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Summary A previous paper by the author showed that the selection of inappropriate combinations of wall and window designs by the 'passive solar' designer could lead to a seasonal auxiliary energy penalty instead of the expected advantage. A simple method was proposed whereby a designer could calculate a 'critical house temperature difference' which would enable the average efficacy of different combinations of window and wall designs for different orientations to be evaluated over a heating season and so reduce the risk of incurring an energy penalty. The proposed method has now been tested using DEMON, a program derived from BREDEM 8, and shown to be effective for the cases used. This paper describes the testing of the proposed calculation method.

Reduction of window design risk in houses: Testing a simple calculation method

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List of symbols

For a facade of a particular chosen orientation:

ΔH	Change in heat flow due to glazing (W)
ΔT	Mean seasonal temperature difference across the facade (K)
A	Total facade area (m^2)
I	Mean seasonal solar transmission through windows (W m^{-2})
U_g	Window transmittance (W m^{-2}K^{-1})
U_w	Opaque wall transmitttance (W m^{-2}K^{-1})
x	Fraction of total wall occupied by windows
ΔT_{crit}	Critical temperature difference (K)
ΔE	Change in seasonal auxiliary heating energy (kWh m^{-2})

1 Introduction

This paper is an extension of previous work concerned with window sizing and it is therefore necessary, first of all, to provide some background information. A paper by Warren in a previous issue of this publication[1], referred to here as Paper 1, discussed some of the problems faced by the designers of 'passive solar' houses, or indeed any other building types, when deciding upon appropriate window sizes. Simple computer performance assessments are usually broadly based on a fixed operational scenario and do not take account of the different operational regimes which may apply over the lifetime of a house. The selection of inappropriate combinations of wall and window designs by the 'passive solar' designer may lead to a seasonal auxiliary energy penalty instead of the expected advantage. A simple method was proposed whereby a designer could calculate a 'critical temperature difference' for a facade based on solar gains and wall and window transmittances over a typical heating season. This could then be compared with the expected seasonal mean house temperature difference. A mean seasonal house temperature difference above the critical temperature difference for a particular facade would mean that an increase in window size in that facade would result in an increase in seasonal heating energy use. Conversely a decrease in heating energy requirement can be obtained by increasing window areas when the seasonal house temperature difference is below the critical temperature difference for the facade.

The critical temperature difference is given by the simple expression

$$\Delta T_{crit} = I/(U_g - U_w) \qquad (1)$$

In Paper 1 graphs of critical temperature difference against wall U-values were presented for single glazed, double glazed and double low-E glazed windows for a range of facade orientations. An example is presented in Figure 1 together with the superimposed seasonal lounge temperature difference for a notional house. In this example, for a lounge window facing East or West and with a mean seasonal lounge temperature difference of 12.5K, increasing window areas result in decreasing the heating energy required when double glazed low-E windows are used and opaque wall U-values are greater than 0.1 W m^{-2} since for these conditions the actual lounge temperature difference is less than the critical temperature difference.

Also from Paper 1 it was shown that the change in the mean seasonal auxiliary heat flow due to the introduction of windows in a facade is given by the expression

$$\Delta H = x(AU_g\Delta T - AU_w\Delta T - IA) \qquad (2)$$

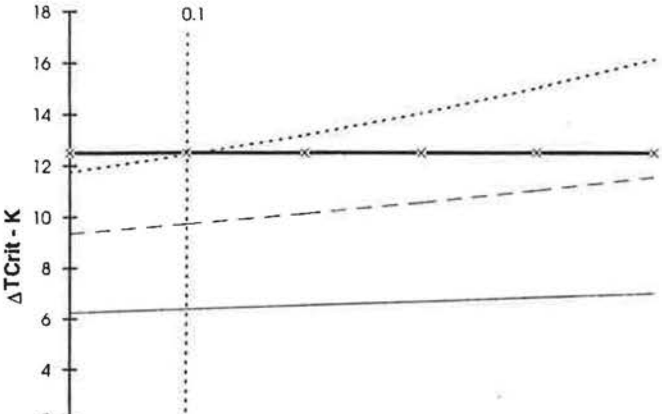

Figure 1 Critical temperature differences for E and W facing facades — with curtains (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity; —×—×— lounge temperature difference)

which, when evaluated for the example given above, was presented graphically as in Figure 2.

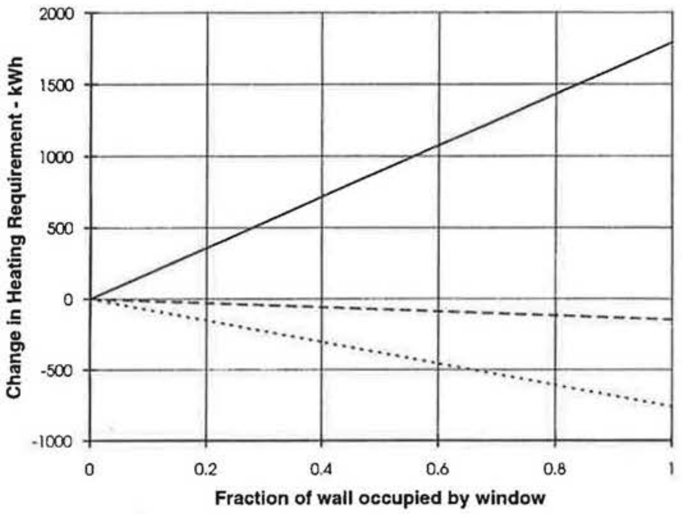

Figure 2 Change in mean seasonal auxiliary heating due to addition of glazing (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

