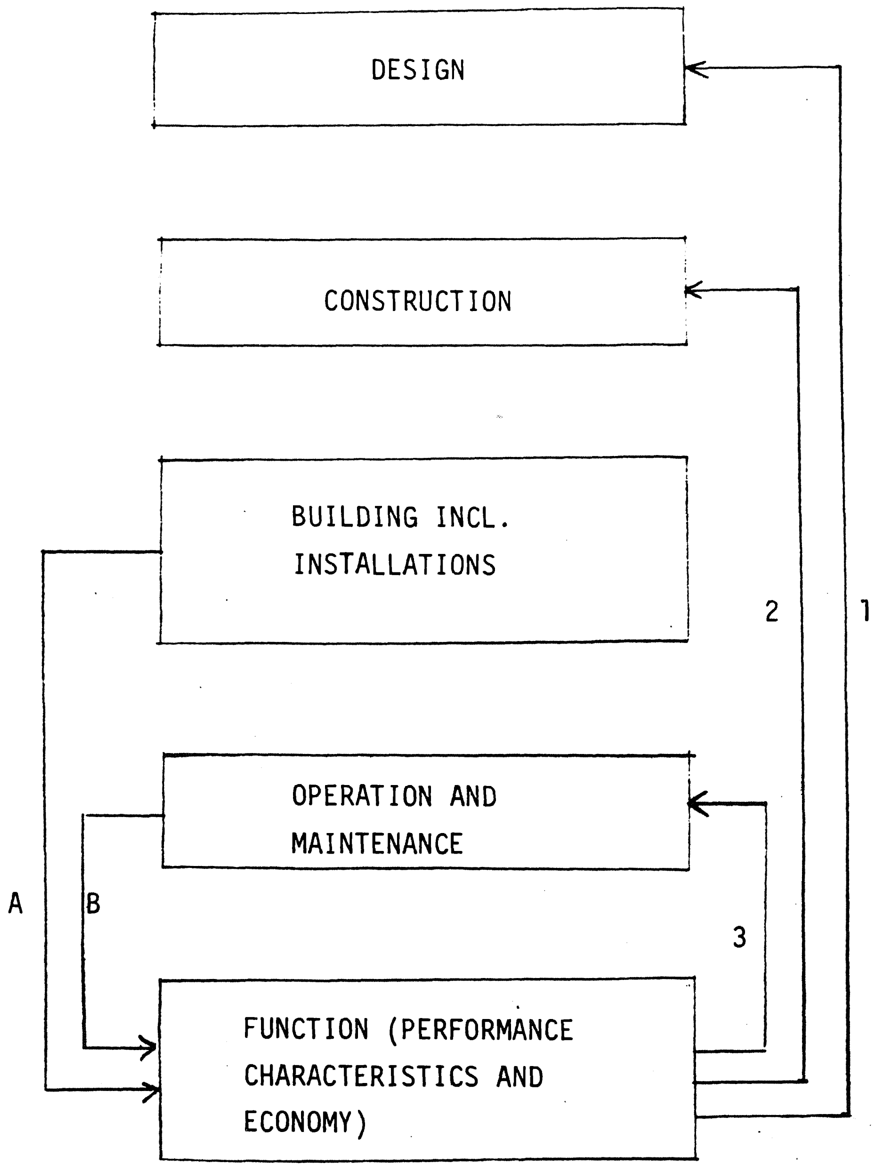

FIG.1 Study of ordinary buildings. Functional results (1, 2 and 3) and measures (A and B).

These studies can also be followed up by measures taken on the building and its installations (A) and on its operation and maintenance (B) with the aim of improving the function. The function of a building embraces all of the requirements which a building is to meet. Energy economization comprises no more than a small part of these requirements, despite the fact that it is an extremely important part today from the national economic point of view. Consequently, the following sub-objective emerges: Energy economization combined with an acceptable function of the building in other respects. Another sub-objective will be to avoid unnecessarily oversizing the building and its installation.

