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Measures used to lower building energy consumption and their cost effectiveness

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Abstract

This study uses the TRNSYS computer program, for the modelling and simulation of the energy flows of modern houses, to examine measures to reduce the thermal load. For the calculations, a typical meteorological year (TMY) and a typical model house are used. The measures examined are natural and controlled ventilation, solar shading, various types of glazing, orientation, shape of buildings, and thermal mass. In summer, ventilation leads to a maximum reduction of annual cooling load of 7.7% for maintaining the house at 25 °C. The effect depends on the construction type, with the better-insulated house saving a higher percentage. Window gains are an important factor and significant savings can result when extra measures are taken. The saving in annual cooling load, for a well-insulated house, may be as much as 24% when low-emissivity double glazing windows are used, which are recommended since the payback period is short (3.8 years). Overhangs may have a length over windows of 1.5 m. In this way, about 7% of the annual cooling load can be saved for a house constructed from single walls with no roof insulation. These savings are about 19% for a house constructed from walls and roof with 50 mm insulation. The shape of the building affects the thermal load. The results show that the elongated shape shows an increase in the annual heating load, which is between 8.2 and 26.7% depending on the construction type, compared with a square-shaped house. Referring to orientation, the best position for a symmetrical house is to face the four cardinal points and for an elongated house to have its long side facing south. In respect to thermal mass, the analysis shows that increasing the wall and roof masses and utilizing night ventilation is not enough to lower the house temperature to acceptable limits during summer. Also, the analysis shows that the roof is the most important structural element of the buildings in a hot environment. The roof must offer a discharge time of 6 h or more and have a thermal conductivity of less than 0.48 W/mK. The life-cycle cost analysis has shown that measures that increase the roof insulation, pay

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back in a short period of time, between 3.5 and 5 years. However, measures taken to increase wall insulation pay back in a long period of time, of about 10 years.

1. Introduction

An important measure for economy is to lower building energy requirements to a minimum. The main concern of engineers, however, is to evaluate the cost effectiveness of the various measures that may be applied.

The objective of this paper is to present an analysis of various measures used to lower building energy consumption and present their cost effectiveness. The measures examined are natural and controlled ventilation, solar shading, various types of glazing, orientation, shape of buildings, and thermal mass.

For the estimations carried out in this paper, a model house was considered, as illustrated in Fig. 1. The model house has a floor area of 196 m^2 and consists of four identical external walls, 14 m in length and 3 m in height, with a total window opening of 5.2 m^2 on each wall.

The window area is approximately equal to the area that a typical house would have, but instead of considering a number of windows on each wall, only one window is considered. Since the same model will be used in evaluating the load for various constructions, this simplification is not important but will assist in drawing conclusions since similar features are present on every wall. The model house is further divided into four identical zones and the partition walls are considered as walls separating the four zones. A flat roof is also considered in this study.

With reference to Table 1, which describes the various wall and roof construction types, the compared buildings are labelled as:

1. No roof insulation, which refers to a house constructed from single walls type D and a flat non-insulated roof type H.
2. 25 mm roof insulation, which refers to a house constructed from single walls type D and a flat insulated roof type I.
3. 50 mm roof insulation, which refers to a house constructed from single walls type D and a flat insulated roof type J.
4. 50 mm roof and wall insulation, which refers to a house constructed from double walls type F and a flat insulated roof type J.

In all the above constructions, partition walls type G are considered.

2. TRNSYS program overview

TRNSYS is a transient systems simulation program with a modular structure and is used in the present study for deriving the results. Each module contains a mathematical model for a system component. The TRNSYS engine calls the system

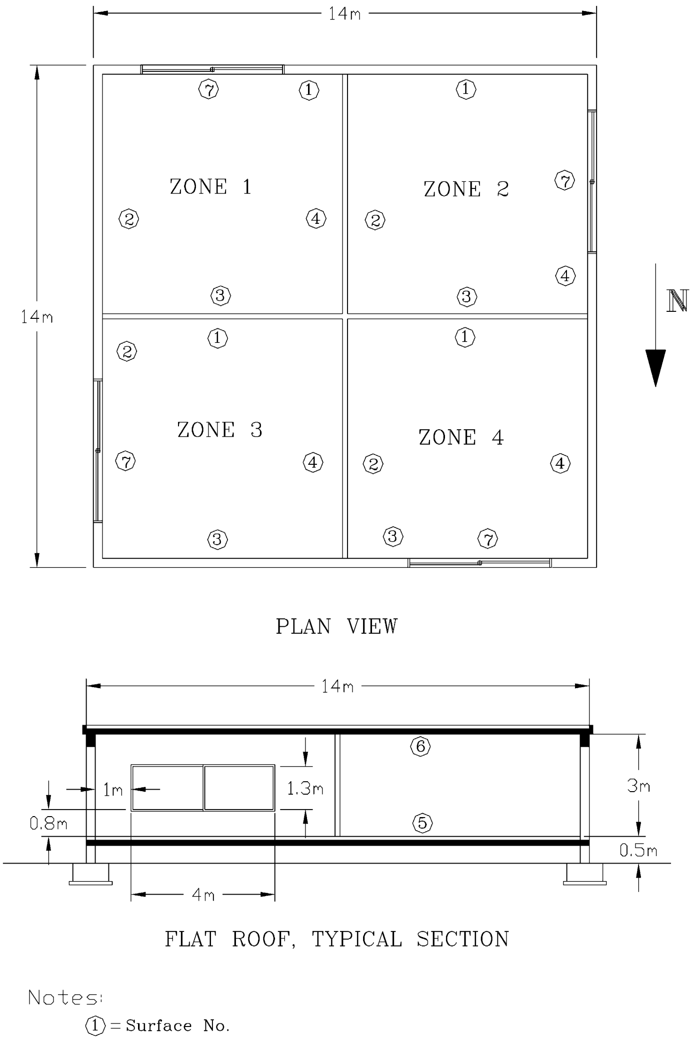

Fig. 1. Model house (Shape 1).

components based on the input file and iterates at each time-step until the system of equations is solved.

For the present study, TRNSYS Type 19 model is used to estimate the heating and cooling loads for a typical house. All heating and cooling loads arising from walls, windows, flat roofs and floors are calculated with Type 19 model, by utilizing the transfer function method [1].

This method simplifies calculations and can provide the instantaneous heat flux entering or leaving a zone through the various parts of the building. The TRNSYS type 19 model uses sol-air temperatures to represent outdoor conditions and assumes an equivalent zone temperature to represent the indoor conditions. Sol-air

Table 1
Overall heat-transfer coefficients of structural elements

Type	Structural element	Overall heat-transfer coefficient, U (W/m^2K)
D	Single wall, hollow brick 0.2 m and 0.02 m plaster on each side	0.886
F	Double-wall, 0.1 m hollow brick and 0.02 m plaster on each side and a layer of 0.05 m polystyrene insulation in between	0.389
G	Partition wall, constructed from 0.1 m hollow brick and 0.02 m plaster on each side	0.889
H	Flat non-insulated roof, constructed from fair-face 0.15 m heavy-weight concrete	1.91
I	Flat insulated roof, fair-face 0.15 m heavyweight concrete, 0.025 m polystyrene insulation, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	0.736
J	Flat insulated roof, fair-face 0.15 m heavy weight concrete, 0.05 m polystyrene insulation, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	0.481

temperature is defined as that temperature of the outdoor air, which in the absence of all radiation exchanges, would give the same heat transfer at the outside surface as actually occurs. The equivalent zone temperature is defined as the inside-air temperature, which in the absence of radiative exchange at the inside surface, gives the same heat transfer as actually occurs [1].