Since Paper 1 was mainly of a theoretical nature, some testing against a validated energy prediction model was considered necessary. Probably the most widely used validated model is BREDEM[2] and it was felt that this would be the most appropriate model to use. BREDEM is available in a number of forms depending on the type of information required and, for the testing envisaged, BREDEM 8, a monthly version, was deemed the most suitable.

It was decided therefore to use DEMON[3] (Domestic Energy Model Newcastle), a commercially available software package developed by the Department of Architecture at The University of Newcastle, which predicts monthly and annual domestic energy consumption in accordance with the algorithms and methods described in BREDEM.

2 Determination of solar transmission and critical temperature differences

Initially the mean solar transmission *I* had to be determined, during the 'heating season', through windows of different orientations and types to enable a set of 'critical temperature difference' curves to be produced for a range of wall transmittances. The values of transmission required were those used in the BREDEM calculations and, since they were not available as DEMON output they had to be derived indirectly from the monthly solar energy gains. DEMON only provides values for 'useful' gains which are defined as those contributing to the house heating requirement. Energy transmitted through the windows which contributes to overheating is not counted. It was therefore necessary to select the DEMON run conditions to ensure that all the transmitted solar energy resulted in 'useful' energy gain to the house.

A three bedroom detached house design, situated in South East England, with a floor area of 91m^2, ETSU Standard Reference Type D[4], was taken as the base case. To ensure that all the energy transmitted through the windows would be 'useful' during the heating season the temperature of the house was set at 20°C for both 'living' and 'other' spaces. *U*-values were set high, all services were electric and there were no people. The heating regime was set to be continuous between the hours of 0700 to 2300. In this case all solar gains would be 'useful'. Windows were only placed in one facade to enable gains for a single orientation to be calculated.

Gains were calculated, using DEMON, for S, E and SE orientations as well as a range of window areas to ensure that there was no difference between the values. Values were obtained for the months October to April inclusive which was taken as the 'standard heating season'. Knowing the number of days in the month and the window areas the window gains, in kilowatt hours, were converted to transmission values in W m^{-2} of window.

Gains were determined for single, double and double low-*E* glazed windows. The gains obtained from DEMON take into account the transmission and shading coefficients for the different window types as well as shading related to the particular type of building location which was assumed to be suburban. The plot of solar gain on a month by month basis, Figure 3, shows that during the months of the heating season changing the window area makes virtually no difference to the calculated solar transmission through the window which indicates that all the gains are 100% 'useful'. The slightly lower values calculated for the 20m^2 window for the months of June, July and August indicate that during these periods not all of the available energy was needed to meet the house heating requirement. From the results of the different DEMON runs the mean solar transmission for the heating season, October to April inclusive, was determined for each case considered. These results are summarised in Table 1.

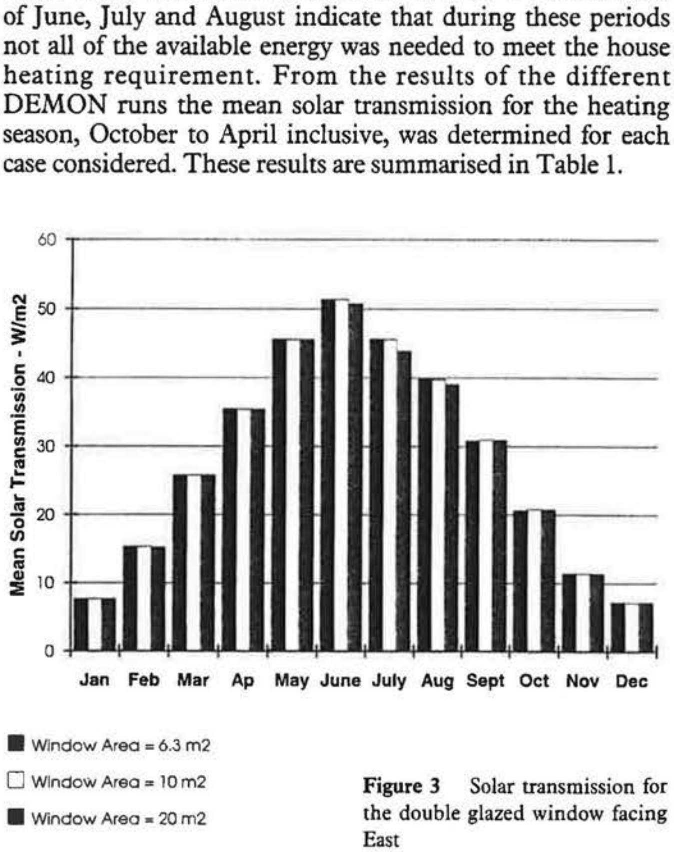

Figure 3 Solar transmission for the double glazed window facing East

This table also includes the relevant *U*-values which were obtained directly from the DEMON output.

