Energy program validation: conclusions of IEA Annex I

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Computer programs for predicting the energy consumption of a building are providing architects and building services engineers with very valuable aids to assist them in the design function. The calculation of building energy flows is extremely complex, and so validation is a vital element in the development of any model. Under the auspices of the International Energy Agency, 23 computer program owners from 8 different countries collaborated in a joint R&D project to compare energy programs, both in terms of consistency between programs, and in considering the accuracy of these same programs in modelling the behaviour of a real building. This paper summarizes the major conclusions that developed out of the project, and gives insight into some of the most important aspects which need to be considered in the development of a reliable computer program.

computer-aided design, building design, energy

In order to strengthen co-operation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for Economic Co-operation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the participants undertake co-operative activities in energy research, development and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, co-ordinates the energy research, development and demonstration programme.

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings. These exercises include the comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The differences and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

The first of these exercises, Annex 1, had as its overall aim 'to evaluate a number of different approaches to modelling the energy requirements of commercial buildings'. This paper describes some of the work carried out under Annex 1, and presents some of the more important conclusions arising out of the project.

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PROJECT PLAN

The project was carried out in two distinct phases. The first stage was the consideration of a highly simplified, hypothetical building. This approach was adopted as it allowed the various component energy flows to be separated, and considered in turn. This enabled the different methodologies for predicting conduction through opaque elements, radiation through glass, etc, to be compared, and the consequences of adopting a particular approach could then be established. This study of the so-called IEA-O building was intended to demonstrate the consistency, or otherwise, of the various programs in predicting the performance of a rigorously defined and relatively elementary building.

The study of a hypothetical building can provide no insight into how well a particular energy program is able to model the real world. Consequently the Annex 1 studies were extended to consider a real building, for which monitored performance data were available. The building chosen for study was the Avonbank office block in Bristol, UK. During commissioning, the building owners, the South West Electricity Board, had carried out a fairly detailed monitoring of the performance of the HVAC systems, along with measurements of air and fabric temperatures at various points through the building. Although not primarily carried out to provide validation data, sufficient information was derived from the monitoring exercise to enable a reasonable assessment of the building performance to be made. Based on an analysis of the likely errors of the monitoring instrumentation it has been estimated that the potential error in the estimates of daily energy consumption is of the order of 25 per cent, and 30 per cent for the peak energy requirements.

IEA-O STUDY

The hypothetical building studied in the first phase of the project was a 12 storey building of light frame construction and an area of 1735 square metres per floor. The external walls were 53 per cent glazed. In order to study the separate components that make up the total building energy flows, participants in the task analysed three variations of the IEA-O building:

- IEA-OA building without windows or internal loads (lights, people, etc)
- IEA-OB with windows, but no internal loads
- IEA-OC with windows and internal loads

This stage-by-stage approach allowed comparison of techniques for evaluating loads resulting from heat transmission and solar gains through opaque surfaces (walls and roofs), heat transmission and solar gains through glazing, and finally the effect of internally generated gains. It should be noted that the IEA-O building does not include any ventilation or infiltration, and no simulation of the HVAC systems. It was assumed that an 'ideal plant' maintained perfect control over the space temperature, maintaining a constant 21.1 °C, 24 hours per day.

Twenty-three programs were used in the comparison exercise. The programs varied from very detailed finite difference models, through response factor models, and models based on the ASHRAE methodology using pre-programmed response factors, to models using various simplified techniques. The results of the analysis work