Transfer function coefficients (TFCs) are used in the transfer function method to describe the instantaneous heat flux. TFCs generally are referred to as response factors and depend on the physical properties of the wall or roof materials and on the scheme used for calculating them. These coefficients are response-time series, which relate a current variable to past values of itself and other variables in periods of 1 h.

Thus the instantaneous heat flux through a wall or roof is given by:

$$q_i = \sum_{h=0}^{M} b_{h,i} t_{sa,i,h} - \sum_{h=0}^{M} c_{h,i} t_{eq,i,h} - \sum_{h=1}^{M} d_{h,i} q_{i,h} \tag{1}$$

where: q = heat transfer rate per unit area at the inside surface of a wall or window; i = surface subscript; h = denotes the term of transfer function. 0 is the current hour, 1 is the previous hour, etc.; M = the number of non-zero TFC values; t_{sa} = sol-air temperature; t_{eq} = equivalent zone temperature; b = TFCs for current and previous sol-air temperature; c = TFCs for current and previous equivalent zone air temperature; d = TFCs for current and previous heat flux to the considered zone.

The b values of the TFCs refer to the current and previous flow of energy through the wall due to the outside conditions, the c values refer to the internal-space conditions and the d coefficients refer to the current and previous heat flux to the considered zone. An appropriate number of these coefficients is required until their value becomes negligible in the calculations.

The TFCs used by the TRNSYS program are included in a library of building structure components. Transfer function coefficients for non-standard components can be estimated using the routine PREP provided with the program.

The TRNSYS Type 19 model has two basic modes of operation, i.e. the energy rate and the temperature level control modes. In this study, the energy-rate control mode is selected, since with this mode the temperature of the building can be maintained between specified limits and the energy required to maintain the zone in the specified temperature is given as output along with the limit temperature. The zone humidity ratio is also allowed to float between a maximum and a minimum limit specified by the user and the humidification or dehumidification energy is considered. Additionally, heat may be added or removed either by the use of a ventilation flow stream or by an instantaneous heat-gain input. A controller is used in conjunction with this mode to control the heating or cooling equipment. Important parameters used in the calculations with TRNSYS Type 19 are shown in Florides et al. [2].

Weather data are needed to perform the simulations with TRNSYS. TRNSYS runs through hourly values of various weather parameters included in a typical meteorological year (TMY) file. The TMY for Nicosia, Cyprus, developed by Petrakis et al. [3], is used. This has been generated from hourly measurements, of solar irradiance (global and diffuse on horizontal surface, ambient temperature, humidity, wind speed and direction), for a 7-year period, from 1986 to 1992.

3. Results

This section describes results of the considered measures that can be applied to minimize the thermal loads.

3.1. *Effect of ventilation*

ASHRAE Standard 62.2 P, ventilation and acceptable indoor-air quality in low-rise residential buildings, specifies the minimum requirements for mechanical and natural ventilation in spaces intended for human occupancy within single-family houses and low-rise multifamily structures. This new Standard is intended to replace ASHRAE Standard 62-1989 because it contains more detail and is clearer on how to apply the ventilation rates [4]. For a model house of floor area of 196 m^2, assuming three bedrooms with four occupants, the required mechanical and or natural ventilation is about 0.31 air changes per hour (ach). This requirement, according to a study in the current stock of buildings in the USA, can be met through infiltration alone, since the buildings are quite leaky [4]. Also, according to Balaras [5], new buildings allow for 0.2–0.5 ach by infiltration, while with the windows wide open during summer, it is possible to achieve 15–20 ach. The equation used in the calculations for TRNSYS Type 19, when the TMY file is used, predicts infiltration rates during all hours of the day, in excess of the minimum ventilation requirements, with a mean yearly infiltration rate of 0.38 ach.

In this section, the effect of introducing naturally or mechanically ambient air into the space when the outdoor air is of a lower temperature than the indoor air during summer and vice-versa during winter, is investigated.

The simulations show that in winter, ventilation air will have a negligible effect in increasing the indoor temperature during periods when the outdoor temperature exceeds the indoor design temperature. This is because these periods are quite short. In summer, the effect of ventilation air when the outdoor temperature is less than the indoor temperature is shown in Fig. 2.

It can be seen that the higher the ventilation rate, the lower will be the indoor temperature for a non-air conditioned building. The effect of ventilation rate on the reduction of the maximum indoor-temperature for a building with no roof insulation is shown more clearly in Fig. 3. It can be seen that without ventilation the indoor temperature will reach 46 °C. With ventilation, this temperature will reduce by about 2 °C for one air change per hour, 3 °C for two air changes per hour and 7 °C for 11 air changes per hour. Fig. 3 also shows that ventilation will have a similar effect on a house with roof insulation. The level of roof insulation has no effect on ventilation effectiveness.

In summer, due to the thermal storage effect of the building envelope, there may be a requirement to extract heat from the building to maintain it between 21 and 25 °C, even in cases when the outside temperature is lower than the inside building temperature. Therefore a reduction of the annual cooling load may be obtained if the ventilation rate is increased mechanically, to take advantage of the lower temperature of the outside air. For this operation, low cost ventilation systems could be installed, independently of the air-conditioning unit, which will operate when the

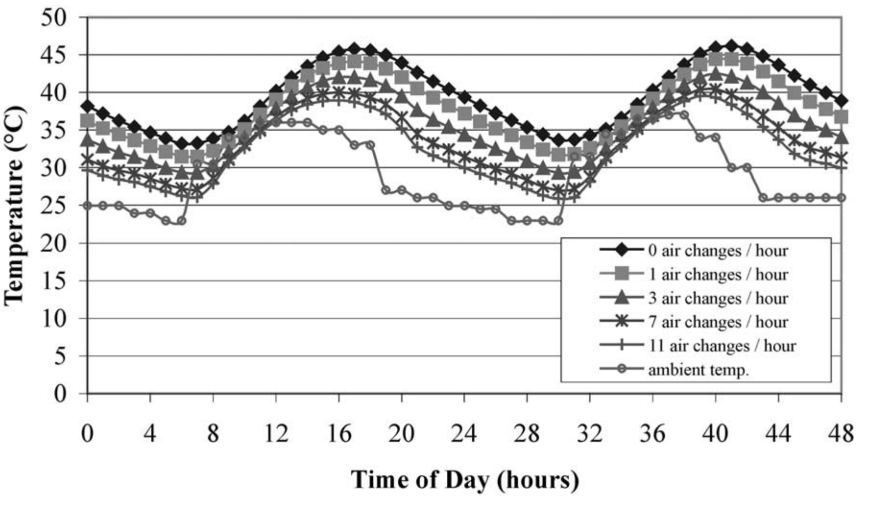

Fig. 2. Temperature variation of a typical house with no roof insulation, indicating the effect of ventilation during 16 and 17 July.