The values from Table 1 were used to calculate critical temperature differences for a range of wall *U*-values using the expression

$$\Delta T_{crit} = I/(U_g - U_w)$$

Curves of critical temperature differences are presented in Figures 4, 5 and 6 for South East England.

Table 1 Summary of mean seasonal window transmission and *U*-values

Orientation	Glazing type	Window transmission (W m^{-2})	Glazing *U*-values (W m^{-2}K^{-1})
	Single	33.78	3.2
S	Double	28.45	2.1
	Double LE	26.68	1.58
	Single	20.95	3.2
E and W	Double	17.64	2.1
	Double LE	16.52	1.58
	Single	29.65	3.2
S E and S W	Double	24.96	2.1
	Double LE	23.39	1.58

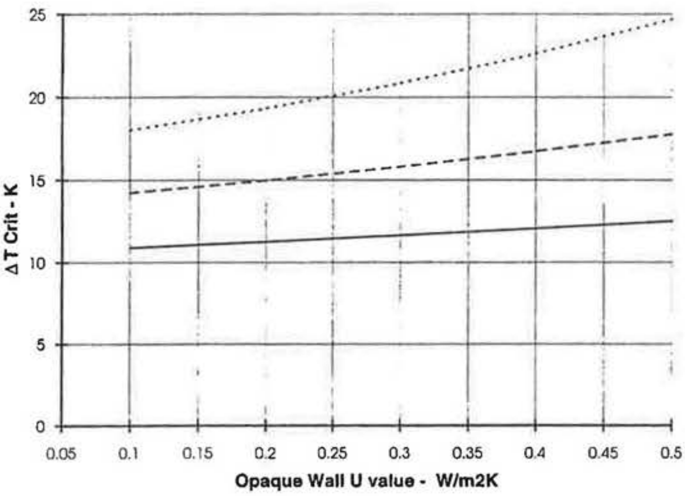

Figure 4 Critical temperature differences for South facing facade (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

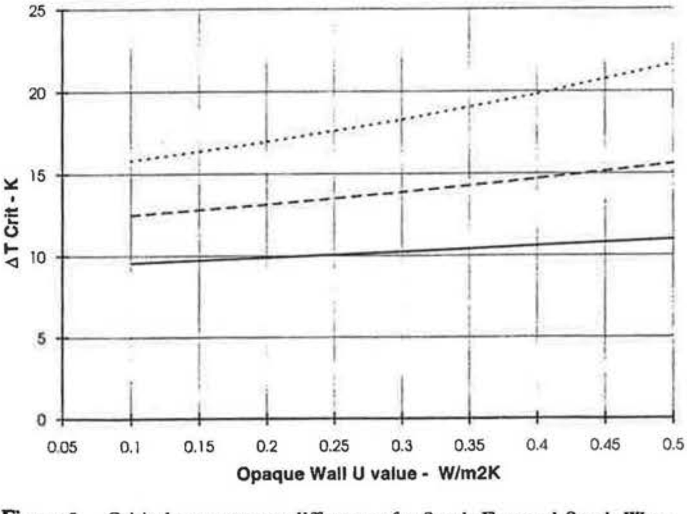

Figure 5 Critical temperature differences for South East and South West facing facades (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

3 Prediction of house temperature difference using DEMON

Runs using DEMON were carried out to determine the mean house temperature difference during a heating season and to find out how the annual heating energy changed due to changes in percentage window area and wall *U*-value for different glazing types. The same house design was used as before but with conditions more representative of a normal

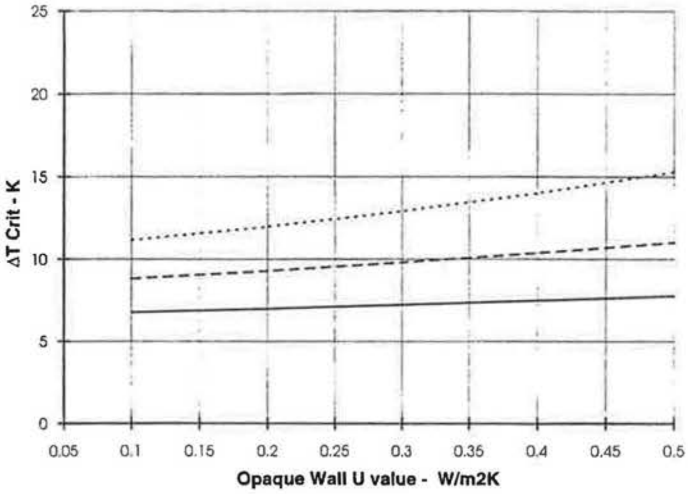

Figure 6 Critical temperature differences for East and West facing facades (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

situation. The *U*-values used were 0.25 W m^{-2}K^{-1} for the roof and floor and 0.45 W m^{-2}K^{-1} for the walls. The windows were all double glazed and thick curtains were closed at night. The house, assumed to be occupied by three persons, was located in South East England in a suburban situation. The set points were taken as 20°C for the living areas and 18°C for all other areas with the heating set to be on between 0700 and 0900 and again between 1500 and 2300. Space and water heating was provided from a condensing gas boiler. An initial set of runs was performed to determine the mean house temperature difference during the heating season. For each month of the heating season values of total energy loss (kWh), and total specific heat loss (W K^{-1}), were recorded and the mean house temperature difference calculated from the expression:

Temperature difference

$$= 1000 \times \text{Total loss}/(24 \times \text{Days in month} \times \text{Specific loss})$$

An example of the results is given in Table 2 with living room windows facing South.

