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Summary Space heating requirements in thermally lightweight temporary school buildings with between 25 mm and 60 mm thermal insulation have been estimated using a simplified dynamic thermal response model. The results suggest that, compared with thermally heavyweight school buildings, lightweight temporary classrooms, even down to 25 mm insulation thickness, should be operable in a reasonably energy-efficient manner under the highly intermittent school occupation pattern. This is because lightweight construction confers a generic advantage for space heating provision under intermittent occupancy. However, this advantage will not be realised unless care is taken about heating plant control (start-up times, occupation and frost protection setpoint temperatures) and the ventilation regime. The penalties for poor performance in these areas are quantified in a practical fashion.

Thermal response of temporary school buildings: I Heating

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1 Introduction

This paper gives the results of a study of space heating requirements in temporary classrooms. It is Paper I of a pair, Paper II(1) of which discusses summertime overheating. The work was undertaken for the South-West Energy Group at the request of Cornwall County Council. Cornwall is particularly interested in Elliott–Medway Buildings (EMB), and this is the type of building which has been considered. The results may of course be relevant to other types.

Cornwall provided drawings and structural details of the EMB used by the Authority since the early seventies(2). There are various configurations built up from units of wooden frame construction. The earliest buildings considered have about 25 mm insulation to roof, floor and walls. More recent types have 50 or 60 mm insulation. Using mathematical modelling, the present study investigates space heating requirements of these buildings operated under a school occupancy pattern.

The buildings are lightweight and so have short warm-up times. This is potentially advantageous for space heating provision under the highly intermittent school occupation pattern. However, to realise the advantage care must be taken about heating control (start-up times, frost protection and occupation temperature settings) as well as the ventilation regime. These considerations are quantified in a practical fashion which, it is hoped, will assist in the energy-efficient operation of this type of school building.

2 Methodology and modelling assumptions

The Exeter University Energy Studies Unit (EXCALIBUR) software was used to model the thermal response of the EMB. EXCALIBUR is a microcomputer-based dynamic thermal response model which performs an hour-by-hour simulation taking into account conductive and ventilation heat losses (the latter separately definable for occupied and non-occupied periods), heat storage effects, metabolic, solar, and electrical casual gains. EXCALIBUR is a simplified model which provides significant savings in computing overheads. A more detailed description is available in the literature(3). Some modification of EXCALIBUR was required for the EMB study; most importantly, because of the relatively low levels of thermal insulation in the older EMB, it was felt necessary to include allowance based on the sol-air temperature approximation for direct solar gains through the opaque fabric of the building.

An EMB configuration designated CCC 693M was chosen as representative for the thermal modelling work. The building is described in Table 1. The steady-state heat loss coefficient naturally varies with the level of insulation and the ventilation rate. Relevant values are given in Table 2. The heat loss of coefficients given in Table 2 are for reference and are not used as such in EXCALIBUR, which is a dynamic model taking transient heat flows into account.

In Table 2, the lower ventilation rate (1 ac h^{-1}) is thought to be representative of the building with windows and doors closed. It was estimated using the *CIBSE Guide* procedure based on the length of openable window joints(4). The higher

Table 1 Summary of EMB Type CCC 693M

Structural element	Area (m^2)	Details (thicknesses in mm, constructions given from the outside in).
Roof	131	Stone chippings (13); bitu. felt (2 layers); extl. ply (9); air gap; insul. (25, 50 or 60); plasterboard (9). Insul. bridged by timber over ~10% of roof area.
Floor	131	Hardboard (3); insul. (25, 50 or 60); chipboard (19). Insul. bridged by timber over ~10% floor area.
Walls	103 (net of openings)	Extl. ply (9); air gap (if insul. 25); insul. (25, 50 or 60); plasterboard (13). Insul. bridged by timber over ~25% net wall area.
Internal partitions	49	Plasterboard (9); air gap; plasterboard (9). Timber bridge over ~10% of area.
Openings	24	Windows, doors. Glazed area 7.5 m^2 (front of bldg.), 7.3 m^2 (back).
Volume	315 m^3	Bldg. is 16.2 m × 8.1 m by about 2.4 m high inside.

