Predictive Power of Short-Term Measurements Data for Building Thermal Performance

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ABSTRACT

Longterm simple measurements and data from utility records have been used to predict the energy consumption of buildings. This is not always possible as utility records may not be available, may include several buildings, and may include errors or involve meters that are out of calibration. An alternative is to carry out shortterm detailed measurements of the end uses of energy in a building.

Conclusions are presented on the predictive power of shortterm measurements based on data records from 44 townhouses and 4 apartment buildings monitored during one year. It is demonstrated that the temperaturedependent part of the energy consumption, the heat loss factor (describing ventilative and conductive heat losses), and the UA-value (describing conductive losses only) can be predicted by monitoring a building for a few weeks. Using measured data from one week, the seasonal heat loss factor may be determined with an error smaller than 10% for townhouses and 5% for residential buildings, and the UA-value with an error smaller than 15% for townhouses and 10% for apartment buildings.

Also investigated is how accurately the average indoor temperature of the heating season can be predicted from shortterm measurements.

INTRODUCTION

Longterm simple measurements and data from utility records have been used for several years to predict the thermal performance and energy consumption of buildings. This is not always a satisfactory procedure as utility records may not be available, may include several buildings and errors, or involve meters that are out of calibration. An alternative or complementary procedure is to carry out shortterm detailed measurements of relevant end uses of energy in a building.

We have investigated the stability and average errors of predictions from shortterm measurements regarding building thermal parameters and the average indoor temperature. As a measure of the average error of a prediction method, based on shortterm measurements, we will use the average percentile error in predicting the heating season energy use. The stability of a method will be judged by looking at the constancy of the value predicted from different parts of the heating season.

In the analysis, we have employed two models, the oneparameter net heating energy method and the twoparameter energy signature method.

To apply the net heating energy method, one must calculate two variables, the net heating energy, <u>NE</u>, the energy contributing to the heat balance of the building, and the accumulated indoor-outdoor temperature difference, <u>AT</u>. For the buildings we have been studying (see the Test Buildings section) the net heating energy has been calculated from the expression:

$\underline{NE}$ = (1)

heat delivered by the heat distribution system
+ solar and sky radiation through windows
+ metabolic energy from residents
+ heating energy delivered by heat recovery devices
+ heat losses from hot water storage
+ electrical energy delivered to the building interior
- electrical energy used for domestic hot water generation
- electrical energy used by exhaust fans
- electrical energy used by heat recovery defrost devices
- electrical energy used by washers and dishwashers.

The accumulated indoor-outdoor temperature difference from time 0 to time t, AT(t), is given by:

$$AT(t) = \int_0^t [T_i(t') - T_e(t')]\, dt' \qquad (2)$$

where T_i is the internal and T_e the external dry-bulb temperature. The accumulated temperature has been expressed in units of K-days. This is not to be confused with, for example, the ASHRAE heating degree day concept, where in equation 2 the internal temperature would be replaced by a fixed base temperature and the integration would be carried out for positive temperature differences only (see Eto 1986).

One can define the one parameter of the net heating energy method describing the energy loss of the building envelope, the heat loss factor (<u>HLF</u>), as the ratio of the net heating energy used during a certain period to the accumulated temperature difference for the same period, or

$$HLF = NE/AT \qquad (3)$$

By subtracting from the net heating energy the ventilative energy losses one can define a parameter, the UA-value (<u>UA</u>), describing the conductive energy losses through the building envelope:

$$UA = (NE - \text{ventilative energy losses})/\ AT \qquad (4)$$

In general, energy signature (Korsgaard 1968) refers to a regression technique where the average power of the heating system, or the average total energy consumption of a building for a period of fixed length (usually a week or a month), is plotted vs. the average external temperature or the average indoor-outdoor temperature difference, for example:

$$P = A * (T_i - T_e) + B \qquad (5)$$

where P is the average power, the temperature difference is the average for the period considered and A and B are the two model parameters describing the energy loss of the building envelope and the base energy consumption, respectively (see Lyberg 1987). The parameters A and B can be determined by linear regression of the data in an energy consumption - temperature difference plot. The parameter A should, in principle, be identical to the HLF parameter of the net heating energy method.