Table 2 Calculation of mean house temperature difference during the heating season

Month	Days	Total loss (kWh)	Specific loss (W K^{-1})	Temperature difference (K)
Jan	31	1623	174.47	12.50
Feb	28	1450	174.47	12.37
Mar	31	1413	174.47	10.89
April	30	1113	174.47	8.86
Oct	31	932	174.47	7.18
Nov	30	1265	174.47	10.07
Dec	31	1507	174.47	11.61
			Mean	**10.50**

A check was carried out to determine the effect of changing the *U*-values of the South facing wall which gave the results in Table 3.

Table 3 Effect of changing *U*-values

U-value of wall (W m^{-2} K^{-1})	Temperature difference (K)
0.1	10.48
0.2	10.48
0.3	10.48
0.45	10.48
Mean	10.48

Changing the orientation of the house so that living room windows faced East made a very slight difference to the mean temperature difference giving a rounded value of 10.47K. The difference between the rounded values of 10.50 and 10.47 is considered to be negligible. Similar DEMON runs and calculations were performed to determine the mean seasonal house temperature difference for a continuous heating regime with heating on from 0700 to 2300. These resulted in a mean value of 11.18K.

4 Comparison of house temperature difference with critical temperature differences

Taking the intermittent heating case, the mean seasonal temperature difference of 10.50K is compared with the critical temperature differences calculated for an East or West facing facade in Figure 7.

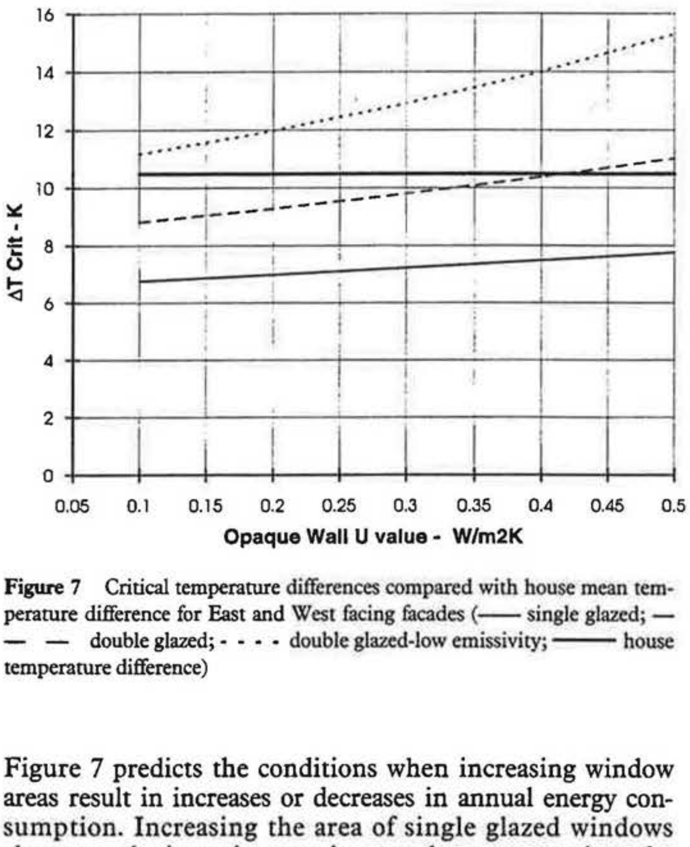

Figure 7 Critical temperature differences compared with house mean temperature difference for East and West facing facades (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity; ——— house temperature difference)

Figure 7 predicts the conditions when increasing window areas result in increases or decreases in annual energy consumption. Increasing the area of single glazed windows always results in an increase in annual energy use since the house temperature difference is always above the critical value. Double glazed low-*E* windows, on the other hand, result in decreasing energy use as they are increased in area since the critical temperature difference is always above the mean house temperature difference. An increase in the area of ordinary double glazed windows will only be beneficial if the wall *U*-value is greater than about 0.4 W m^{-2}K^{-1}.