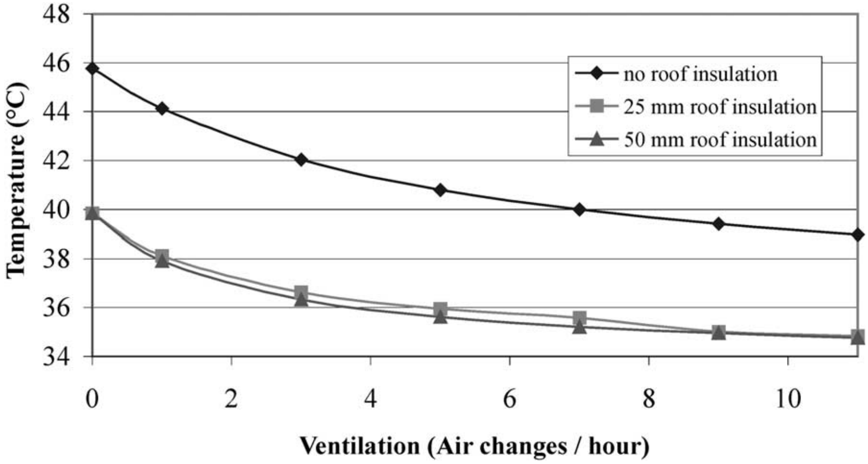

Fig. 3. Ventilation effect for different types of construction in July.

room temperature is above the outside temperature in summer, increasing the air changes per hour. The simulation results are presented in Fig. 4 and show that a reduction of the annual cooling load is obtained, which increases when the air changes per hour increase. The ventilation rate could also be increased in winter when the outside temperature is higher than the inside temperature and when heating is needed.

The effects of ventilation on the cooling and heating loads for various constructions are analysed in Table 2. As it is seen, when maintaining the house at 21 °C in winter, there is no appreciable load reduction arising from ventilation. In summer, ventilation leads to a maximum reduction of annual cooling load of 7.7% for

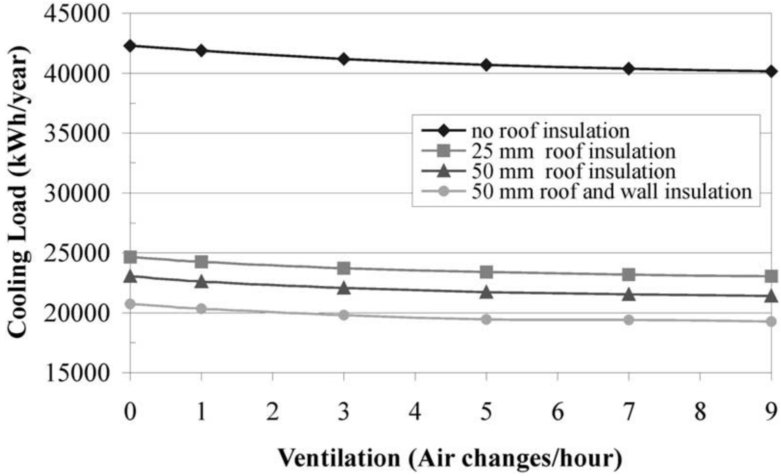

Fig. 4. The effect of ventilation on the annual cooling load for maintaining the model house at 25 °C.

Table 2
Annual cooling and heating loads for various roof constructions indicating the effect of ventilation

Air changes per hour	Process	No-roof insulation		25 mm roof insulation		50 mm roof insulation		50 mm roof and wall insulation	
		Annual load (kWh)	Load reduction (%)	Annual load (kWh)	Load reduction (%)	Annual load (kWh)	Load reduction (%)	Annual load (kWh)	Load reduction (%)
0	Cooling	42 300	–	24 660	–	23 050	–	20 743	–
	Heating	16 012	–	6506	–	5348	–	3740	–
1	Cooling	41 902	0.9	24 239	1.7	22 606	1.9	20 346	1.9
	Heating	16 012	–	6504	–	5347	–	3739	–
3	Cooling	41 159	2.7	23 707	3.9	22 052	4.3	19 785	4.6
	Heating	15 999	0.1	6500	0.1	5345	0.1	3737	0.1
5	Cooling	40 676	3.8	23 393	5.1	21 731	5.7	19 465	6.2
	Heating	15 979	0.2	6496	0.2	5335	0.2	3732	0.2
7	Cooling	40 359	4.6	23 192	6.0	21 529	6.6	19 270	7.1
	Heating	15 967	0.3	6489	0.3	5331	0.3	3729	0.3
9	Cooling	40 157	5.1	23 062	6.5	21 399	7.2	19 150	7.7
	Heating	15 948	0.4	6487	0.3	5329	0.4	3728	0.3

maintaining the house between 21 and 25 °C. The reduction in cooling load depends on the type of construction. Comparing the constructions presented in Table 2, it is observed that the ventilation effect increases with improved insulation levels.

3.2. *Effect of window glazing*

In this section, an analysis of the impact of window glazing on the cooling load is presented. A number of cases are investigated which can partly obstruct solar radiation and offer a wide range of conductance. These cases are presented in Table 3.

The results of the simulations are presented in Table 4. As observed, a saving in the annual cooling load of between 3100 and 7300 kWh can result, when compared to the corresponding construction with clear double-glazing windows (case W1). The saving in cooling load for the house with 50 mm roof and wall insulation, can be as much as 35.3% in the case that no extra lighting is used for case W3. But since in this case (W3) the transmittance for visible radiation is only 0.41, extra lighting will be needed, depending on the occupant needs. Assuming an 150 W extra lighting consumption, the savings reduce to 24%. However, window glazing will also reduce solar radiation transmission into the house, which would have been beneficial in cold days. This will result in an increase of the annual heating load, which in the latter case would be 877 kWh or 23.5%. Since the cooling load reduces but heat demand increases, the appropriate glazing type can be decided only after an economic analysis has been applied.

3.3. *Effect of overhangs*

Overhangs are devices that block direct solar radiation from entering a window during certain times of the day or the year. These are desirable for reducing the cooling loads and avoid uncomfortable lighting in perimeter rooms due to excessive contrast. To investigate the effect of the overhang length, a number of simulations were performed. For these simulations the overhang was assumed to be located 0.5 m above the window and extend 1 m on both sides of the window. The cooling and heating load of the four zones of the model house, constructed from single walls with no roof insulation for various overhang projections is indicated in Fig. 5. As

Table 3
Properties of window glazing

Case	Window type	Unit conductance (U, W/m^{2}K)	Transmittance for visible radiation (τ_v)
W1	Clear double-glazing	3.42	0.80
W2	Reflective double-glazing, bronze	2.27	0.10
W3	Low-emissivity double-glazing, bronze	1.89	0.41

Table 4
Effect of window shading on annual cooling-loads

Wall and roof construction	Window Type (Table 3)	Annual cooling load (kWh)	Annual cooling load decrease, compared to case W1 (kWh)	Annual cooling load decrease, compared to case W1%	Annual heating load (kWh)	Annual heating load increase, compared to case W1 (kWh)	Annual heating load increase, compared to case W1%
Single wall, no roof insulation	W1	42 300	–	–	16012	–	–
	W2	39 169	3131	7.4	16737	725	4.5
	W3	36 725	5575	13.2	17934	1922	12
50 mm roof and wall insulation	W1	20 743	–	–	3740	–	–
	W2	16 520	4223	20.4	4655	915	24.5
	W3	13 429	7314	35.3	6187	2447	65.4
50 mm roof and wall insulation plus extra lighting	W1	20 743	–	–	3740	–	–
	W2 plus 150 W	17 693	3050	14.7	3956	216	5.8
	W3 plus 150 W	15 773	4970	24.0	4617	877	23.5

can be seen, by increasing the overhang projection, the yearly cooling load decreases but at the same time the yearly heating load increases as some useful solar radiation is blocked during wintertime. The effect on the cooling load, as expected, is greater for the east and south windows located in Zones 3 and 1, since these windows receive more solar radiation during the year. The rate of cooling load decrease in Fig. 5 is higher than the rate of heating load increase for every zone.