One difference between the two-parameter energy signature method as applied here and three-parameter models such as the Princeton Scorekeeping Method (PRISM; see Fels 1986) is that the indoor temperature of equation 5 in PRISM would be replaced by a heating reference temperature and only days with a positive temperature would be considered. As a model, PRISM is also more refined and complex than the simple energy signature model applied here.

Normally, heating degree day methods and methods such as PRISM are applied to energy data consisting of monthly readings of energy consumption, while in this paper we are interested in the predictive power of short-term measurements extending from a few days up to some weeks.

THE TEST BUILDINGS

For the analysis of the predictive power of shortterm measurements one needs data from some different building types having different heating and ventilation systems, different insulation levels, and different complexity regarding the importance of free heat gains such as passive solar energy gains and occupancy-related end uses of energy such as domestic hot water and electricity. Preferably, the data should be detailed, accurate, complete, and reliable and cover the whole heating season. Data of this kind are not very common.

We have used data from two investigations, one including measurements on four apartment buildings (Adamsson et al. 1975) and one including measurements of 44 townhouses of identical design but having different systems for heat recovery, ventilation, and hot water production (Svensson et al. 1975). The length of the measurement periods was one heating season or more. The data collection was carried out by onsite computers and the data bases consist of 10-minute averages for the apartment buildings and four-hour averages for the townhouses. However, in this analysis, only daily averages have been used. The systems of the buildings are described in Tables 1 and 2.

PREDICTING HEAT LOSS FACTOR AND UA-VALUE

When predicting the heat loss factor for a building, the data file consists of points, as in Figure 1. Here, the vertical difference between two consecutive points equals the net heating energy of one day, the lateral difference equals the average indoor-outdoor temperature difference of one day, and the slope of a straight line joining two consecutive points equals the heat loss factor of one day.

Let a group of B buildings be enumerated by an index b running from 1 to B and a heating season D days long by an index d running from 1 to D. We want to estimate the seasonal heat loss factor from measurements starting day d and going on for a period of nd days. The estimate HLF (b, nd, d) will then be given by:

$$HLF(b,nd,d) = [NE(b,nd+d) - NE(b,d)] \; / \; [AT(b,nd+d) - AT(b,d)] \qquad (6)$$

where NE (b, d) is the net heating energy of building b from day 1 to day d and AT (b, d) is the corresponding accumulated temperature difference. A UA-value estimate can be obtained in the same manner.

The stability of the net heating energy method is judged by the time invariance of the estimated values of HLF and UA. Some examples of sliding estimates of the seasonal HLF and UA parameters for a measurement period of length nd = 7 days are shown in Figure 2 and 3. The curves have been obtained by applying equation 6 and carrying out the calculation for every day d of the heating season, keeping the number nd = 7 fixed. Two sets of curves are for apartment buildings having fairly constant values over the heating season, while the curves of a townhouse display a certain seasonality, the curves being slightly concave. Using a run test statistics to test for stationarity of the time series of estimates of the HLF and UA yield stationarity at the 5% confidence level for individual apartment buildings and townhouses. The stability of the net energy method seems to be acceptable.

The average percentile error in predicting the heating season value of the HLF for a building, belonging to a group of B buildings, from measurements extending over a period of nd days is given by:

$$Err(nd) = \frac{100}{B} * \Sigma_{b=1}^{B} \frac{\surd[\; \Sigma_{d=1}^{D-nd} (HLF(b,nd,d) - HLF(b,nd=D,d=1))^2]}{HLF\;(b,\; nd=D,\; d=1) * \surd\;(D-nd)} \qquad (7)$$

where Err (nd) is the average error and HLF (b, nd=D, d=1) by definition is the heating season value of the HLF for building b. The average error of the

UA-value is analogously defined. The results for various lengths of the measurement period are displayed in Figure 4.

For a townhouse, the seasonal HLF can be predicted using data from one week with an average error smaller than 10% and the UA-value with an average error smaller than 15%. The corresponding numbers for the apartment buildings are 10% and 5%, respectively (see Figure 4).