A number of energy studies have been executed or have been planned at the Lund Institute of Technology, Department of Building Science. The experience obtained from these studies will be presented and discussed here. The determination of the annual energy consumption is, of course, an essential part of studies on energy economization. Consequently, this problem will be discussed first.

Determination of annual energy consumption

The gross energy consumption in an inhabited building is dependent on the following factors:

1. a) transmission losses through external walls, roofs and windows
   b) transmission losses through foundations and soil
2. a) heat losses through controlled ventilation
   b) heat losses through natural ventilation
   c) heat losses through airing
3. household energy consumption for lighting and electric appliances
4. energy for hot water
5. utilized solar and sky radiation
6. energy utilized from household energy and hot water
7. heat utilized from humans and animals
8. heat production efficiency

These can be divided into factors dependent on the outdoor climate, on design and on users, see TAB.1. as TAB.1 indicates, the user-dependent factors have a considerable effect on the energy consumption. This means that a determination of the annual energy consumption is relevant only for the user habits which applied during the measurement period. The outdoor climate varies from year to year and the energy consumption which has been measured apply only for the measurement period. In other words, methods for generalizing the measurement results must be established. The following are a number of methods for this purpose:

1. Measurements in uninhabited houses

Energy measurements can be carried out in newly constructed houses which have not yet been taken into use by inhabitants. The prerequisite for this is that the indoor temperature control be carried out automatically and, preferably, that dwelling conditions be simulated with regard to energy consumption. This simulation may be difficult to achieve. If the aim is to study the effect of certain components on the energy consumption, i.e. the effect of building or installation components, the simulation of dwelling conditions may, in some cases, be omitted. The diffi-

Factors	1a	1b	2a	2b	2c	3	4	5	6	7	8
Factors dependant on outdoor climate											
Outdoor temperature	x	x	x	x	x						
Solar and sky radiation								x			
Wind				x	x						
Factors dependant on design											
The building	x	x		x				x			
The installations			x								
Controlled regulation of indoor temperature	x	x	x	x				x	x	x	
Factors dependant on users											
Indoor temperature selected	x	x	x	x	x						
Manual regulation of indoor temperature	x	x	x	x	x			x	x	x	
Airing					x						
Household electricity, hot water, occupants						x	x		x	x	
Operation and maintance			x								x

TAB.1 Factors which affect the gross energy consumption (fuel and electricity) for a building.

culties inherent in obtaining a correct result are illustrated by the following relationship for the annual net energy consumption

$$W_{year} = \int_{year} P_t \, dt \qquad \text{where } P_t \geq 0 \tag{1}$$

or

$$W_{year} \approx \sum \bar{P}_t \Delta t \qquad \text{where } P_t \geq 0 \tag{1a}$$

$$P_t = (T+V_t)(\vartheta_i - \vartheta_u) + P_{h,t}(1-a_h) + P_{VV,t}(1-a_{VV}) -$$

$$P_{dt}\, a_d - P_{p,t}\, a_p + P_{\ell,t} \tag{2}$$

where

P_t = additional output required to maintain the indoor temperature selected

ϑ_i = indoor temperature

ϑ_u = outdoor temperature

T = transmission losses per degree temperature difference indoor-outdoor

V_t = heat losses resulting from controlled or other ventilation per degree temperature difference indoor-outdoor

$P_{h,t}$ = household electricity supplied at time t (W per hour)

a_h = utilized part of household electricity P_h

$P_{VV,t}$ = energy supplied for hot water at time t (Wh per hour)

a_{VV} = utilized part of hot water energy P_{VV}

$P_{d,t}$ = entering energy from daylight, sun and sky at time t (Wh per hour)

$a_{d,t}$ = utilized part of daylight at time t

$P_{p,t}$ = heat from occupants supplied during time t (Wh per hour)

a_p = utilized part of heat from occupants

$P_{\ell,t}$ = energy supplied to and stored in the inner surfaces of the room (Wh per hour)