The total annual cooling and heating loads difference of the model house is presented in Fig. 6. As can be seen, the greater the overhang projection, the greater will

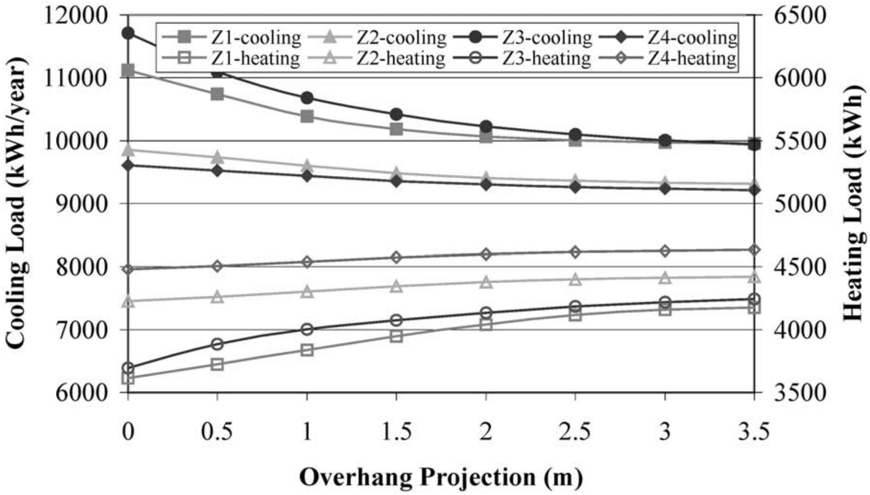

Fig. 5. Annual cooling and heating load of the four zones against overhang length for a model house constructed from single walls with no roof insulation.

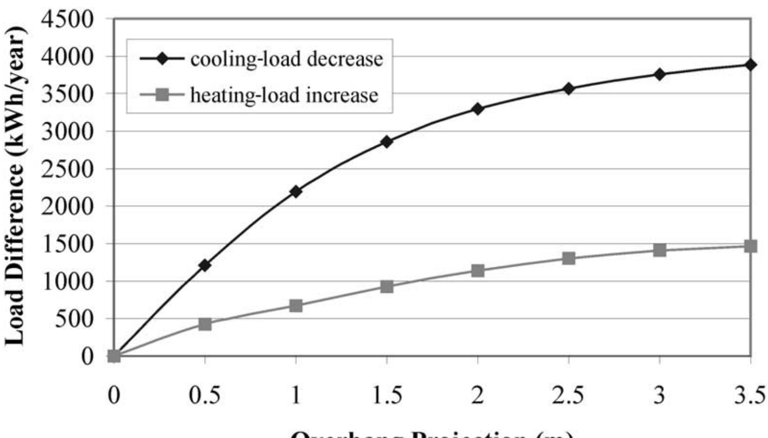

Fig. 6. Annual load difference against overhang length for a model house constructed from single walls with no roof insulation.

be the cooling load decrease. The heating load will increase though, since some useful solar radiation is also blocked during cold days. The difference between the cooling and heating loads would increase with increasing overhang projection because greater amounts of direct and indirect radiation will be blocked both during summer and winter. Therefore, it would be advantageous to use long overhang projections in the summer that could be retracted in winter, but in 'real' buildings the strategy will be based not only on economic but also on aesthetic grounds.

For the model house constructed from walls and roof with 50 mm insulation, the cooling and heating load of the four zones would change in a similar way. Fig. 7 shows the annual load difference against overhang projection for this type of construction. As can be seen, there would be about a 25% greater savings resulting for the same overhang length, compared to the case above, because of the better insulation of the house.

3.4. Effect of house shape and orientation

The exposed surface area of a building is related to the rate at which the building gains or loses heat while the volume is related to the ability of the building to store heat. Thus, the ratio of volume to exposed surface area is widely used as an indicator of the rate at which the building will heat up during the day and cool down at night. A high volume-to-surface ratio is preferable for a building that is desired to heat up slowly, as it offers small exposed surface for the control of both heat losses and gains [6].

In order to examine the effect of the shape and orientation of the building, a new model house plan is necessary that will increase the wall area but will keep the same volume. This model, named Shape 2, is illustrated in Fig. 8. Shape 2, has half the width and double the length of the original model house resulting in a wall perimeter of 70 m instead of the 56 m of the original model.

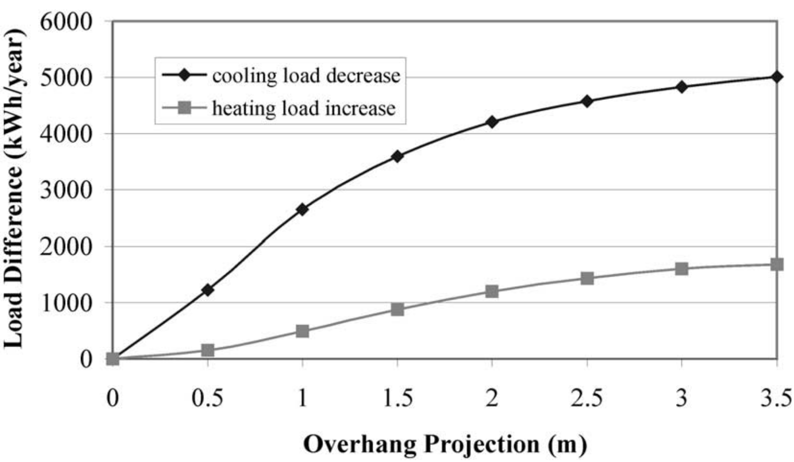

Fig. 7. Annual load difference per year against overhang length for a model house constructed from walls and roof with 50 mm insulation.