The dependence of the average error when predicting the seasonal HLF or UA-value on the type of HVAC systems in a building has been investigated by carrying out the error analysis, as described above, for the three groups of townhouses separately (see Section 2 and Table 1), with each group consisting of about 15 houses. The data are displayed in Figure 5. The average error falls with increasing length of the measurement period in about the same manner for the three groups of townhouses for measurement periods longer than one week.

The heating season values obtained for the HLF and the UA are given in Table 3. The variation quoted in Table 3 is given by the expression

$$\sqrt{\left[\Sigma_{b=1}^{B} HLF(b,nd=D,d=1)^2 / B - \left(\Sigma_{b=1}^{B} HLF(b,nd=D,d=1) / B\right)^2 \right]} \qquad (8)$$

This variation demonstrates how houses, by design supposedly identical with regard to insulation level and ventilation rate, in practice may behave differently from a thermal point of view.

The average UA-values of the different groups agree fairly well with one another and with the design UA-value, which takes a value between 1.85 and 1.95 kWh/K-day (between 3500 and 3700 Btu/F-day). The range given is mainly due to the uncertainty of window U-values and soil conductivity.

The effect of replacing a measured end use of energy of the townhouses by a default value is shown in Figure 6. The default values for domestic electricity and service hot water have been put equal to 11.0 and 12.5 kWh/day, respectively. These numbers are about equal to the average daily consumption for Swedish single-family homes, but differ from the actual average of the group of townhouses considered by about 1 and 2 kWh/day, respectively. The default ventilation rate has been put equal to 0.5 air changes per hour, corresponding to the requirement of the Swedish Building Code. This is also the actual average ventilation rate of the townhouses. The default sky radiation is equal to the average daily insolation through the windows for the month in question, as calculated from the BKL-method (Kallblad and Adamsson 1984).

Apart from the solar contribution, which is relatively small for those houses, the use of default values may increase the error by several percent. The oscillations shown in Figures 2 and 3 and the errors shown in Figures 4, 5 and 6 may be caused by several factors:

1. Errors in the net heating energy model, equation 1. Errors of this kind would show up as non-linearities in Figure 1.
2. Dynamic effects. Heat stored in the building fabric during one day may affect the net heating energy the next day. For the buildings considered here, this is the most important source of error. Also, heat losses to the ground are not proportional to the daily indoor-outdoor temperature difference but depend on the outdoor temperatures of the previous one or two months.
3. Factors out of control such as airing by residents.

PREDICTING PARAMETERS OF THE ENERGY SIGNATURE MODEL

The energy signature parameters A and B can, for a measurement period nd days long, be determined by linear regression of the nd points representing the daily values in an energy consumption - temperature difference plot (see Section 1). This procedure then replaces equation 6 used in the net heating energy method.

The energy consumption when applying the energy signature method has been defined as the total energy consumption. For the buildings considered here this means district heating energy + electrical energy + energy from heat recovery devices.

The stability of the energy signature method is demonstrated in Figure 7. The sliding values of the parameters A and B for a measurement period of 28 days are displayed along with the HLF determined by the net heating energy method for a measurement period of 7 days (the same curve as in Figure 2) for one apartment building. Using a measurement period of seven days for the energy signature method produces oscillations too large to be shown in a plot. Parameter A is the parameter that should correspond to the HLF value.

There is obviously a great interdependence between the values of the A and B parameters. With the scales used in Figure 7, the parameters almost seem to be mirror images of one another. This instability is mainly caused by a strong seasonal variation of non-heating end uses of energy such as domestic hot water and electricity for appliances (for a more thorough discussion of this effect, see Fels et al. 1986). The seasonality causes the data points to fall more on an ellipse than on a straight line (Lyberg and Fracastoro 1986), as assumed in the energy signature model.

This instability also causes the average error in the predicted seasonal value of the parameters to be large. The average errors of parameters A and B have been determined in the same manner as the average error of the HLF (see equation 7). The data are shown in Figure 8.

The average error of parameter A is larger than 10% even for a measurement period of three months and is even larger for parameter B. This indicates that the energy signature method should only be applied for measurement periods longer than about six months, provided one demands an average error of the predicted annual parameter values of the order of 10%.