In Paper 1 it was shown that the change in the mean seasonal auxiliary heating requirement due to the introduction of windows into the facade in question is given by the expression

$$\Delta H = x(AU_g\Delta T - AU_w\Delta T - IA)$$

which can be restated as:

$$\Delta H\,(\text{m}^{-2}) = x(U_g\Delta T - U_w\Delta T - I) \qquad (3)$$

where ΔH (m^{-2}) is the change in heating requirement of the house due to the introduction of glazing into the specified facade, A is the facade area and x is the fraction of the total wall area occupied by the window. From equation 3 the change in annual auxiliary energy ΔE for the different cases is given by:

$$\Delta E = \Delta H\,(\text{m}^{-2}) \times 212 \times 24/1000 \text{ kWh m}^{-2}$$
$$= 5.088{*}\Delta H \text{ m}^{-2} \text{ (kWh m}^{-2})$$

where 212 is the number of days in the heating season from October to April inclusive. In this case, using a house mean seasonal temperature difference of 10.48K we have:

$$\Delta E = 5.088x(10.48U_g - 10.48U_w - I) \qquad (4)$$

Substituting the solar transmission and *U*-values for the windows from Table 1, values of ΔE for a range of wall *U*-values and percentage window area were determined. The results from this calculation for an East facing facade with a wall *U*-value of 0.45 W m^{-2}K^{-1} are plotted in Figure 8.

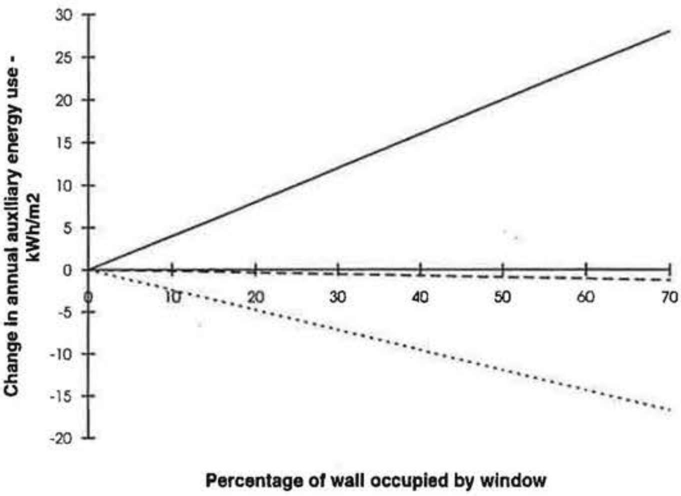

Figure 8 Change in auxiliary energy per m^2 of East facing facade for a wall *U*-value of 0.45 W m^{-2}K^{-1} (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

These results complement the results from Figure 7 for a wall *U*-value of 0.45 W m^{-2}K^{-1}. Single glazing results in increasing energy use, double glazing is effectively neutral and double glazing with a low emissivity coating reduces energy use.

5 Comparison of theoretical results with DEMON runs

A series of runs using Demon was carried out on the same house design, occupancy and intermittent heating conditions as in section 3 above to determine the annual heating energy use for a range of conditions. Runs were carried out for a range of opaque wall *U*-values, percentage window area in the facade and window type applied to the East facing living room facade. The total area of the living room facade was 8.4 m^2. Table 4 shows a sample of the results obtained with the wall *U*-value set at 0.45 W m^{-2}K^{-1}. Sets of results similar to those in Table 4 were also obtained using wall *U*-values of 0.1, 0.2, 0.3 and 0.5 W m-2K. The variation in annual auxiliary heating energy is shown in Figure 9.

From Figure 9 it is seen that the auxiliary energy use obtained using DEMON follows the pattern from the theoretical prediction in Figure 8. The use of single glazing always results in an increase in energy use with increasing window area while the use of double low-*E* glazing gives a decrease. Increasing the area of double glazing can increase or margin-

Table 4 Sample results from DEMON runs

1	2	3	4	5	6	7	8	9	10
Wall *U* value (W m^{-2}K^{-1})	Window area (m^2)	Wall area (m^2)	Proportion of window (%)	Annual auxiliary heating energy from DEMON			Change in energy requirement		
-				Single (kWh)	Double (kWh)	Double low-*E* (kWh)	Single (kWh)	Double (kWh)	Double low-*E* (kWh)
0.45	0.1	8.3	1.19	4749	4744	4742	0	0	0
0.45	1	7.4	11.90	4781	4739	4716	32	–5	–26
0.45	1.7	6.7	20.24	4809	4736	4698	60	–8	–44
0.45	2.3	6.1	27.38	4833	4735	4682	84	–9	–60
0.45	3	5.4	35.71	4862	4733	4665	113	–11	–77
0.45	4	4.4	47.62	4905	4734	4643	156	–10	-99
0.45	5	3.4	59.52	4950	4736	4623	201	-8	–119

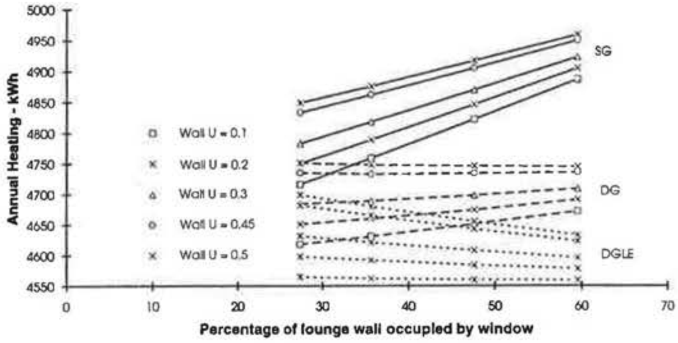

Figure 9 Variation of annual auxiliary heating energy with different proportions of window in East facing living room wall