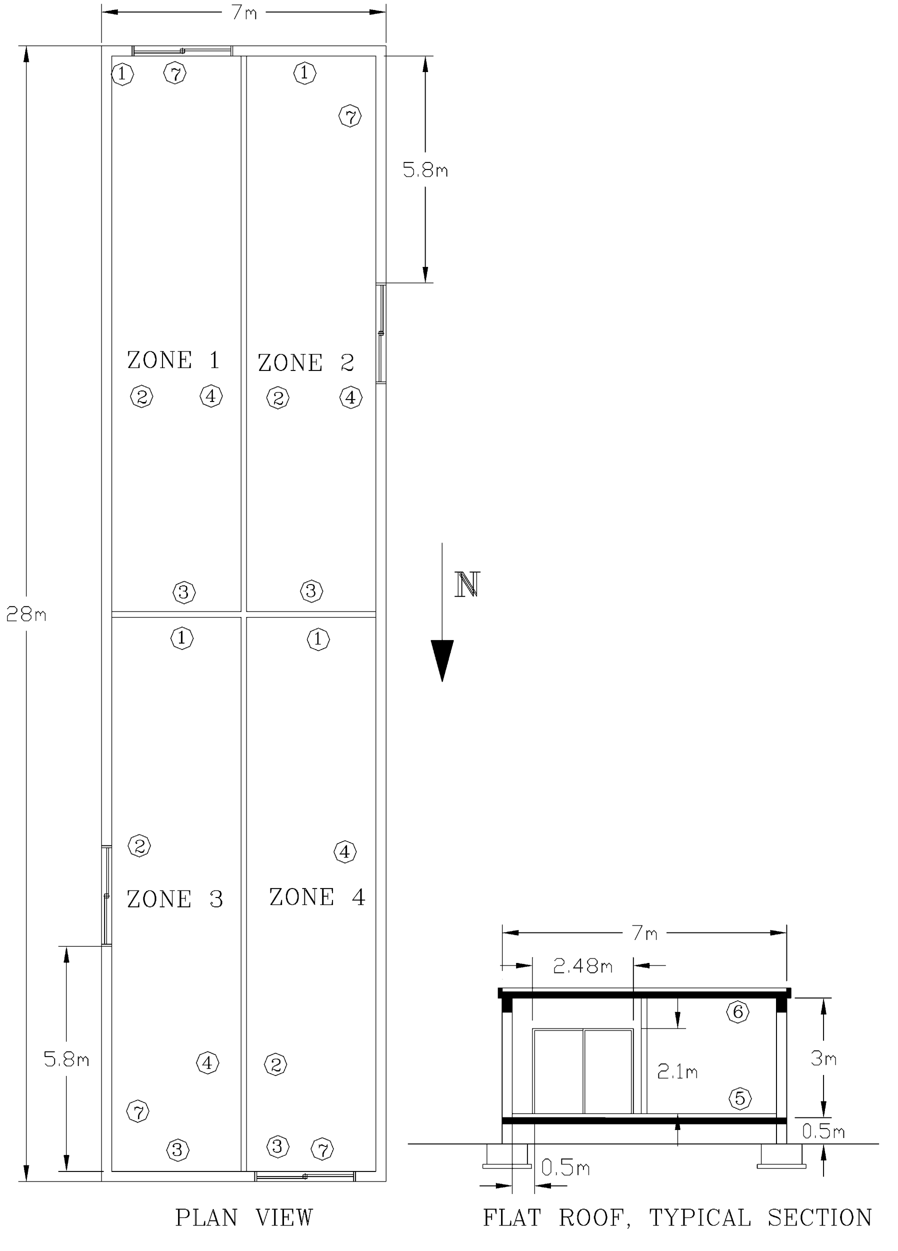

Fig. 8. Model house Shape 2, with glass doors and changed dimensions but with the same floor area and volume.

Table 5
Annual thermal load variation between houses of different shapes

Case	Model house type	Shape 1		Shape 2		Percentage difference in respect to Shape 1	
		Annual cooling load (kWh)	Annual heating load (kWh)	Annual cooling load (kWh)	Annual heating load (kWh)	Cooling load (%)	Heating load (%)
A	Single wall, no roof insulation (types D and H)[a]	42 300	16 012	43 526	17 323	2.9	8.2
B	50 mm wall and roof insulation (types F and J)[a]	21 710	3485	21 665	4417	−0.2	26.7

[a] Table 1.

Table 5 presents the thermal load variation between the houses with different shapes. For this analysis, two construction types were examined for every shape. These are the single wall (type D) model with no roof insulation (type H) and the 50 mm wall insulation (type F) model with roof insulation (type J). The results show that the elongated Shape 2 model has about the same annual cooling load but shows a significant increase in the annual heating load, of between 8.2 and 26.7% in respect to the model house of Shape 1, depending on the construction type. Therefore the results show that a smaller area-to-volume ratio is preferable.

To examine the effect of orientation for the climate conditions encountered in Nicosia, Cyprus, the four models are rotated from their present orientation, in a clock-wise direction through 180°. Fig. 9 shows the cooling load difference presented by the four models for different orientations.

Shape 1, presents the minimum annual cooling load with no rotation and at every 90 degrees because of the symmetry of its four sides. Depending on the construction type, an increase in annual load of between 400 and 600 kWh occurs at a rotation of 45°.

Shape 2, presents the minimum cooling load at 90° because at this position the east wall area, which has the biggest load contribution, is minimized. Depending on the construction type, an increase in the annual cooling load of 900 kWh can result, if the model is rotated by 45° from its minimum load position. Fig. 10 shows the annual heating-load difference presented by the four models during rotation. Shape 1, presents the minimum annual load at no rotation as happens with the annual cooling load. Depending on the construction type, an extra heating load of 125 to 150 kWh results at a peak position of about 45°. Shape 2, presents the lowest annual heating load at about 75°. Depending on the construction type, an extra annual heating load of 200 kWh can result, if the model is rotated from its minimum load position. Therefore, the best position for a rectangular house is to have its long side facing south. Of course architects cannot always orient the buildings at the best position, since orientation is mainly dictated by the plot shape and location with respect to roads.

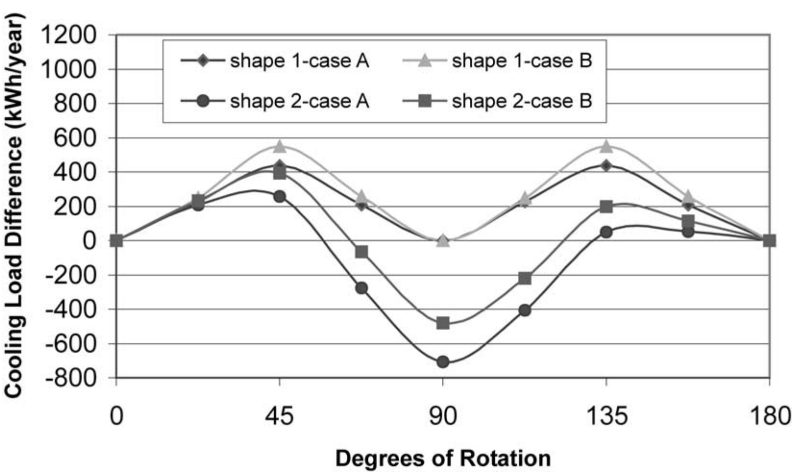

Fig. 9. Annual cooling load difference against degrees of rotation of the models.

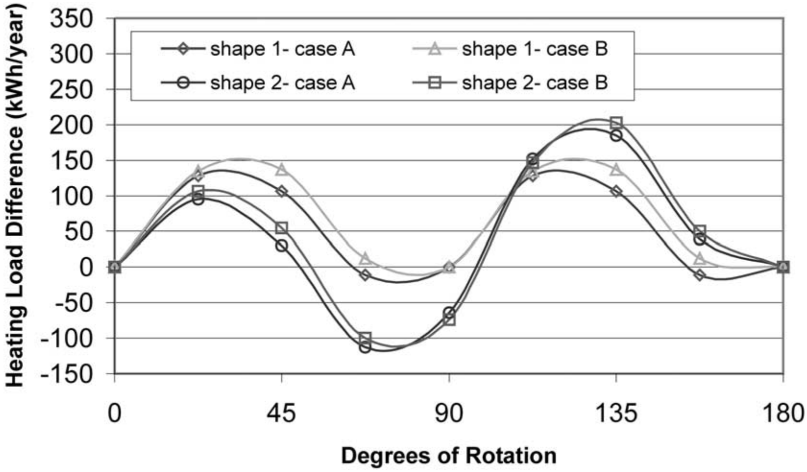

Fig. 10. Annual heating load difference against degrees of rotation of the models.