$P_{\ell,t}$ can be ignored for integration over a long period of time. If, for example, extra thermal insulation is introduced so that T is reduced by ΔT, the following expression can be obtained:

$$\Delta W_{year} = \int_{\tau'} \left[(T+V_t)(\vartheta_i - \vartheta_u) + P_{e,t} \right] dt - \int_{\tau''} \left[(T- \quad T+V_t)(\vartheta_i - \vartheta_u) + P_{e,t} \right] dt \tag{3}$$

where $P_{e,t}$ is the net energy for a household and hot water minus the utilized energy from daylight and occupants. Since P_t in equation (1) must be greater than 0 to be integrated, it can easily be seen that the integration limits are reduced when extra thermal insulation is provided. It can similarly be seen that ΔW_{year} becomes dependent on the magnitude of T, V_t and $P_{e,t}$. The same applies if V_t is reduced by the introduction of heat exchange in the ventilation air.

Consequently, if the effect of new components on the annual energy consumption is to be examined, either the user-dependent factors must be simulated or a calculation must be made of the annual energy requirement using reasonable assumptions for the net outputs supplied for household electricity and hot water and the utilized portions of the heat supplied from daylight and occupants. This can be done if V_t and $P_{e,t}$ can be simulated at each point in time t in a reasonable manner and if W_{year} can then be calculated from equation (1a) with $P_{\ell,t} = 0$. The outdoor temperature can also be changed then.

2. Measurements in inhabited houses

If the aim is to study an inhabited house, the net energy can be measured and recorded as

$W_{\Delta t}$ = total energy supplied during the time period Δt
$W_{r,\Delta t}$ = energy supplied through radiators during Δt
$W_{v,\Delta t}$ = energy supplied for pre-heating of ventilation air during Δt
$W_{VV,\Delta t}$ = energy supplied for heating hot water during Δt
$W_{h,\Delta t}$ = energy supplied for household electricity during Δt

i.e.

$$W_{\Delta t} = W_{r,\Delta t} + W_{V,\Delta t} + W_{VV,\Delta t} + W_{h,\Delta t}$$

In addition, the following should be measured and recorded:

$\bar{\vartheta}_{i,\Delta t}$ = mean indoor room temperature during the time period Δt
$\bar{\vartheta}_{u,\Delta t}$ = mean outdoor temperature during Δt
s_n = incoming energy from solar and sky radiation on vertical external wall (n = 1,2,3,4) during the time period Δt (Wh/m^2)
$\bar{v}$ = mean wind velocity during the period Δt

If the following equation is written

$$Q_{\Delta t} = \int_{\Delta t} (\vartheta_i - \vartheta_u)\, dt = (\bar{\vartheta}_i - \bar{\vartheta}_u)\, \Delta t \qquad (4)$$

the following applies

$$W_{\Delta t} - W_{vv,\Delta t} - W_{h\Delta t} = A \cdot Q_{\Delta t} + B \cdot \sum_{n=1} A_{qn} \cdot s_n + C_v - D \qquad (5)$$

where A_{qn} is the glazed area of the vertical external wall n. D represents the user-dependent factors such as manual regulation of heat and airing and the energy stored in floor constructions etc. Since only net energies are recorded, the operation and maintenance of the heating plant are excluded. The efficiency of the plant can be studied separately as a function of the output obtained.

If the units mentioned above are recorded during a large number of periods of the year, A, B, C and D can be determined in principle. In practice, however, this proves difficult since, for example, the parameters low outdoor temperature and little sunlight vary in an interrelated manner. Experiments with Δt = 1 day (24-hour) have given results which appear doubtful, probably as a result of the energy stored in floor constructions etc. Δt might, perhaps, be set at one week or more and thus provide better results.