This result could be compared to the length of the optimal estimation period when the PRISM method is applied (Rachlin et al. 1986). The length of this period is also found to be longer than six months.

PREDICTION OF INDOOR TEMPERATURE

The average indoor temperature of the heating season can be predicted using data from short term periods of the heating season. This is of interest, for instance, when investigating if an excessive energy consumption may be due to a too high indoor temperature. If T (b, nd, d) is the average indoor temperature of building b during a period of nd days starting day d, the average error of the predicted seasonal (the season comprising D days) indoor temperature, estimated from a period of nd days, has been calculated from the expression:

$$\frac{1}{B} * \Sigma_{b=1}^{B} \surd \left[\Sigma_{d=1}^{D-nd} \left(T(b,dn,d) - T(b,nd=D,d=1) \right)^2 / (D-nd) \right] \qquad (9)$$

where T (b, nd=D, d=1) by definition is the average seasonal indoor temperature of building b.

The resulting average errors are displayed in Figure 9 for different lengths, nd, of the measurement period. Using a measurement period of one week, the average indoor temperature can be predicted by an average error of 0.5 K (about 1 ^{o}F) for apartment buildings and 0.8 K (about 1.5 ^{o}F) for townhouses.

In addition to the (statistical) average error described above, there will also be systematic errors due to, for example, non-representativity of the sensor positions and faulty calibrations of the sensors. The systematic error is often estimated to be on the order of magnitude of 0.5 K (about 1 ^{o}F) and this should be added to the average error of Figure 9 to obtain the total error.

CONCLUSIONS

It has been demonstrated that, using measurements from one week and the net heating energy method, the heat loss factor may be determined with an average error smaller than 10% for townhouses and 5% for residential buildings and the UA-value with an average error smaller than 15% for townhouses and 10% for apartment buildings. The net heating energy method provides predictions that are stable over the heating season.

The energy signature method is too unstable to predict parameter values from short-term measurements. The results indicate that it should only be applied to data covering a whole heating season.

The average indoor temperature of the heating season can be predicted from one week of measurements with a resulting average statistical error smaller than 0.5 K ($1^{0}F$) for apartment buildings and 0.8 K ($1.5^{0}F$) for townhouses.

The average errors can be made smaller by extending the length of the measurement period, but in general the improvement becomes marginal for measurement periods longer than about one month.

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TABLE 1

Systems of the townhouses

	1 Exhaust air house	2 Heat exchanger house	3 Heat pump house
Heating	District heating	District heating	District heating
Heat recovery	None	Air to air heat exch. (nominal flows, see Ventilation)	Heat pump connected to exhaust air (see Ventilation and DHW)
Ventilation	Exhaust air. Nominal flow 45 L/s.	Supply and exhaust Nominal flows 41 and 45 L/s. Electr. preheating of supply air.	Supply and exhaust Nominal flows 41 and 45 L/s.
Domestic hot water	District heating heat exchanger	District heating heat exchanger.	Heat pump connected to exhaust air (compressor power 350 W) with electrical back-up (1.5 kW) and storage.

TABLE 2

Systems of the apartment buildings

Building	1	2	3	4
Heating	Distr. heating	Electrical	Distr. heating	Electrical
Heat recovery	None	Air too air heat exch. (flows, see Ventilation)	None	Air to air heat exch. (flows, see Ventilation)
Ventilation	Supply and exh. air (1140 and 1640 L/s). Preheating of supply air.	Supply and exh. air (930 and 970 L/s)	Supply and exh. air (1030 and 1150 L/s). Preheating of supply air.	Supply and exh. air (930 and 970 L/s).
Domestic hot water	Distr. heating heat exch. (176 kW).	Electrical (60 kW)	Distr. heating heat exch. (180 kW).	Electrical (60 kW) with storage

TABLE 3

Seasonal Heat Loss Factor and UA-value of the townhouses (kWh/K,day)

	HLF	UA-value
Exhaust air houses	3.00+-0.34	1.80+-0.32
Heat exchanger houses	3.35+-0.38	1.96+-0.24
Heat pump houses	3.32+-0.40	1.92+-0.25
All houses	3.26+-0.39	1.91+-0.26