3.5. Thermal mass

Heat can be stored in the structural materials of the building in order to reduce the indoor temperature, reduce the cooling-load peaks and shift the time that the maximum load occurs. The storage material is referred to as thermal mass. In winter, during periods of high solar-gain, energy is stored in the thermal mass so avoiding overheating. In the late afternoon and evening hours, when energy is needed, heat is released into the building, satisfying part of the heating load. In summer, the thermal mass acts in a similar way as in winter reducing the cooling load peaks.

Thermal mass causes a time delay in the heat flow, which depends on the thermo-physical properties of the materials used. To store heat effectively, structural materials must have high density (ρ), thermal capacity (C) and conductivity (k), so that heat may penetrate through all the material during the specific time of heat charging and discharging. A low value of ρCk indicates a low heat-storage capacity, even though the material can be quite thick. The depth that the diurnal heat wave can reach within the storage material depends on thermal diffussivity, which is the controlling transport property for transient heat transfer and equals to $k/\rho c_p$ where c_p is the specific heat of the material [5]. The time lag for some common building materials of 305 mm thickness, is 10 h for common brick, 6 h for face brick, 8 h for heavyweight concrete and 20 h for wood because of its moisture content [7]. Thermal storage materials can be used to store direct energy by solar radiation in the building envelope or in places where incident radiation enters through openings in the building envelope. Also, these materials can be used inside the building to store indirect radiation, i.e. infrared radiation and energy from the room's air convection.

The distribution of thermal mass depends on the orientation of the given surface. According to Lechner [7], a surface with north orientation has little need for a time lag, since it only exhibits small heat gains. East orientation surfaces need either a very long time lag, greater than 14 h, so that heat transfer is delayed until the late evening hours, or a very short one, which is preferable because of the lower cost. South orientations can operate with 8-h time lag, delaying the heat from midday until the evening hours. For west orientations, an 8-h time lag is again sufficient since they receive radiation for only a few hours before sunset. Finally, the roof requires a very long time lag since it is exposed to solar radiation during most hours of the day. However, because it is very expensive to construct heavy roofs, the use of additional insulation is usually recommended instead.

The performance of thermal mass is influenced by the use of insulation. Where the heating of the building is the major concern, insulation is the predominant effective envelope factor. In climates where cooling is of primary importance, thermal mass can reduce energy consumption, provided the building is unused in the evening hours and the stored heat can be dissipated during the night. In this case, either natural or mechanical ventilation can be used during the night, to introduce cool outdoor air into the space and remove heat from the massive walls and roof.

To check how the use of thermal mass can influence the performance of the model house, a number of cases are investigated. Table 6 presents various wall and roof constructions of the model house of Fig. 1 and their effects on the annual heating and cooling load. In order to examine the limits to which the effect is observed, two exaggerated cases are included, case MC with a very light construction and case MK with a very heavy construction.

The TFCs for the non-insulated roof (type H—Table 1) are:

b coefficients: 0.0646154, 0.5816295, 0.3101954, 0.0101877
c coefficients: 8.9761130, −9.3677430, 1.3641040, −0.0058420 and
d coefficients: 1.0, −0.9922078, 0.1328027, −0.0002878

In number, there are four transfer-function coefficients for every parameter.

As can be observed (Table 6), the number of TFCs of the various types of walls and roofs used in building the Cypriot houses (cases MA and MB) is high. This number varies from four to seven. Since every transfer-function coefficient refers to the heat flux history of the structural element in time intervals of 1 h, this number actually represents the discharge time in hours. Therefore, such materials, when used in buildings, need 4–7 h to be discharged. This effect is indicated in Fig. 11 where, for the days of 16 and 17 July, the temperature of the model house is plotted for every hour. As can be seen, the two construction cases MA and MB, used in Cyprus, attain their maximum temperature at 5 p.m. i.e. at the same time that an 600 mm heavy concrete wall and roof house (case MK) reaches its maximum temperature.

A much lighter construction made from metal panels and 25 mm insulation (case MC) attains its maximum temperature at 2 p.m. at which time the ambient temperature reaches a maximum value: therefore there is a difference in time lag of 3 h between the heavy and light constructions. Also, as expected, the lighter the building construction the closer it follows the ambient temperature variation throughout the day.

Fig. 11 also shows that case MK has a daily variation of only 2°C attaining a very uncomfortable temperature of about 35–37 °C during day and night. The results for

Table 6
Thermal effects of various wall and roof types

Case	Wall type	Number of wall TFCs	Wall thermal conductivity (W/mK)	Roof type	Number of roof TFCs	Roof thermal conductivity (W/mK)	Annual heating load (kWh)	Annual cooling load (kWh)
MA	**Single wall**, hollow brick 0.2 m and 0.02 m plaster on each side (Type D[a])	6	0.886	**Flat non-insulated roof**, constructed from fair-faced 0.15 m heavy-weight concrete (type H[a])	4	1.91	16 012	42 300
MB	**Double-wall**, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (type F[a])	7	0.389	**Flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity (type J[a])	6	0.481	3485	21 710
MC	Steel siding A3[b], 0.025 m insulation B2[b], and Steel siding A3[b]	2	0.978	Steel siding A3[b], 25 mm insulation B2[b], and Steel siding A3[b]	2	0.978	13145	31 978
MD	0.1 m face brick A2[b], 0.1 m insulation B13[b] and 0.025 m wood B7[b]	6	0.325	0.012 m stone E2[b], 0.01 m felt and membrane E3[b], 0.15 m insulation B15[b] and 0.025 m wood B7[b]	6	0.236	2793	21 385
ME	**Single wall**, hollow brick 0.2 m and 0.02 m plaster on each side (Type D[a])	6	0.886	0.012 m stone E2[b], 0.01 m felt and membrane E3[b], 0.15 m insulation B15[b] and 0.025 m wood B7[b]	6	0.236	4735	22 550
MF	**Double-wall**, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (type F[a])	7	0.389	**Flat insulated roof**, fair-faced **0.25 m heavy weight concrete, 0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	7	0.468	3430	21 625

(*Continued on next page*)

Table 6 (*continued*)

Case	Wall type	Number of wall TFCs	Wall thermal conductivity (W/mK)	Roof type	Number of roof TFCs	Roof thermal conductivity (W/mK)	Annual heating load (kWh)	Annual cooling load (kWh)
MG	**Double-wall**, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (Double wall type F[a])	7	0.389	**Flat insulated roof, 0.05 m wood (B10[b])** under- covering, fair-faced 0.15 m heavy weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	7	0.397	3194	22 035
MH	**For W and N walls: Double-wall**, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (type F[a])	7	W and N, 0.389	**Flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity (type J[a])	6	0.481	3438	21 654
	For E and S walls: Double wall type F,[a] **with additional 0.1 m heavy concrete inside**	8	E and S 0.377					
MI	**Double-wall**, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (type F[a]), with additional **0.1 m heavy concrete inside**	8	0.377	**Flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity (type J[a])	6	0.481	3410	21 619
MJ	**Double-wall**, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (type F[a]), with additional **0.25 m heavy-weight concrete outside**	9	0.365	**Flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity (type J[a])	6	0.481	3399	21 661

(*Continued on next page*)

Table 6 (*continued*)

Case	Wall type	Number of wall TFCs	Wall thermal conductivity (W/mK)	Roof type	Number of roof TFCs	Roof thermal conductivity (W/mK)	Annual heating load (kWh)	Annual cooling load (kWh)
MK	0.6 m heavy-weight concrete	9	1.278	0.6 m heavy weight-concrete	9	1.278	11 050	29 884
ML	0.02 m plaster E1,[b] 0.3 m clay brick, 0.1 m insulation B13[b] and 0.02 m plaster E1[b]	9	0.261	0.2 m plaster E1,[b] 0.3 m clay brick, 0.1 m insulation B13[b] and 0.2 m plaster E1[b]	9	0.261	2772	20 865
MM	0.3 m heavy concrete C11[b]	6	1.638	**Flat non-insulated roof**, constructed from fair-faced 0.15 m heavy-weight concrete (type H[a])	4	1.91	18 704	43 500
MN	0.3 m heavy concrete C11[b]	6	1.638	0.3 m heavy concrete C11[b]	6	1.638	14 985	37 739
MO	**Double-wall**, 0.1 m hollow brick and 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between (type F[a])	7	0.389	**Flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.10 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	6	1.022	2705	20 669

TFCs = transfer function coefficients.