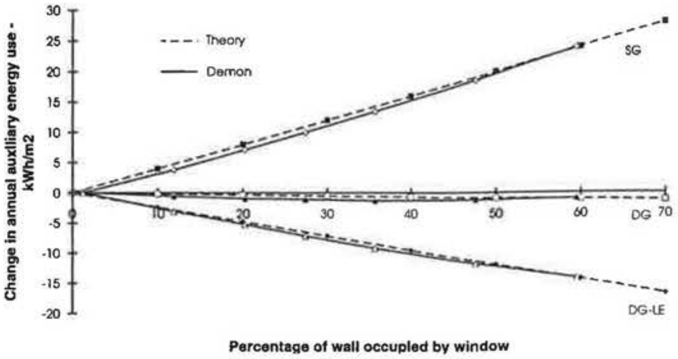

Figure 11 Comparison of theoretical results with those from DEMON runs for an East facing wall having a *U*-value of 0.45 W m^{-2}K^{-1}

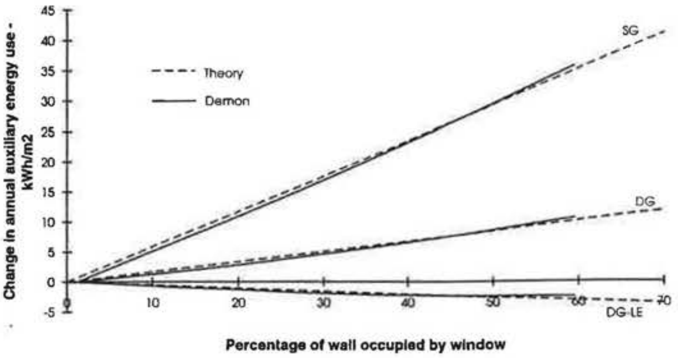

Figure 12 Comparison of theoretical results with those from DEMON runs for an East facing wall having a *U*-value of 0.1 W m^{-2}K^{-1}

ally decrease energy use depending on the wall *U*-value. For comparison with the theoretical values in Figure 8 the figures from columns 8, 9 and 10 of Table 4 were each divided by the lounge facade area, 8.4m^2, to give the change in annual auxiliary heating in kilowatt hours per square metre of facade and plotted in Figure 10. It should be noted here that whereas the theoretical figures were based on a 212 day heating season the values in Figure 10 are the annual figures obtained from the DEMON runs which do not apply to a fixed heating season.

For comparison purposes the combination of Figures 8 and 10 is presented in Figure 11; Figure 12 shows the results of a check to show the influence of a wall *U*-value of 0.1 W m^{-2}K^{-1}.

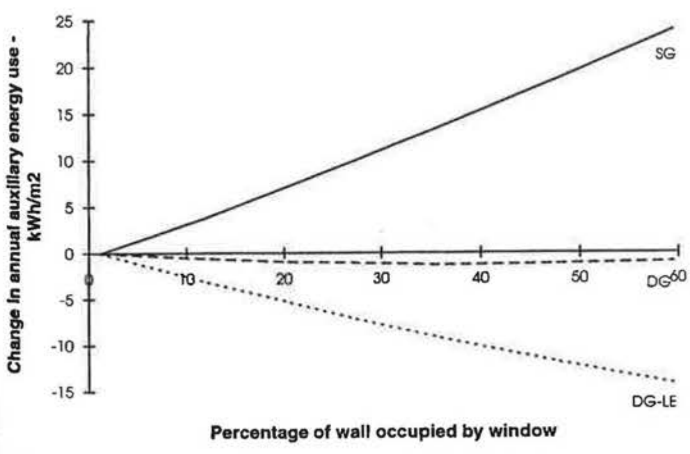

Figure 10 Change in auxiliary energy per m^2 of East facing facade for a wall *U*-value of 0.45 W m-2K from DEMON runs (—— single glazed; — — — double glazed;- - - - double glazed-low emissivity)

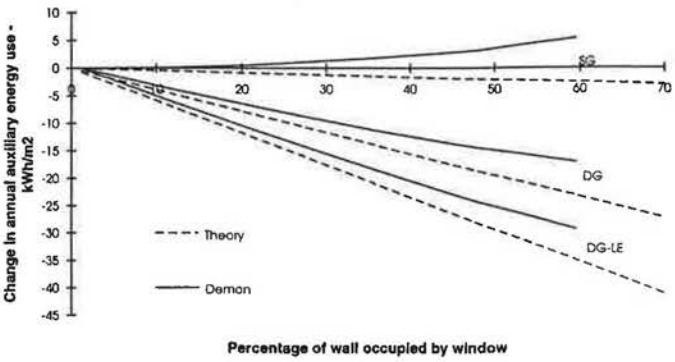

Figure 13 Comparison of theoretical results with those from DEMON runs for a South-East facing wall having a *U*-value of 0.45 W m^{-2}K^{-1}