Table 2

Insulation thickness (mm)	Ventilation rate (ac h^{-1})	Heat loss	
		kW K^{-1}	W K^{-1} per unit floor area
25	1	0.636	4.85
25	5.7	1.124	8.58
50	1	0.504	3.85
50	5.7	0.992	7.57
60	1	0.471	3.60
60	5.7	0.959	7.32

ventilation rate (5.7 ac h^{-1}) is based on a maximum estimated occupancy of 60 in an EMB type CCC 693M, and the fresh air supply rate of 30 m^3 $person^{-1}$ h^{-1} recommended by the UK Department of Education and Science (DES) as a level which should be attainable in working areas in schools(5).

EXCALIBUR requires a range of information in addition to the ventilation rate, and the basically geometrical data summarised in Table 1. These inputs to the model are outlined in Table 3.

Besides these inputs, the model needs numerical data on the physical properties of the building materials. The values used were mostly taken from the *CIBSE Guide*(6) and are shown in the Appendix.

Depending on the density of occupation there seem to be two limits to the way which an EMB might be used. If a building were being heated for a few occupants only, the closed-down ventilation rate of about 1 ac h^{-1} should meet fresh air requirements and might be assumed to apply both during and outside occupied periods in the heating season. In the limiting case (which will be called occupation case A) the building would be heated and lit during working hours for no occupants at all.

On the other hand the number of occupants might approach the assumed maximum of 60 during working hours. In this limit (to be called occupation case B), ventilation would be increased to an assumed 5.7 ac h^{-1} during occupied hours, but would probably be reduced to 1 ac h^{-1} outside occupation, since the building would be shut up when empty. Warm-up before occupation would be at 1 ac h^{-1}.

At first sight it seems that the space heating energy consumption should be considerably greater in occupation case

Table 3 Basic modelling assumptions

Item	Assumption/Relevance
Heating plant	Maximum output 25 kW, assumed seasonal efficiency 0.7 (EMB type CCC 693M has three heaters, commonly gas, rated output 21 800 Btu h^{-1} or 31 600 Btu h^{-1}. Two larger and one smaller heater are assumed.
Frost protection	5°C minimum internal temperature.
Control	Optimum start control to bring building to temperature just before occupation. (In practice the heating plant is likely to be under manual control, but for modelling some standardised assumption is necessary).
Occupancy	5-day, 0900–1600; BST or GMT as appropriate.
Vacations	Autumn half-term 27 Oct–4 Nov Christmas 15 Dec–6 Jan Spring half-term 23 Feb–3 March Easter 8 Apr–21 Apr
Heating season	1 Oct–30 Apr
Meteorological data	Hourly values of screen temperature, direct and diffuse radiation as measured at Kew observatory, 1965/66 season. 1 Jan in first year assumed to be Monday.
Occupation target temp.	18°C
Lighting gains	8.2 W m^{-2} of floor, ON whenever estimated working plane illumination less than 250 lux.
Metabolic gains	90 W $person^{-1}$.
Number of occupants	0 or 60 maximum.
Colour of external walls	Grey; short wave absorptivity 0.8. This is relevant to calculation of mean effective sol-air temperature.
Orientation	Front facing 45°E of S. Glazing about equally divided between front and back of building (see Table 1). This orientation, meant to be about average with respect to solar gains, was used for the heating requirement calculations and was changed for consideration of overheating (see Paper II).

B, because of the much higher ventilation rate. Working against the assumption is the metabolic gain, assumed zero in occupation case A, but averaging about 4.2 kW during school hours in case B. Maximum occupancy of 60 and metabolic gains assumed to be about 90 W person^{-1} suggests peak metabolic casual gain of 5.4 kW, but this has been cut by about 20% for the average during school hours because of reduced occupancy during break periods.

Most practical cases might be assumed to lie between these two limiting cases, which will be used as the basis for the modelling work reported below.

3 Results

Results of EXCALIBUR runs for different insulation levels are shown in Table 4.

At a given level of insulation, Table 4 shows that the estimated case A and case B space heating requirements are remarkably close. This means that the much higher ventilation rate (during occupied hours) in case B is almost exactly compensated by the increased metabolic gain. This leads to the surprisingly firm conclusion that, provided window opening does not produce ventilation rates in excess of the DES figure of 30 $\text{m}^3\ \text{person}^{-1}\ \text{h}^{-1}$, the space heating requirements of an EMB should not much exceed the values shown in Table 5. Of course this assumes the building conforms reasonably well to the modelling assumptions outlined above.