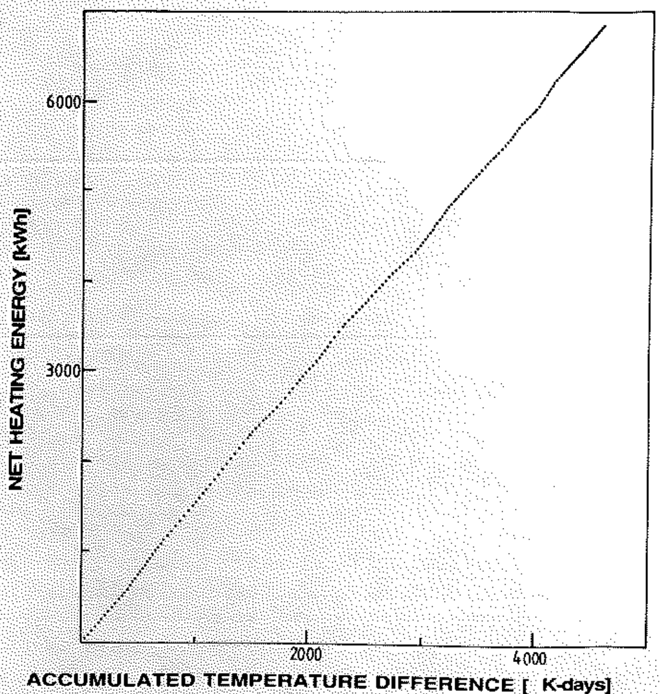

Figure 1. Net heating energy vs. accumulated indoor/outdoor temperature difference for apartment building 1; The vertical difference between two consecutive points is the net heating energy for one day and the lateral difference is the average temperature difference for one day. The plot contains one heating season (182 days).

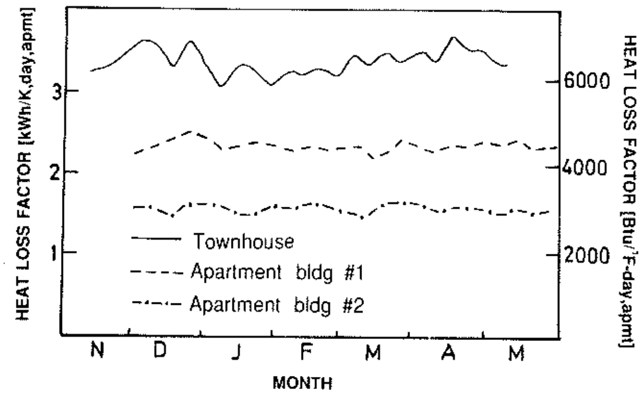

Figure 2. Stability of heat loss factor during the heating season; the curves represent a sliding value calculated from data of a seven-day measurement period.

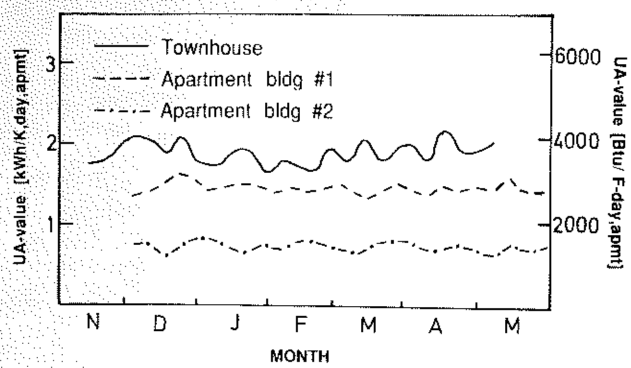

Figure 3. Stability of the UA-value during the heating season; the curves represent a sliding value calculated from data of a seven-day measurement period.