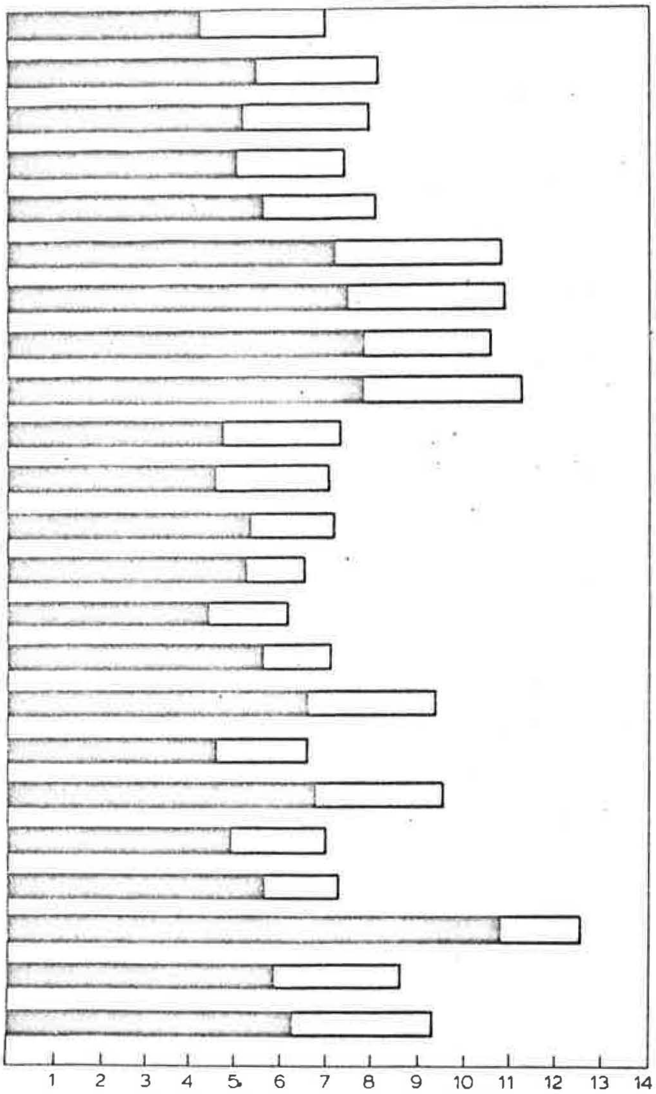

Figure 1. Program estimates of total annual energy consumption for heating and cooling loads (building IEA-OC) (Energy consumption is based on calculated annual heating and cooling assuming a heating plant efficiency of 100 per cent and a chiller plant coefficient of performance of 3.0)

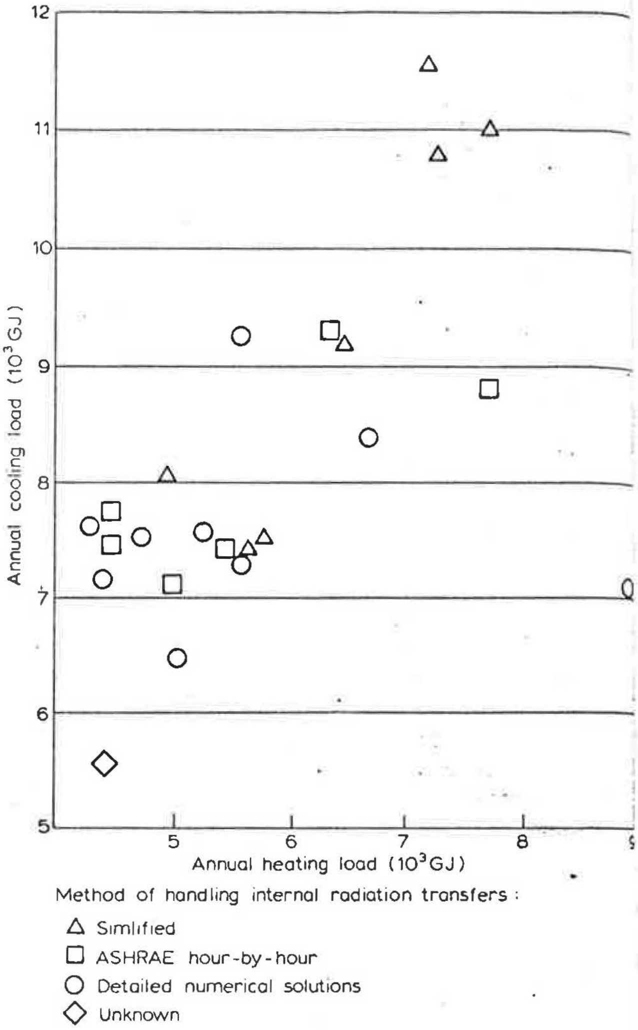

Figure 2. Program estimates of annual heating and cooling loads (building IEA-OC)

indicated that significant differences exist between the predicted energy flows. Figure 1 shows the annual energy consumption for the building broken down into the two components, heating and cooling. The absolute values of the energy consumption figures are unrealistic, since the actual HVAC plant was not modelled. The values plotted represent the sum of the room heating loads over the year, plus one third of the yearly total cooling load (representing a chiller plant coefficient of performance of 3.0).