Besides the three basic insulation thicknesses found in the EMB stock under consideration, Tables 4 and 5 also show the estimated space heating requirement of an EMB with 25 mm of thermal insulation, if an additional 50 mm were added externally to the roof and floor. This has been suggested as a possible cost effective retrofit(2). The estimated energy saving is about 13 kWh m^{-2} of floor area per year, roughly 14% of gross space heating energy requirement (Table 5) of an EMB insulated to 25 mm.

Table 5 Calculated average seasonal space heating requirements for EMB based on Kew meteorological data; see Table 3. (See text for assumptions.)

Insulation level (mm)	Energy/Unit floor Area†	
	Net ($\text{kWh m}^{-2}\ \text{y}^{-1}$)	Gross ($\text{kWh m}^{-2}\ \text{y}^{-1}$)
25	66	95
50	56	81
60	54	77
25 + 50	57	82

† Net figures are heat output to the occupied space. Gross figures are energy supplied to the heating plant (assumed seasonal efficiency 0.7).

4 Discussion

At the 25 mm insulation level the U-value of the opaque structure averages about 1.1 $\text{W m}^{-2}\ \text{K}^{-1}$. This is high in modern terms, yet the energy required per unit floor area for space heating given in Table 5 is low in comparison with the Audit Commission's Normalised Performance Indicator (NPI) which for ordinary schools without swimming pools is 180 or 190 $\text{kWh m}^{-2}\ \text{y}^{-1}$(7). Of course the NPI includes all energy inputs, not just space heating, but the latter may be expected to account for say 80% of the total. The comparison therefore suggests that in principle at least even the poorly insulated EMB should be operable in a reasonably energy efficient manner. The low thermal mass of the EMB will reduce energy consumption under intermittent occupation, and this is of course a likely reason for its potential energy efficiency.

This is not to say that the EMB will necessarily be energy efficient in practice. Heaters might be turned on unnecess-

Table 4 Seasonal space heating results

Insulation level (mm)	Ventilation during occupation (ac h^{-1})	Occupation case	Frost protection energy (kWh y^{-1})	Warm-up energy (kWh y^{-1})	Energy to maintain occupation temperature (kWh y^{-1})	Total energy to occupied space		Supplied energy to heating plant	
						(kWh y^{-1})	($\text{kWh m}^{-2}\ \text{y}^{-1}$)	(kWh y^{-1})	($\text{kWh m}^{-2}\ \text{y}^{-1}$)
a	b	c	d	e	f	g	h	i	j
25	1.0	A	2086	2669	3515	8271	63.1	11816	90.2
25	5.7	B	2078	2644	3952	8675	66.2	12393	94.6
50	1.0	A	1551	2573	2861	6985	53.3	9978	76.2
50	5.7	B	1550	2553	3289	7392	56.4	10560	80.6
60	1.0	A	1447	2493	2702	6642	50.7	9488	72.4
60	5.7	B	1444	2452	3140	7036	53.7	10051	76.7
25 + 50	1.0	A	1567	2626	2879	7072	54.0	10103	77.1
25 + 50	5.7	B	1563	2608	3318	7489	57.2	10699	81.7

Notes

Col a	Insulation thicknesses generally apply to roof, walls and floor. 25 + 50 results are for an extra 50 mm of insulation applied externally to roof and floor of a building otherwise insulated to 25 mm.
Col b	Ventilation is assumed to be 1.0 ac h^{-1} in all cases outside the hours of occupation.
Col c	Cases A and B are respectively minimum and maximum number of occupants during working hours, as explained in the text.
Cols d & e	Frost protection and warm-up are assumed to be at 1.0 ac h^{-1} in all cases.
Col f	—
Col g	Figures summed from data in cols d, e and f.
Col h	Col g figures divided by floor area (131 m^2).
Cols i & j	Cols g and h divided by 0.7 to allow for plant efficiency (See Table 3).