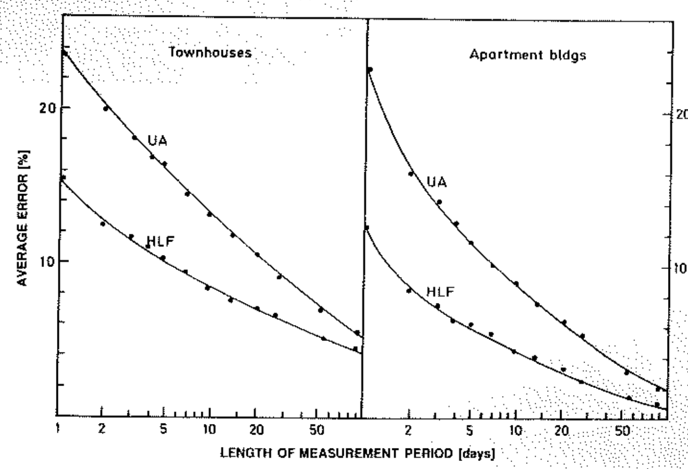

Figure 4. Average error (one standard deviation) in the prediction of the heat loss factor and UA-value from short-term measurements for a townhouse (left) and an apartment building (right)

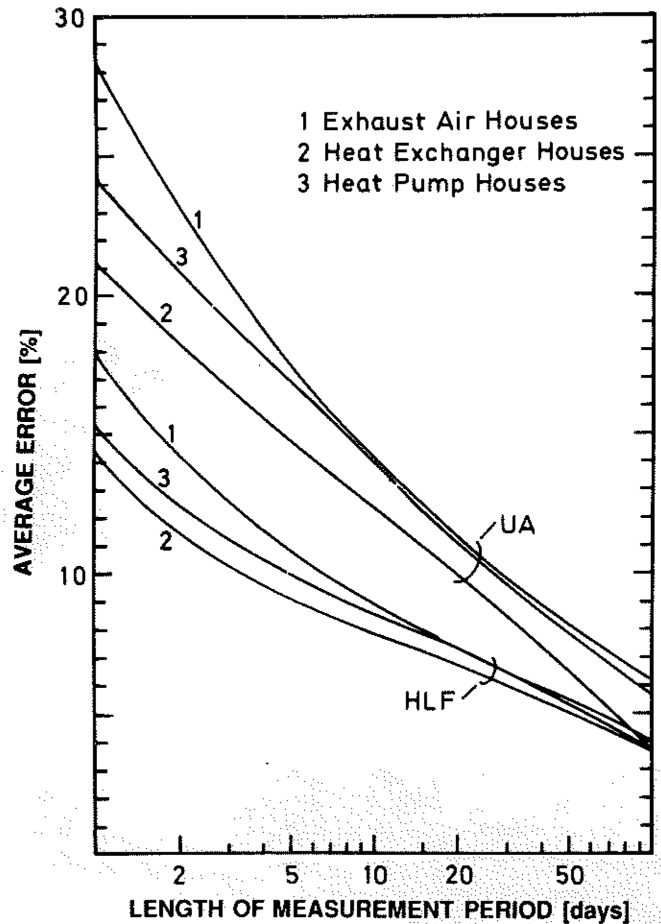

Figure 5. Average error (one standard deviation) in the prediction of the seasonal heat loss factor and UA-value from short-term measurements for town-houses with different heat recovery, ventilation, and domestic hot water systems

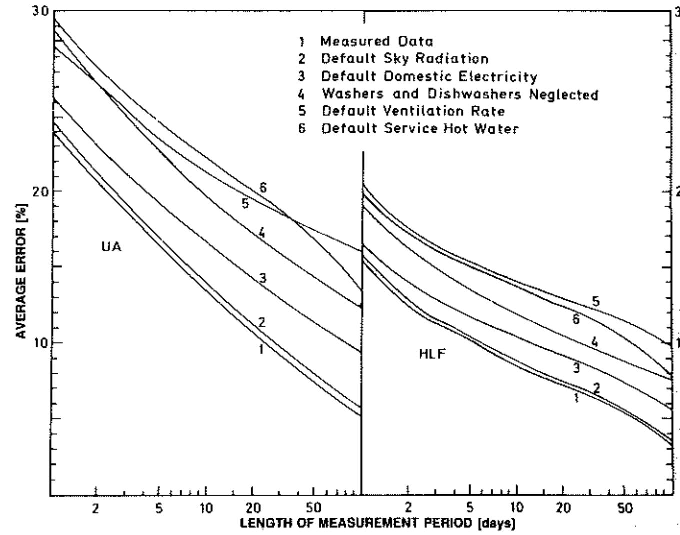

Figure 6. Impact on the size of the average error made in predicting seasonal heat loss factor and UA-value from short-term measurements when one measured end use of energy at a time is replaced by a default value