[a] Table 1.

[b] ASHRAE code numbers for wall and roof materials [8].

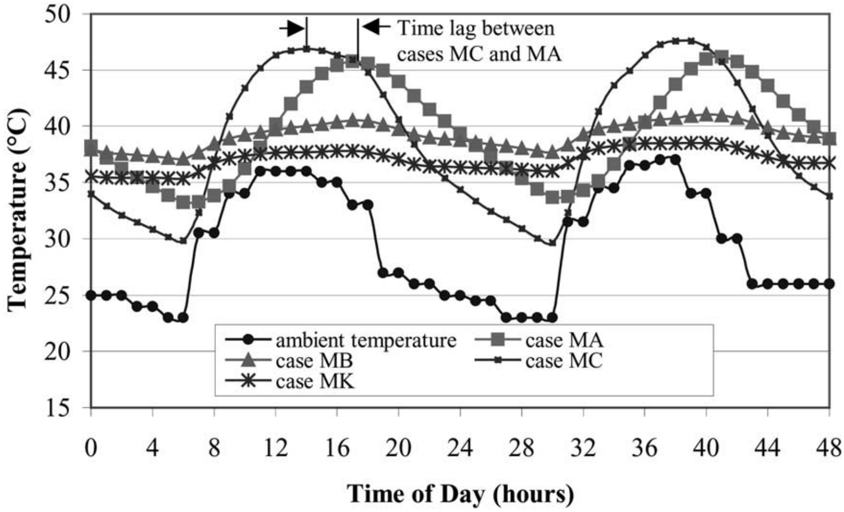

Fig. 11. Temperature variations for various wall constructions during 16 and 17 July, showing the effect of thermal mass.

winter, during 13 and 14 January, are shown in Fig. 12. During this period the temperature variation of case MK is again about 2°C, i.e. between 15 and 17 °C.

The data presented in Table 6 clearly show that the thermal load is divided into three main categories. The first category presents annual cooling loads of about 32 000 kWh and annual heating loads of 14 000 kWh, the second 42 000 and 16 000

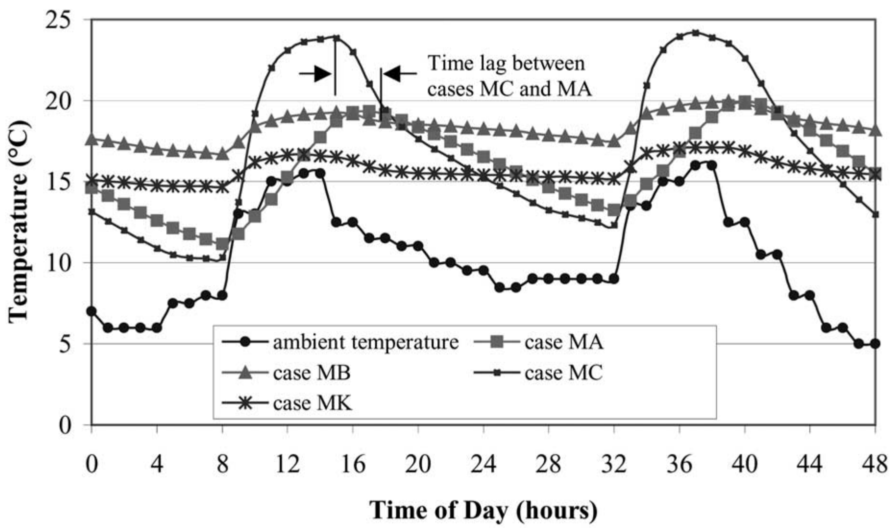

Fig. 12. Temperature variations for various construction types during 13 and 14 January, showing the effect of thermal mass.

kWh, and the third 21 000 and 3000 kWh, respectively. The first category includes light constructions of roofs and walls with the number of TFCs being between two and four. Roofs and walls constructed of these materials absorb and release thermal energy, rapidly. The second category includes light constructions of roofs but heavier walls with six TFCs, which during summer, trap the energy, passing through the roof, inside the building. Finally the third category includes heavy constructions of roofs and walls with 6–9 TFCs, which present great resistance to the heat flow and high heat storage capacity. As can also be seen, increasing the mass of the roof further than case MB, as for example in case MF, does not produce significant changes in the load. When though, instead of the roof mass, the roof insulation is increased as in case MO, the annual cooling-load decreases by about 1000 kWh and also the annual heating load decreases significantly by about 800 kWh. Increasing the mass of walls further than case MB, as for example, in cases MH, MI and MJ does not result in significant changes in the load. Constructing both the walls and roof with 0.3 m heavy-weight concrete as in case MN, results in increasing the heating load by 4.2 times and the cooling load by 1.7 times compared to case MB.

Thermal mass actually is used to store heat during the day, for the purpose of dissipating it during the evening hours with ventilation. To check the effectiveness of this method in the Nicosia environment, the response of a model house, constructed from various materials, with low-emissivity and double-glazed windows (Table 3), was simulated using a night ventilation-rate of six air changes per hour. As can be seen in Fig. 13, the model house of case MB is more sensitive than the more massive case MK: it keeps the temperature between 27 and 33 °C. Case MK keeps the temperature about 1–2°C higher but in neither of the two cases is the temperature reduced to acceptable levels. It must be noted that similar constructions to the

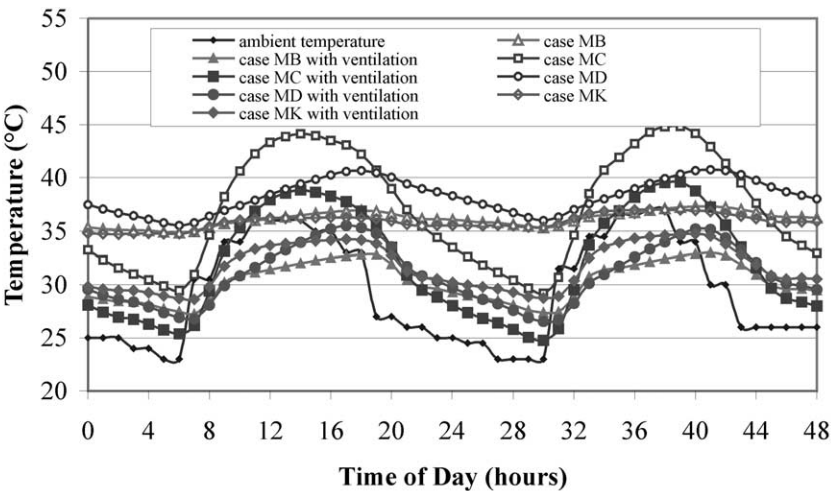

Fig. 13. Effect of night ventilation for various wall constructions during 16 and 17 July in combination with thermal mass.

earlier cases, give analogous results with very small variations in temperature of less than half a degree. A very light-weight roof with thick insulation, as in case MD, results in temperature variations of between 27 and 35 °C, again higher than case MB. Very light-weight constructions, like case MC, result in great temperature variations between 25 and 40 °C. Therefore, the earlier analysis shows that the roof is the most important structural element of the building in the Cypriot environment. The roof must offer a discharge time of 6 h or more and be insulated, as in case MB or better.