If the aim is to study energy saving measures, useful results can be achieved by means of the following equation:

$$W_{\Delta t} - W_{vv,\Delta t} - W_{h,\Delta t} = E\, \vartheta_u + F \qquad (6)$$

Month	A (kW/°C)	
	Bollnäs	Stockholm
1971 October	1.55	4.27
November	1.60	4.05
December	1.54	4.40
1972 January	1.49	4.67
February	1.37	4.47
March	1.26	4.35
April	1.20	4.39
May	0.82	3.44

TAB.2 The coefficient A in equation (7) for monthly energy consumption for heating in Bollnäs (radiator thermostats) and Stockholm (outdoor thermostats)

Energy savings in inhabited houses

Careful measurements have been carried out in two blocks of flats, namely:

1. Stockholm. (59.3 ^{O}N lat) 35 flats. District heating. Hot water radiators. Outdoor thermostat. Pre-heated fresh air. Collective metering of heating and hot water and separate metering of household energy.

2. Bollnäs. (61.4 ^{O}N lat) 28 flats. Electrical panel radiators with thermostats. Heat exchange from exhaust air to supply air. Collective metering of heating, hot water and household energy.

The outdoor climate, indoor temperatures and energy consumption, broken down by radiators, air pre-heating, hot water and household energy, were studied hour by hour during the year 1971/72. If the following equation is applied:

$$W_{\Delta t} - W_{vv,\Delta t} - W_{h,\Delta t} = A\ Q_{\Delta t} \qquad (7)$$

with $Q_{\Delta t}$ in accordance with (4) and Δt = 1 month, A in TAB.2 is obtained.

In Bollnäs, where radiator thermostats are used, A varies with the time of year. This is obviously the result of additional heat from occupants etc. A is more constant in Stockholm since the radiator temperature is controlled by the outdoor temperature as long as manual regulation is not used.

The following measures have been carried out to reduce the energy consumption in Stockholm:

1. the heat and ventilation system was adjusted
2. the room temperature was reduced
3. the ventilation was reduced
4. the supply air temperature was reduced to the room temperature
5. instructions on how hot water can be saved were distributed
6. a general energy saving campaign was carried out in conjunction with the oil crisis.

The energy consumption in Bollnäs has only been affected by saving instructions and the general energy saving campaign.

Measurements of Energy Consumption

The 24-hour energy consumption for radiator heating R and supply air heating L respectively has been correlated with the mean 24-hour value of the outdoor temperature ϑ_u for the months January-May 1972 and 1974 respectively. The following values are then obtained:

<u>Stockholm:</u>	1972	$R = 47.77 - 2.162\ \vartheta_u$	kWh/flat,day
		$L = 24.44 - 1.064\ \vartheta_u$	"
		$R+L = 72.71 - 3.226\ \vartheta_u$	"
	1974	$R = 31.97 - 1.688\ \vartheta_u$	kWh/flat,day
		$L = 11.78 - 0.609\ \vartheta_u$	"
		$R+L = 43.75 - 2.297\ \vartheta_u$	"
<u>Bollnäs:</u>	1972	$R = 19.96 - 1.187\ \vartheta_u$	kWh/flat,day
		$L = 5.78 - 0.294\ \vartheta_u$	"
		$R+L = 25.74 - 1.481\ \vartheta_u$	"
	1974	$R = 18.78 - 1.111\ \vartheta_u$	kWh/flat,day
		$L = 7.85 - 0.225\ \vartheta_u$	"
		$R+L = 26.63 - 1.706\ \vartheta_u$	"

As can be seen, the energy consumption for heating was markedly reduced in Stockholm but not in Bollnäs.

Using the mean outdoor temperature during the normal heating season in Stockholm (= +2.2 °C) as a basis, the relationships given above become the following for January-May 1972:

$R = 43.0$ and $L = 22.1$ kWh/day per flat

The mean 24-hour output supplied for the entire house (35 flats) becomes:

radiators	$P_R = 62.7$ kW
air preheating	$P_L = 32.2$ kW
	$(P_R + P_L) = 94.9$ kW

In 1971/72 the supply air had a temperature of approximately 3 °C above the room air. This corresponds to 4 kW. Room temperature supply air then requires 28.2 kW. A careful calculation of the transmission losses gives 2.20 kW/°C. $(P_R + P_L)$ can then be allocated amongst the following loss items - the room temperature was 23 °C during 1971/72:

transmission 2.20 (23.0 - 2.2)	45.8 kW
supply air at room temperature	28.2 kW
airing + natural ventilation, "free heat" from occupants, household energy etc.	20.9 kW
	94.9 kW