Several important points emerge from Figure 1. Firstly, it is clear that there is quite a wide scatter in the results of the energy use estimates of the program (of the order of 2:1), although 40 per cent of the programs were clustered together, predicting energy consumptions of 7–8 TJ. Part of the reason for this variation begins to become apparent if the two components of the total (ie heating and cooling) are plotted separately (Figure 2). A trend of increasing cooling with increasing heating is apparent, and this trend is even clearer if the peak hourly heating and cooling loads as predicted by the programs are compared.

Further analysis showed that all the programs handle steady state effects in a very similar manner, but differences begin to emerge when considering dynamic effects. During periods when there is a time varying energy input, the various methodologies diverge greatly when predicting the effect of the structural thermal mass in lagging and decrementing the gains. That the differences are due to dynamic effects, and not to steady state effects, can be shown by calculating regression coefficients derived from the monthly heating and cooling estimates for the IEA-OA (without windows and internal loads) building and the IEA-OB (with windows but without internal loads) building.

They relate the net monthly heating minus cooling loads to building construction characteristics and climatic factors. Two programs, program 1 using a simplified technique for accounting for storage effects, and program 2 using pre-programmed response factors, produce similar values for the regression coefficients, which implies that the methodologies used produce similar results for the net effects of steady state characteristics. Therefore the substantial differences between the programs must be because of the way the programs handle dynamic effects, such as internal radiation transfer and thermal storage.

To show these differences, the hourly load profiles calculated by the programs for the IEA-OC (with windows and internal loads) were plotted (Figure 3). It can be seen that the fluctuations of program 2 were more damped than those of program 1, with program 1 predicting a heating load during the early morning with a peak cooling load of 7500 MJ/hr and program 2 predicting no heating load and a peak cooling load of 5500 MJ/hr.

Further differences arise between the various programs when considering the amount of detail used to simulate the building's interior surface heat exchange. Detailed modelling of the radiation exchange and heat balance of interior surfaces is used by numerical solution programs, such as program 3, whereas ASHRAE hour-by-hour calculation programs, such as program 2, use tables developed from previous calculations on 'typical' buildings. These two types of program give similar annual heating and cooling load estimates but different peak load estimates. For example, program 2 predicts higher loads resulting from heat gains, transmission through glass and internal lighting for the IEA-O building. The calculated heating load is therefore decreased and the cooling load increased, although the difference for the estimated annual energy consumption for the IEA-OC building is only small.

The way the amount of detail used by each program affects the results can be analysed as follows for one of the component energy flows, namely conduction through glass. The results for a repeating winter day (a constant dry bulb

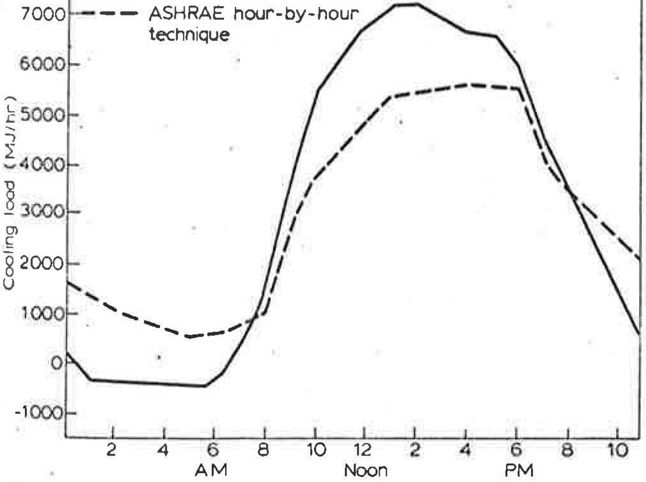

Figure 3. Comparison of hourly load profiles (building IEA-OC, cyclic summer day)

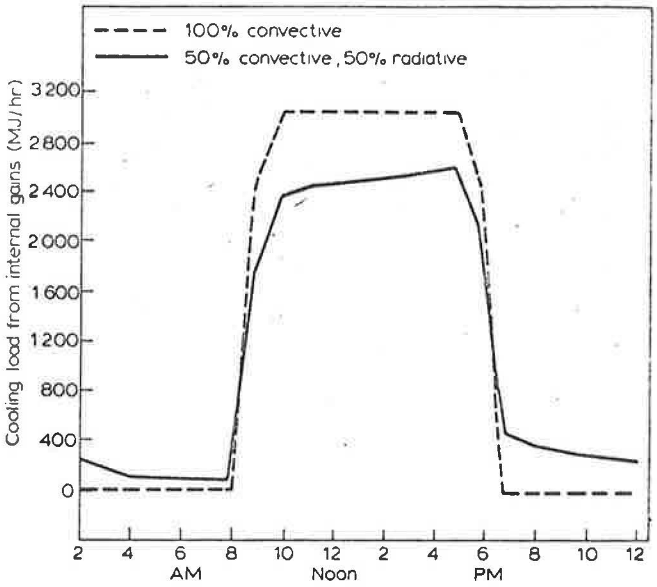

Figure 4. Comparison of estimates of hourly cooling loads due to internal heat gains (building IEA-OC)