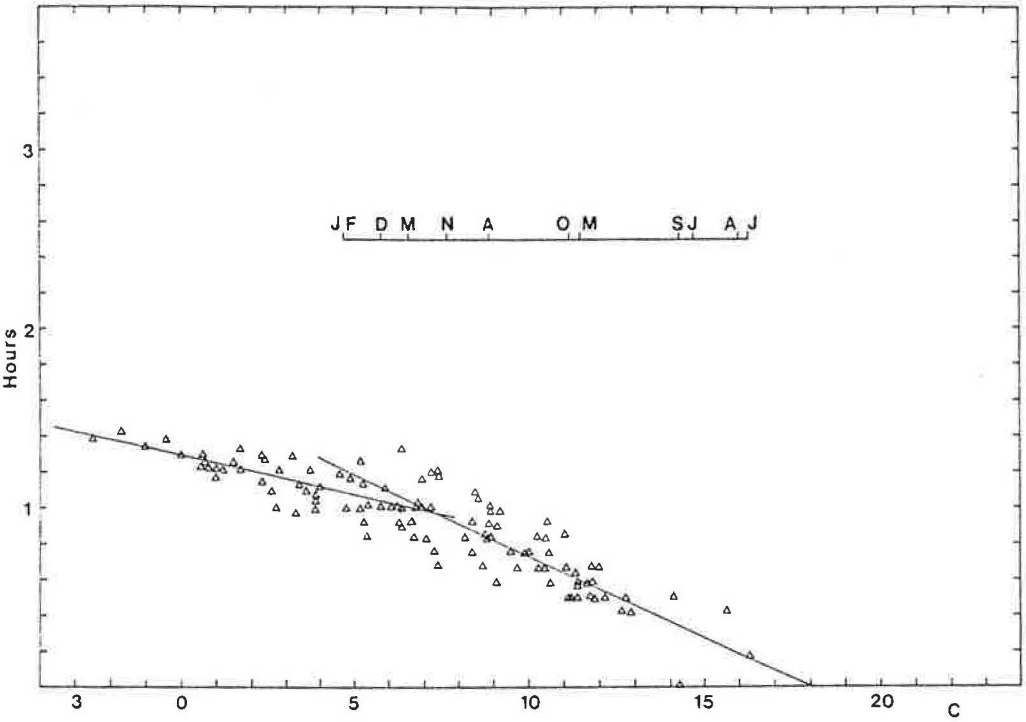

Figure 1 Estimated warm-up time in hours (vertical axis) for an EMB insulated to 25 mm against daily mean outside temperature in degrees Celsius (horizontal axis). An EMB insulated to 60 mm would have about 6% shorter warm-up time for given outside temperature. Monthly mean of daily temperatures at Exeter are shown on the horizontal scale for illustrative purposes.

arily early. A closed-up ventilation rate of 1 ac h^{-1} might not be achievable. Windows might be opened wide at low occupancy, producing a ventilation heat load not compensated for by metabolic gains. The buildings might be operated with a thermostat setting in excess of 18°C. The frost protection temperature might be set too high. These possibilities will be quantified, and the role of thermal mass in reducing energy consumption examined.

4.1 Effect of switch-on time

We have assumed optimum start control (Table 1), which in practice is unlikely to be implemented in temporary classrooms. However, unless the start-up time is set much too early, it appears that sub-optimal control is unlikely to have a very serious effect on energy consumption.

To a first approximation we can assume that the frost protection and warm-up energies are unaffected by changes in the start time. The main effect will be felt in the energy to maintain occupation temperature. Under case A conditions, this is say 3100 ± 400 kWh y^{-1} supplied to the occupied space (Table 4 col. f). We have been assuming a 7 h working day. If the heating plant is switched on one hour early the additional energy requirement will be about one-seventh of 3100 ± 400, say 450 ± 60 kWh y^{-1}, or about 3.5 ± 0.5 kWh m^{-2} of floor. Dividing by 0.7 the seasonal efficiency assumed appropriate to balanced flue gas heaters$^{(8)}$, we arrive at a gross additional annual energy requirement of 5 ± 0.7 kWh m^{-2} of floor. This is less than 10% perturbation on the figures in Table 5.

Figure 1 shows the relationship found by EXCALIBUR between warm-up time and 24 h mean outside temperature for an EMB with 25 mm insulation. The data are reasonably represented by two lines intersecting at about 5°C, the frost protection set-point temperature. Energy supplied for frost protection will reduce warm-up time, which is the reason for the change of slope at about 5°C. The tendency to increased scatter in warm-up times at higher external temperature is probably due to uncertainties introduced by the greater influence of solar gain on warm-up away from the coldest months.

Warm-up times will of course be influenced by the maximum power of the heating plant and the closed down ventilation rate and many other factors besides the level of insulation and the frost point set temperature. However to the extent that EMB and other lightweight school buildings are similar, the information in Figure 1 could, in the absence of an optimum start controller, be put to practical use for estimating the time for manual heating plant switch-on from local meteorological conditions. Monthly mean temperatures for Exeter are shown on the figure. Warm-up times for EMB with 60 mm thermal insulation are estimated to be about 6% shorter, for given outside temperatures, than those shown in Figure 1.