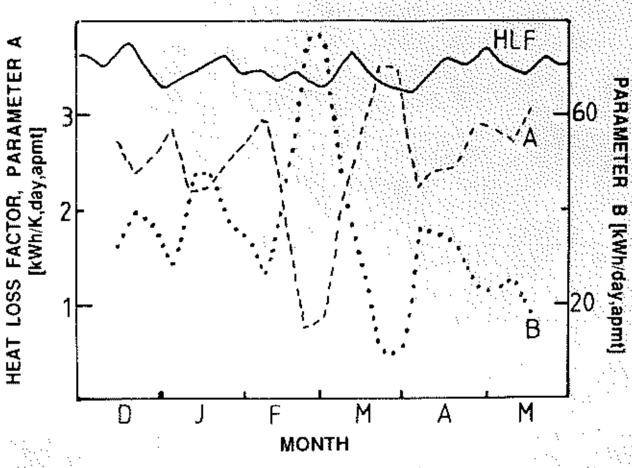

Figure 7. Stability of the energy signature parameters A and B compared to the stability of the heat loss factor; the curves represent sliding values based on measurement data from periods of 28 days (A and B) and 7 days (HLF). The data are from apartment building 1.

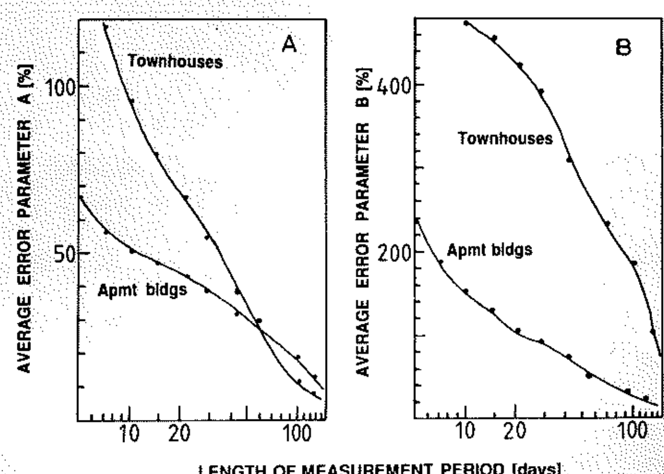

Figure 8. Average error (one standard deviation) in predicting the seasonal energy signature parameters A and B from short-term measurements

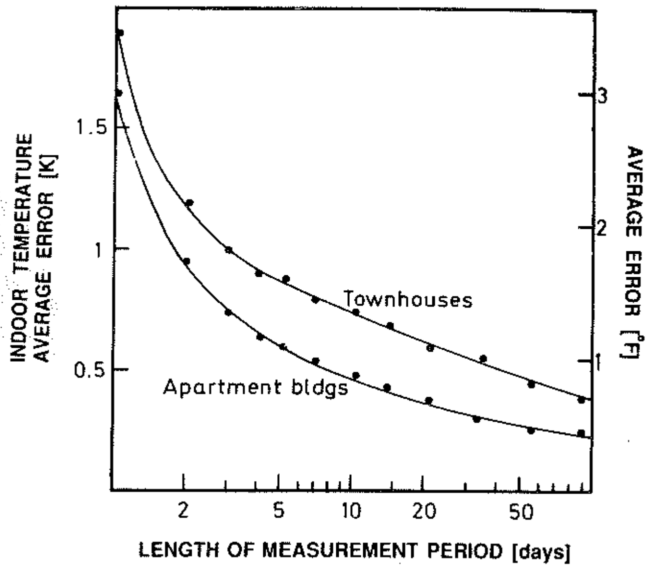

Figure 9. *Average error (one standard deviation) in predicting the average heating season indoor temperature from short-term measurements*