ambient temperature of -6.6°C and no insolation) for the IEA-OA (no windows), and IEA-OB (with windows) are compared, where any differences between the loads for the building must be due to conduction losses through the glass. Program 2 assumes that the indoor surface temperature equals the indoor air temperature, giving a heat gain through the building shell that is proportional to the inside–outside temperature difference. Program 3 splits the indoor surface coefficients into radiative and convective portions and uses weighted shape factors. It therefore calculates an interior surface glass temperature which is lower than the average room temperature and thus predicts less heat loss (13 per cent less) than does program 2.

Even among the detailed numerical solution programs, estimates of energy consumption and peak demand differ significantly, because of the way the programs split the radiative and convective portions of internal heat gains (from lights and people) and the radiative and convective portions of the indoor surface coefficients. For example, program 3 assumes that heat gains from lights are 50 per cent radiative and 50 per cent convective; program 4 assumes that they are totally convective. When the two programs are run for IEA-OB (no internal load) the results for room loads, consumption and peak demand are similar, implying that they handle solar and transmission effects in a similar manner. However, substantially different room loads (Figure 4) are obtained for the IEA-OC (with internal gains) with program 4 predicting a total energy consumption 19 per cent higher than program 3.

The different techniques for splitting indoor surface film coefficients into radiative and convective portions can lead to differences in estimates for total annual loads and peak hourly loads. Monthly and annual energy consumptions for IEA-OC were calculated for four programs which all assumed a 50/50 split between radiative and convective internal heat gains but which used different modelling assumptions for interior heat transfer, thus giving differences in estimates of conduction through glass and of net space solar energy gains through glass. The lowest estimate was 13 per cent less than the highest estimate.

To determine the effects of transmission through glass, the IEA-OB and IEA-OA runs for the winter repeating day were compared. Less heat loss is obtained if the transmission through the glass is assumed to be wholly radiative than if it is assumed to be only partly radiative. The higher the assumed value of the radiative surface coefficient (and hence the lower the value of the convective surface coefficient where their sum is kept constant), the lower the calculated heat transmission through glass.

However, having shown that the conductive and radiative split for inside surface coefficients affects estimates of both peak demand and annual loads when their sum is constant, the feasibility of using a constant sum (as in the IEA-O specifications) should also be questioned. In reality, while the radiative coefficient is relatively constant, the convective coefficient is dependent on air circulation in a room and on the direction of heat flow. Therefore it is evident that the convective coefficient is dependent on such details of the HVAC system as the location of air discharge vents. If a building is still under design, the detailed pattern of air movements will not be known and so it may not be possible to model the interior precisely. If these details are unknown, the extra computational effort of the more sophisticated methodologies may not be worth while.

A more detailed discussion of the results of the analysis of the IEA-O building is given elsewhere[1]. The analysis of the IEA-O building only reveals differences between the various methods of analysis but does not necessarily define which method most accurately models real building behaviour. The validation work on the Avonbank building is the first stage in the process.

AVONBANK BUILDING

The Avonbank building is an all-electric air conditioned office building on three floors. Basically, it is a rectangular concrete box with regularly spaced recessed windows. The important aspects of the building construction are:

- the low glazing area (12 per cent of the facade)
- the relatively large mass of the structure
- the wall insulation is on the inside of the building fabric
- the fan coils used for the air conditioning consist of cooling only units in the core areas and heating and cooling units in the perimeter

The use of computer techniques for estimating the thermal behaviour of a building can only be assessed after a complete description of the heat transfer taking place both within the building and through to the exterior has been described. Whilst some of the parameters controlling the heat exchanges are well defined, eg conductivities of the fabric, others are only poorly understood and therefore crudely modelled. The main area of this uncertainty is convective heat transport and this is seen in three areas within the Avonbank building.