4.2 Effects of ventilation rate

It seems likely that the EMB will be closed down outside occupation, but the assumption that the ventilation rate is then 1.0 ac h^{-1}, though not unreasonable, may be questioned.

The effect of a higher basal (closed down) ventilation rate has been explored by reworking two examples (25 mm and 60 mm thermal insulation) from Table 4, under the assumption that ventilation cannot be reduced below 2.0 ac h^{-1}. The results are shown in the first four entries of Table 6.

The percentage increase in energy consumption varies from 7 to about 20% and, as would be expected, is greater for case A, minimum assumed occupancy during working hours. The estimated energy increase is almost independent of the level of thermal insulation in the EMB and per year is about 6 kWh m^{-2} of floor (case A) and 15 kWh m^{-2} (case B, maximum occupancy during working hours). Viewed conversely, these would be the expected savings from remedial measures to reduce basal ventilation rate in an EMB from 2.0 to 1.0 ac h^{-1}.

Table 6 Effect of varying ventilation rate assumptions

Insulation level (mm)	Ventilation (ac h^{-1})		Occupation case	Gross energy consumption ($kWh\ m^{-2}\ y^{-1}$)	Increase over Table 4 values	
	Outside occupation	During occupation			Percentage	($kWh\ m^{-2}\ y^{-1}$)
a	b	c	d	e	f	g
25	2.0	2.0	A	105	16	15.0
25	2.0	5.7	B	101	7	6.4
60	2.0	2.0	A	87.5	21	15.0
60	2.0	5.7	B	83.6	9	6.9
25	1.0	5.7	A	127	41	37.0
60	1.0	5.7	A	108	49	36.0

Notes

Col e This is the fuel supplied to the heating plant (kWh per m^2 of floor area).

Col f This is the difference between the Col e figure and the appropriate entry in Table 4, Col j expressed as a percentage of the latter.

Col g As Col f except that the absolute increase is shown.

As indicated in section 2, average metabolic gains have been reduced in recognition of the likelihood that occupancy but not ventilation rate will fall during break periods. There is also the possibility of windows being opened wide during classes even if occupancy is low. In the limit case A occupation might be combined with the ventilation regime assumed for case B. Of course this would be ventilation far in excess of the DES recommendation. Nevertheless, using the model it is estimated that space heating requirements would increase by about 36 $kWh\ m^{-2}\ y^{-1}$ or between 40 and 50% of the space heating that would be required under case A if daytime ventilation remained at 1 ac h^{-1}. These results are shown as the two remaining entries in Table 6.

4.3 *Effect of occupation target temperature*

School buildings may sometimes be heated with thermostat settings higher than the 18°C recommended temperature.

The effect of 20°C occupation temperatures is shown in Table 7, based again on a reworking of the 25 mm and 60 mm cases from Table 4. The increase in gross energy consumption is about 20% (case A values) and 25% (case B values), with absolute increases in the range 14 to 22 $kWh\ m^{-2}\ y^{-1}$. These are also the expected savings consequent on controlling the temperature to 18 rather than 20°C.

4.4 *Effect of frost protection temperature*

Using the same illustrative cases as Tables 6 and 7, Table 8 shows the effect of assuming frost protection temperatures set at 10°C, rather than 5°C as in Table 4. Table 8 also shows what happens to gross space heating energy consumption if there is no provision for frost protection.

Table 8 shows that setting frost protection at 10 rather than 5°C results in a rise of calculated energy consumption of between 50 and 65% for the types of EMB considered. If on the other hand there is no frost protection, gross space heating energy consumption falls by between 15 and 20% from the 5°C value.

This sensitivity is due to the lightweight structure of the EMB, which allows the internal temperature to fall much more rapidly than in a conventional building. Frost protection will therefore be needed more often. The rapid decay of internal temperature has its counterpart in short warm-up times, which of course reduce energy consumption of the EMB under intermittent occupation. However, it is clear that to realise this advantage the frost protection temperature must be set as low as is reasonable, and be carefully controlled.

A practical recommendation would be to check the thermostats and frost protection settings in lightweight school buildings. It may be worth investing in more accurate thermostats. From the energy point of view, in lightweight school buildings, accurate setting and control of the frost protection temperature may be more important than accurate setting and control of the occupation target temperature. Obviously frost protection should not be used where it is not needed.