6 Discussion of results

The results in Figure 11 for the East facing facade show very good correspondence between the theory and DEMON both with respect to their trend as well as the actual values. Only

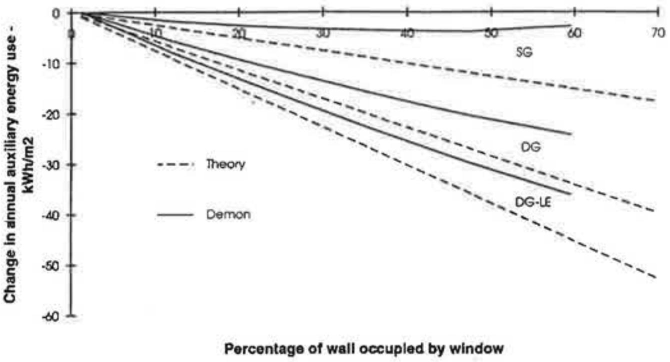

Figure 14 Comparison of theoretical results with those from DEMON runs for a South facing facade having a U-value of 0.45 W $m^{-2}K^{-1}$

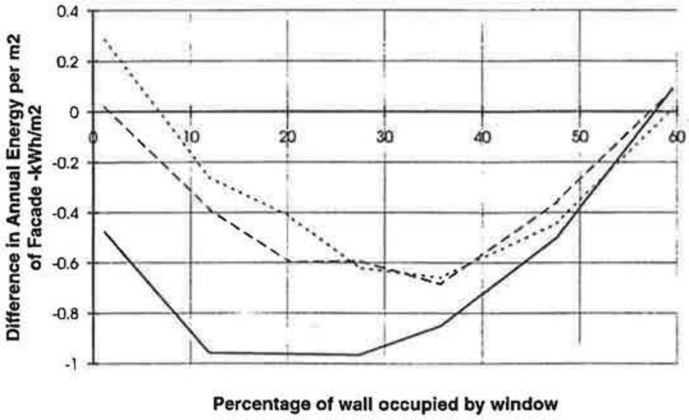

Figure 15 Annual energy differences for an East facing facade (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

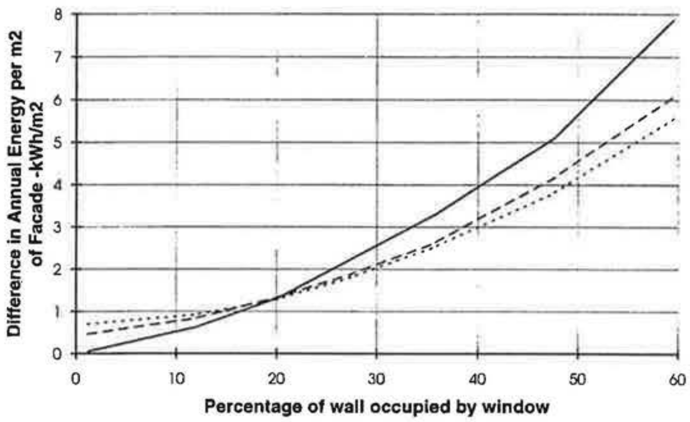

Figure 16 Annual energy differences for a South East facing facade (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

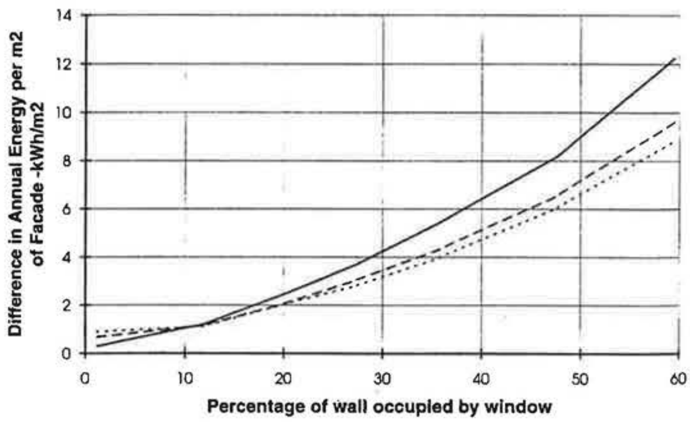

Figure 17 Annual energy differences for a South facing facade (—— single glazed; — — — double glazed; - - - - double glazed-low emissivity)

the single glazing case shows an increase in energy use with increasing window area confirming the prediction from Figure 7 where this is the only case having the mean house seasonal temperature difference above the critical value. Changing the wall U-value to 0.1 W $m^{-2}K^{-1}$ (Figure 12) shows that only the double glazing low-E case gives an advantage, again as predicted from Figure 7.

Considering the South East facing facade, Figure 13, the theoretical values are all optimistic compared with the values derived from DEMON. The most likely reasons for the differences are:

- that the simple theory assumes that all solar gains are useful, which is not the case for DEMON
- that the simple theory uses a fixed heating season of 212 days and
- that during the DEMON runs slight changes in mean internal temperature would have taken place which would in turn have produced small changes in the ventilation losses.