The first area is that of convective coupling between the separate zones into which every floor is divided. These zones correspond to areas served by separate fan coil units, these areas are not physically divided along the zone boundary and therefore mixing between spaces occurs. This is difficult to allow for in computer simulation and so the zones were treated as separate entities. Consequently when the plant is switched off, and the space conditions drift, the temperatures at the perimeter fall off more rapidly than those in the core. The programs thus predict considerable temperature differences across the boundaries during plant-off periods. These differences would not exist in practice, but they have a significant effect on the predicted plant response following start up.

Table 1. Heat gains and losses to perimeter zone at winter design condition

Source of heat gain/loss	Magnitude (MJ/hr)
Infiltration	-20.0
Lighting	+12.6
Occupancy	+ 8.2
Small power	+ 5.4
Conduction	-13.7
Net gain	- 7.5

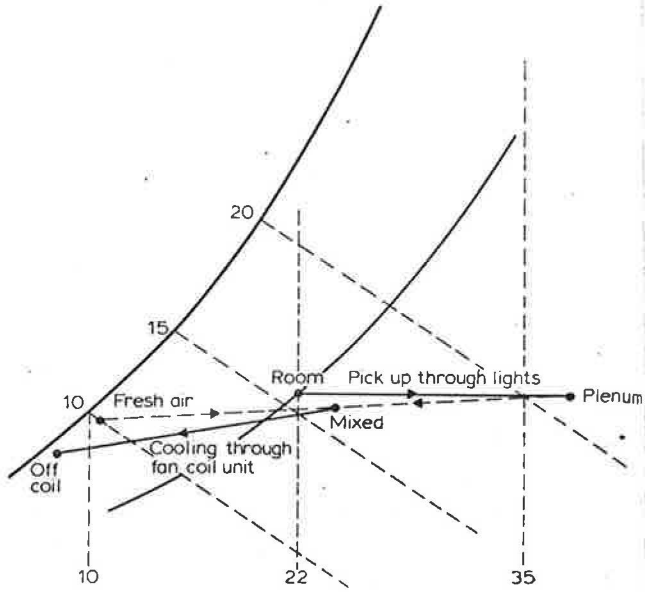

Figure 5. Psychrometrics around fan coil unit

The second area of uncertainty is that of infiltration, which has never been measured at Avonbank and is difficult to predict with any accuracy. It will be noted that the importance of any error in the assumption of an infiltration rate is magnified as the difference between the enthalpy of inside and outside air increases. By use of a simple steady state calculation it can be shown that at the winter design condition, the assumed infiltration rate results in a heat loss which is almost three times larger than the net space heat gain (see Table 1).

The third area of uncertainty is the fresh air supply to the individual zones. The flow rates used in the simulations were design values that were set up when the system was commissioned but were not rechecked. Errors in the simulation could arise if the total fresh air flow has changed, or if the distribution of the air to the separate zones has changed. Simple calculation shows that the effect on the net space heat gain will be minor unless the difference between assumed and real values is very large.

The total heat extraction rates predicted by the programs were initially compared with the actual building performance for the daily total for the winter and summer period, and also for each hour of the selected winter and summer days.

The following observations can be made from the results of the analysis which help to identify certain areas of divergence between the programs and the measured building performance.

- In winter, the programs tend to underestimate the heating, but the average results for the programs tie in reasonably well with the measured winter cooling.
- In summer, the programs consistently underestimate the cooling requirements (there being negligible heating requirement).

These effects can be put down to modelling uncertainties, the major component for which in the heating demand is infiltration. The cooling underestimation is probably due to convective coupling across zone boundaries, but may also be because of latent cooling on the coils, although the system is designed in such a way that all the latent control should be done by the fresh air unit. Calculation of the psychrometric processes going on around the individual fan coil units indicates that as the duty approaches the summer design condition, then in order to extract the required sensible heat, latent cooling must also occur (Figure 5). This shows the importance of modelling the detail of the plant behaviour if accurate building energy estimates are to be made.

A full appreciation of the various effects causing differences in the results for the whole building loads is difficult to achieve because of the multi-zonal nature of the problem. However consideration of the behaviour of a single floor of the Avonbank building helps clarify the situation. During the summer selected day, all the fan coil units are cooling only, there being no heating demand, and so the zoning effects are of less significance. The basic trend of the predicted heat extraction rates is similar, although the absolute magnitudes vary. This could be, as with the IEA-O study, because of the building storage effects, and Figure 6 tends to confirm this, showing that the plot of annual cooling demand against annual heating demand gives a trend line of increased cooling with increased heating, as the storage effects of the building are reduced.