Table 7 Effect of increasing occupation target temperature from 18 to 20°C

Insulation level (mm)	Occupation case	Gross energy consumption ($kWh\ m^{-2}\ y^{-1}$)	Increase over Table 4 values	
			Percentage	($kWh\ m^{-2}\ y^{-1}$)
a	b	c	d	e
25	A	107	19	17
25	B	117	24	22
60	A	86	19	14
60	B	96	25	19

Notes

Col c See Table 6, note to Col e

Cols d & e See Table 6, notes to Cols f and g respectively.

Table 8 Effect of varying frost protection assumptions

Insulation level (mm)	Occupation case	With frost protection at 10°C			Without frost protection		
		Gross energy consumption	Difference from Table 4 values		Gross energy consumption	Difference from Table 4 values	
			Percentage	(kWh m^{-2} y^{-1})		Percentage	(kWh m^{-2} y^{-1})
a	b	c	d	e	f	g	h
25	A	150	66	60	73	−20	−18
25	B	154	63	59	77	−19	−18
60	A	112	55	40	62	−15	−11
60	B	116	51	39	66	−14	−11

Notes

Cols c and f	See note to Table 6, Col e.
Cols d and g	See note to Table 6, Col f.
Cols e and h	See note to Table 6, Col g.

Table 8 suggests that, compared with a building without frost protection, an EMB with frost protection set at 10°C (admittedly rather high) may show 100% increase in space heating consumption when operated under a school occupation pattern.

4.5 The role of low thermal mass

The previous section mentioned the advantage of thermally lightweight construction for buildings, such as schools, with highly intermittent occupation. Low thermal mass is easier to heat up and carries less heat over into the unoccupied periods.

To study the effect of thermal mass on space heating requirements, a fictitious heavyweight alternative building (FAB) was specified. The structural elements of this building had areas like those of EMB CCC 693M but the floor, internal partitions and inner leaf of the external wall were changed to be thermally heavyweight. This was done by assuming the plasterboard inner leaf and internal partitions of the EMB replaced by 100 mm heavyweight blockwork finished with 13 mm lightweight plaster. The EMB suspended floor was replaced by an edge insulated 200 mm concrete slab. The resultant steady-state heat loss coefficient for the FAB insulated to 25 or 60 mm is slightly less than that for the comparable EMB (Table 9).

Table 9 EMB vs FAB steady-state heat loss comparison

Insulation thickness (mm)	Ventilation rate (ac h^{-1})	Heat loss (kW K^{-1})	
		EMB	FAB
25	1	0.636	0.529
25	5.7	1.124	1.017
60	1	0.471	0.427
60	5.7	0.959	0.915

Despite the more favourable steady-state index, the EXCALIBUR simulations undertaken for the FAB indicate that under the intermittent occupancy pattern described in Table 3 the heavyweight alternative uses considerably more energy for the same occupation target temperature of 18°C. EXCALIBUR results for the FAB are compared with EMB results in Table 10.

Table 10 Comparison between fictitious (heavyweight) alternative building and EMB

Insulation level	Case	Gross energy consumption (kWh $m^{-2}y^{-1}$)	Difference from Table 4 values	
			Percentage	kWh m^{-2} y^{-1}
a	b	c	d	e
25	A	143	59	53
25	B	138	46	43
60	A	112	55	40
60	B	110	43	33

Notes
As for Table 7.

It seems from Table 10 that, despite the lower steady-state loss, heat storage effects associated with the greater thermal mass of the FAB produce space heating requirements between 45 and 60% greater than that of the comparable EMB for meeting the same occupation pattern, frost protection and occupation target temperature. The reason for this has already been mentioned: thermal mass absorbs heat during the day and then loses all or part of it during the unoccupied period. Thermally lightweight buildings are therefore likely to be more energy efficient than heavyweight for *intermittent* occupation, even if the steady-state design heat loss is the same. Under *continuous* occupation at constant temperatures thermal mass makes no difference to space heating requirements.

4.6 Comparison with other results

There are therefore three main reasons why at 80 to 95 kWh m^{-2} the annual gross space heating requirements for the EMB (Table 5) are calculated to be so much lower than the Audit Commission's NPI of between 180 and 190 kWh m^{-2} for schools without indoor swimming pools.

Firstly, as already mentioned, NPI includes all energy uses in the school (space heating plus lighting; other electrical power, DHW and cooking). The present calculations are only for classroom space heating.