The room temperature during January-May 1974 was 21 °C and the supply air temperature was equal to the room temperature. At +2.2 °C, we get R = 28.3 and L = 10.4 kWh/day per flat. The mean 24-hour output for the entire house then becomes:

radiators	P_R = 41.3 kW
air preheating	P_L = 15.2 kW
	$(P_R + P_L)$ = 56.5 kW

The output supplied can now be broken down by

transmission 2.20 (21.0 - 2.2)	41.4 kW
supply air at room temperature	15.2 kW
airing + natural ventilation, "free heat" from occupants, household energy etc.	-0.1 kW
	56.5 kW

Since the "free heat" can be assumed to be the same during 1971/72 and 1973/74, the reduction (20.9 + 0.1) = 21 kW must be the result of airing and any changes which may have taken place in the natural ventilation. Interview surveys which were carried out did, in fact, indicate reduced airing.

The measures taken result in a reduction of (94.9 - 56.5) = 38.4 kW (= 40%) divided between

1.	reduced room temperature (from 23.0 to 21.0 °C)	
a)	reduced transmission losses (45.8 - 41.1) = 4.4	
b)	reduced ventilation losses 28.2 $(1-\frac{21.0-2.2}{23.0-2.2})$ = 2.7	7.1 kW
2.	reduced ventilation when the room temperature was lowered (28.2 - 2.7 - 15.2) =	10.3 kW
3.	reduced airing and, in certain cases, reduced natural ventilation (20.9 + 0.1) =	21.0 kW
		38.4 kW

Item 3 is surprisingly large. This may be a result of room temperatures which were too high in certain parts of the house before the adjustment was made.

The energy saving in hot water between 1971/72 and 1973/74 was approximately 40% during December and January, approximately 30% during February and approximately 20% during March in Stockholm. No savings were noted after March. This agrees well with the course of the oil crisis. The energy saving in hot water in Bollnäs was, on the other hand, insignificant - approximately 10%.

The energy saving in household energy between 1971/72 and 1973/74 was 20% in Stockholm and less than 10% in Bollnäs during the actual crisis. A certain residual effect of approximately 5% could be discerned.

It is difficult to explain the difference in saving between Stockholm and Bollnäs. It is due to the fact that city dwellers are more aware of the problems involved than are rural dwellers?

References

Use of energy in buildings. Measurements and studies in blocks of flats, National Swedish Building Research. R10:1974.

Adamson, B., Hämler, J. & Mandorff, S.: Energy saving. A study of two blocks of flats, National Swedish Building Research. R23:1975.

DISCUSSION

N.I. Ngoka; Brunel University, Uxbridge, United Kingdom: The factors taken into account in arriving at equation (5):

$$W_{\Delta t} - W_{vv,\Delta t} - W_{h\Delta t} = A \cdot Q_{\Delta t} + B \cdot \sum_{n=1} A_{qn} \cdot s_n + C_v - D$$

did not include heat gains (mostly of latent heat) from the occupants and heat losses due to human movements in the houses, i.e. by opening external doors several times a day. It is essential that these factors are taken into consideration in arriving at an energy balance equation in occupied buildings. May I know what Mr. Adamson's opinion about this is?

Author: Equation (5) should read:

$$W_{\Delta t} - W_{vv\Delta t} - W_{h\Delta t} = A \cdot Q_{\Delta t} + B \cdot \sum_{n=1}^{4} A_{qn} \cdot s_n + C \cdot \bar{v} - D.$$

The equation refers to measured quantities and the coefficients A-D are to be estimated by means of a statistical procedure. Thus heat gain from the occupants will affect the coefficient D. Natural ventilation will have influence on A and C through cracks and other gaps and by opening external doors. It has, however, to be pointed out that we have had difficulties in estimating B and C with a reasonable degree of accuracy.