Unlike the IEA-O study, the differences in storage effects are probably not only due to methodology as the limited number of programs participating in the Avonbank exercise were all fairly sophisticated. Other reasons are

- Intermittency of plant operation (IEA-O was continuous); intermittency will tend to emphasize the importance of the need for accurate modelling of the effects of building storage.
- The effect of the insulating layer on the storage characteristics of the external walls: although the walls have a large thermal capacity, the insulating layer is close to the inside surface. Consequently the inside surface temperature will respond quite quickly to changes in the internal environment, and so as far as the internal spaces are concerned, the building is effectively of light rather than heavy weight construction. This effect was not properly modelled by all the programs.
- The proportion of convective/radiant gains from internal heat sources. This again relates to the storage effects of the building fabric, in that the radiant portion of the gains is only seen as a room load after being absorbed and retransmitted by the room surfaces.

Further detail on the results of the study of the Avonbank building is given elsewhere[2].

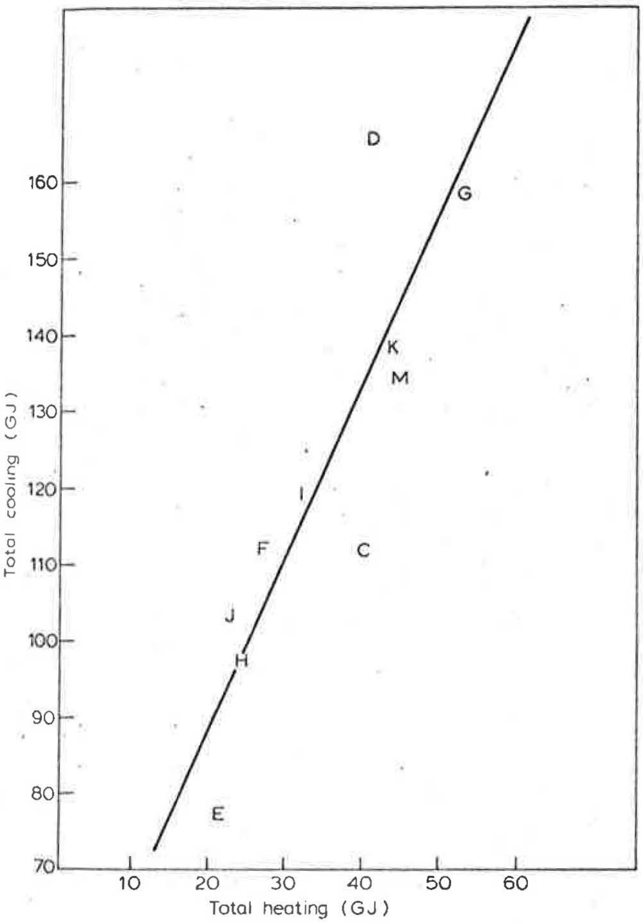

Figure 6. Annual heating and cooling demand

CONCLUSIONS

The work carried out under Annex 1 of the IEA programme on Energy Conservation has revealed many important points which should be borne in mind when developing or using computer models for predicting building energy flows. These important conclusions can be summarized as follows.

The modelling of thermal storage in the building fabric is a key factor in determining the calculation of room loads. This factor is obviously of increasing importance the 'heavier' the building becomes.

The degree of complexity in the modelling of the interior heat balances can significantly affect the results of the simulation. However it must be remembered that in some cases the accuracy of the data is inferior to the quality of the model, and so the potential benefits of the more sophisticated model should be viewed in this light.

There is a large degree of uncertainty in the prediction of infiltration rates. This gap in our knowledge is becoming increasingly important with the trend to better insulation. As a result of this deficiency, a separate IEA task (the Air Infiltration Centre) has been set up to improve the state of knowledge in this area.

Coupling between spaces plays an important role in modifying the thermal response of adjacent zones. This factor can be especially important in large open plan areas.

The calculation of room loads is only the first stage in carrying out an energy prediction for a building. It is necessary to calculate what is going on around each plant component if a full appreciation of building energy flows is to be established.

ACKNOWLEDGEMENTS

This work was carried out under the auspices of the International Energy Agency. The contribution of the many Task Participants is gratefully acknowledged. Participating countries were Belgium, Canada, Denmark, Germany, Holland, Italy, Sweden, Switzerland, UK and USA.

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2 Oscar Faber and Partners *IEA Report Annex 1 and analyses of Avonbank building simulation*