Secondly, the calculations assume that the heating plant is well controlled (both for start-up times and occupation and frost protection set temperatures), and that the EMB do not have excessive ventilation rates during unoccupied periods, or when occupation is low. The percentage increases in space heating requirement identified with less favourable assumptions in 4.1 to 4.4 above could together easily be responsible for doubling the calculated space heating requirement. This is not to say that the original assumptions were unattainable in practice, only that realistic departures from them could produce a large effect.

Thirdly, for intermittent heating applications the low thermal mass of the EMB gives them a generic advantage over the heavyweight construction which is more typical of school buildings.

The UK Department of Education and Science (DES) has also published figures which can be compared with the present results(9). The DES figure for space heating only in permanent school buildings is 45 GJ per 100 m^2 of floor per annum. This is the equivalent of 125 kWh m^{-2} per annum, which is within the range of the calculated FAB space heating requirements listed in Table 10. The DES figure is a calculation said to be for a mixture of pre- and post-1945 traditional (and so, presumably, relatively heavyweight) buildings.

The DES quotes 58.5 GJ/100 m^2 floor area as the annual space heating requirement for mobile or other post-1965 timber classrooms. This is equivalent to 162.5 kWh m^{-2} per annum, roughly twice the EMB figures quoted in Table 5. However, it appears from the DES tabulation that their calculations have taken no account of the fact that the lightweight construction of temporary accommodation should reduce energy consumption for space heating under intermittent occupation. The DES figures show the same ratio (3.75×10^6 s) between steady-state heat loss and net annual heating requirement for permanent (hence heavyweight) and mobile (hence lightweight) school buildings. This cannot be correct, because it implies that the intermittency correction factor is the same in both cases.

In fact, reasonable intermittency correction factors built up in the usual way from the *CIBSE Guide*(10) suggest that, other things being equal, a lightweight building with responsive plant under 5 day/week, 7 hour/day occupation would have a space heating requirement in the range 55 to 65% that of a heavyweight building with long time-lag plant similarly operated. A factor in this range suffices to reconcile the DES figures and Table 5 above.

Mention of plant response reminds us that the EMB calculations assume a responsive heating plant. The advantages of low structural mass for intermittently heated buildings will be compromised if the heating plant has a slow response—for example storage heaters, particularly if case losses are appreciable during the unoccupied period.

5 Conclusions

The main conclusion of this study is that lightweight school buildings need not be regarded as irredeemably energy inefficient, even down to relatively poor levels (25 mm) of thermal insulation.

This is because, under intermittent occupations, low structural thermal mass, so long as it is combined with responsive (lightweight) and well controlled heating plant, confers a considerable generic advantage over heavyweight buildings heated intermittently. This advantage has been quantified, and it is suggested that published DES estimates of space heating requirements in temporary classrooms do not take it properly into account.

The advantage will however only be realised if the buildings and plant are well maintained. This includes making some concession to optimum start control (e.g. by varying start-up time according to season as discussed above); ensuring that the basal ventilation rate is not excessive during unoccupied periods and that the buildings are not overventilated at low occupancy; correct setting of occupation target temperature and, perhaps even more important, frost protection temperature. Quantitative estimates are given of the penalties of poor performance in these areas.

Table 11 Assumed physical properties of structural materials

Material	Conductivity ($W\ m^{-1}\ K^{-1}$)	Density ($kg\ m^{-3}$)	Specific heat ($J\ kg^{-1}\ K^{-1}$)
Stone chippings	0.96	1800	1000
Bituminous felt	0.50	1700	1000
External ply	0.14	530	1200
Insulation	0.04	12	840
Plasterboard	0.16	950	840
Timber	0.14	650	1200
Chipboard	0.15	800	1200
Hardboard	0.13	880	1200
The following properties are for material assumed only in the FAB:			
Screed	0.41	1200	840
Cast concrete (floor)	1.13	2000	1000
Heavyweight block	1.63	2300	1000
Lightweight plaster	0.16	600	1000
Other relevant quantities			
U-value of external wall openings	5.6 $W\ m^{-2}\ K^{-1}$		
External film resistance	18 $W\ m^{-2}\ K^{-1}$		
Internal film resistance	8 $W\ m^{-2}\ K^{-1}$		

Although lightweight structure has an advantage so far as intermittent heating is concerned, it will also make a building more susceptible to summertime overheating. The likely extent of, and ameliorative measures for, this problem are discussed in Paper II(1).

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