However, with the exception of the single glazing case, the simple theory predicts the same trend as DEMON although the values diverge. The differences are however small. For a 60% glazing area, in both the double and double low-E cases, the difference between theory and DEMON is only 6 kWh m-2 of facade, i.e. for a 10 m^2 facade only some 60 kWh for the heating season which is almost negligible when compared with a total heating requirement of the order of 4800 kWh, i.e. about 1.25%. The differences reduce for lower percentages of glazing.

In the single glazing case the simple theory indicates a small saving whilst DEMON shows an energy increase; again the difference is small in annual energy terms but the trends are in opposite directions. One could argue however that for new buildings one could ignore single glazing since it is unlikely to be used. If however one were considering a house refurbishment and replacing single glazing with double glazing, or double low-E, the calculated advantage in energy saving would be about the same whether one used DEMON or the simple theory. For the South facing situation the trend is the same for all glazing types indicating that savings can be made but similar differences exist between the simple theory and DEMON results as for the South East case. Figures 15, 16 and 17 show the differences between the simple theory and Demon for each orientation; Figure 18 shows the results of a check for a south facing facade with continuous heating.

All the DEMON comparisons were made for a three person house with a continuous ventilation rate of one air change per hour. If, however, a four person house had been chosen then one would have expected incidental gains to have been higher which would have tended to raise the mean internal temperature. The four-bedroom house however would probably have had a higher infiltration loss which would have tended to reduce the mean internal temperature.

To test this a check was made for a south facing continuously heated house firstly using a ventilation rate of 1.5 air changes per hour, which resulted in a mean house temperature differ-

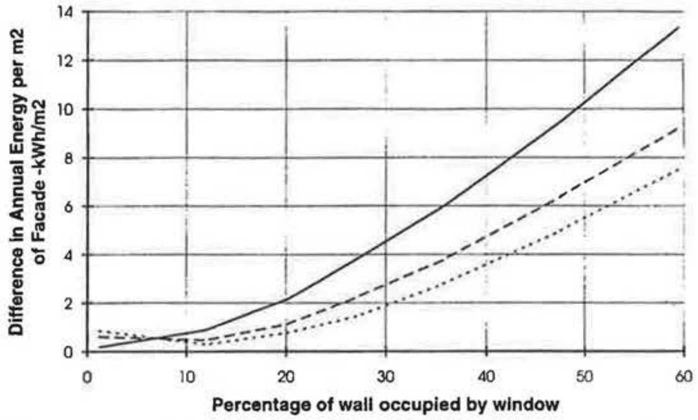

Figure 18 Annual energy differences for a South facing facade with continuous heating from 0700 to 2300 (—— single glazed; — — — double glazed;- - - - double glazed-low emissivity)

ence of 10.98K and then, with the same air change rate, the number of occupants was increased to four, which gave a mean house temperature difference of 11.03K. This compares well with the three person continuously heated case of 11.18K.

7 Conclusions

For the intermittently heated three-person house, for which comparisons were made, the results give very good agreement between the simple theory and DEMON. A check carried out for a continuously heated South facing four person house gave similar results to the three person case. The simple theory enables a designer to decide whether, for a particular window type and wall *U*-value, an increase in window area is beneficial or not. It also enables an estimate of energy savings or losses to be made which in turn may lead to an evaluation of the cost effectiveness of varying the proportion of window in the facade. The results from the single glazed cases generally resulted in the biggest differences between the simple theory and DEMON but can be discounted for new housing and refurbishments. Results from the double glazed and double glazed low emissivity cases gave good agreement, the differences between them being small. It is suggested that designers use the *U*-values and solar transmission values provided in Table 1 with adjustments, if necessary, to take into account known shading situations.

The selection of an appropriate actual mean house temperature difference over the heating season may be made by reference to the *Domestic Energy Fact File*[5], to obtain the mean house temperature. The value of 16.69°C, taken in combination with a mean outside temperature during the heating season for the South East of England of 6.2°C results in a temperature difference of 10.49 K which compares well with that of 10.50 K used for the comparisons. Different temperature differences may thus be obtained for different areas of the country. The temperatures tabulated in the *Domestic Energy Fact File* are for a range of years up to 1989 and temperatures are now likely to have increased. From field tests of the performance of ten well insulated passive solar houses, carried out by others as part of the Energy Performance Assessments (EPA)[6] project initiated by ETSU, the house mean temperatures during the heating season ranged from 17.6°C to 21.8°C giving an overall average of 19.4°C.

Temperatures are whole-house means whereas living room temperatures are likely to be about one or two degrees higher. If considering a living room facade therefore one should make an appropriate adjustment. This temperature is probably more indicative of that achieved in new designs. It is considered that the approach used may be useful to designers in the early stages of a building design to enable them to make initial decisions on window sizing and in the selection of windows for refurbishment projects. It enables one to estimate the average performance of the facade as a whole over typical seasonal conditions since one cannot consider window performance in isolation, the wall performance must also be taken into account. The approach does not however attempt to give guidance on the likelihood of the occurrence of overheating.

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