Other measures, which can be taken to reduce the energy consumption of buildings, are energy management methods [9]. These have to be considered with respect to the operation of the system.

4. Cost effectiveness

This section presents a feasibility study of the various measures that can be taken to lower the building's thermal-load. For the economic study, a life-savings analysis method was employed as described below.

4.1. Life savings analysis method

The life savings analysis method takes into account the time value of money and allows detailed consideration of the complete range of costs. Energy conservation measures such as use of insulation in buildings is generally characterized by high initial cost and low operating costs, due to either the improved thermal resistance of the building envelope or reduction in the conventional fuel used. Thus, the basic economic problem is that of comparing an initial known investment with the estimated future operating costs.

Life-cycle cost (LCC) is the sum of all the costs associated with an energy delivery system over its lifetime in today's money, and takes into account the time value of money. The life-cycle savings (LCS), for an insulated building, is defined as the difference between the LCC of a non-insulated building and the LCC of an insulated one. This is equivalent to the total present worth (PW) of the gains from the reduced fuel and electricity costs for an insulated building, compared to the fuel and electricity costs for a non-insulated one.

4.2. Description of method

With reference to Table 7, which shows the parameters required for the various calculations, by multiplying the area dependent cost with the wall or roof area, the total cost of the insulation related to the size of the building is obtained. The total system cost can be obtained by adding to the above the area independent cost, which refers to labour.

The analysis is performed annually and the following are evaluated [11]:

Table 7
Economic analysis input parameters

Input parameters	Value	Units
Fuel inflation rate	6[a]	%
Wall area	147.2	m^2
Flat-roof area	196	m^2
Inclined roof area	202.8	m^2
Boiler efficiency	85	%
Electric chiller efficiency	200	%
Area dependent extra cost		
Double wall, 0.025 m polystyrene insulation (type E, Table 1)	3.5	[b]C£/m^2
Double wall, 0.05 m polystyrene insulation (type F, Table 1)	5	C£/m^2
Insulated roof, 0.025 m polystyrene insulation (type I, Table 1)	11	C£/m^2
Insulated roof, 5 cm polystyrene insulation (type J, Table 1)	14	C£/m^2
Inclined roof, tile covered (type K, Table 1)	16	C£/m^2
Overhangs made of concrete and extending less than 2 m	27	C£/m^2
Overhangs made of concrete and extending more than 2 m	35	C£/m^2
Economic parameters		
Annual market discount rate	6.5[a]	%
Price of electricity	0.0525	C£/kWh
Annual increase in electricity cost	4.9[a]	%
Current price of fuel	0.171	C£/lt

[a] Mean value for the years 1978–1998 [10].
[b] Current exchange rate: C£1 = US$1.55 = €1.73.

- Fuel savings
- Extra mortgage payment
- Electricity savings
- Extra tax savings
- Building energy savings

The word "extra" appearing in some of the above items assumes that the associated cost is also present for a non-insulated building and therefore only the extra part of the cost incurred by the installation of the insulation should be included. The inflation, over the period of the economic analysis, of the fuel savings is estimated by using the equation [12]:

$$F = c\,(1 + i)^{N-1} \tag{2}$$

where i is the fuel annual inflation rate, c the purchase cost at the end of the first time period, N is the number of years, and F the future fuel cost.

The income tax law varies from country to country. In Cyprus, tax relief of 40% can be reclaimed against interest paid on loans made for building a house. Therefore, the equation used for the tax savings estimation is:

$$\text{Tax savings} = 0.4\,[\text{Interest paid}] \tag{3}$$

The building energy savings can be represented by the following equation:

$$\text{Building energy savings} = \text{Electricity savings} + \text{Fuel savings} + \text{Extra tax savings} - \text{Extra mortgage payment} \quad (4)$$

Electricity will be assumed to be used for providing cooling and fuel oil (diesel) for heating.

Finally the present worth of each year's savings is determined by using equation [12]:

$$P = F/(1 + d)^N \quad (5)$$

where F is the cash flow, occurring N years from now, reduced to its present value P, and d is the market discount rate (%). The P values are added for all years considered to give the total Present Worth of the building's energy consumption over its life.

4.3. Results of economic analysis

The life-cycle cost analysis method is applied for a 20-year period. As the building elements considered in this analysis are parts of the building structure, the economic scenario considers that the element cost (e.g. extra insulation) is included in the 20-year long-term loan required to build the house. The reference construction, built from single walls and flat non-insulated roof presents an annual cooling load of 42 300 kWh and an annual heating load of 16 012 kWh, when the building is conditioned at all hours of the year. The extra cost refers to the added cost for applying the examined measure. The results are presented in Table 8.

As can be observed, measures that increase the roof insulation pay back in a short period of time, of between 3.5 and 5 years. This is due to the fact that the main load in the building comes from the roof. However, measures taken to increase the wall insulation pay back in a longer period of time, of about 10 years.

The life cycle savings for a 20-year period that results for various window-glazing types is presented in Table 9. Because the window glazing reduces useful solar radiation during the cold days, that results in an increase of the heating load. All types of glazing examined have a short pay back period of 3–4 years.

Finally, Table 10 presents the economic analysis for various types of overhangs for windows and doors. As is observed, concrete constructions hardly cover their cost when placed over windows and result in loss when placed over doors because of their high initial cost. The appropriate construction that is economically sound should have a unit price of 10 C£/m^2 or less, which corresponds to cheap movable overhangs.

5. Conclusions

In summer, when ventilation air enters into the house whenever the outside temperature is less than the house temperature and the room is not conditioned, there is

Table 8
Saving in C£ for cooling at 25 °C and heating at 21 °C for a 20-year period for various wall and roof constructions

Type of construction	Building annual cooling load (kWh)	Building annual heating load (kWh)	Additional expenditure required (C£)	Resulting life-cycle savings (C£)	Payback period (years)
***Reference construction*: Single wall**, hollow brick 0.2 m and 0.02 m plaster on each side and **flat non-insulated roof**, fair-faced 0.15 m heavy-weight concrete	42 300	16 012	–	–	–
Double-wall, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of 0.025 **m polystyrene insulation** in between and **flat non-insulated roof**, fair-faced 0.15 m heavy-weight concrete	41 550	14 746	515	345	10
Double-wall, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of 0.05 **m polystyrene insulation** in between and **flat non-insulated roof**, fair-faced 0.15 m heavy-weight concrete	41 300	14 312	735	423	10.5
Single wall, hollow brick 0.2 m and 0.02 m plaster on each side and **flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.025 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	24 660	6506	2156	9143	3.5
Single wall, hollow brick 0.2 m and 0.02 m plaster on each side and **flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity	23 050	5348	2744	9762	3.8

(*Continued on next page*)

Table 8 (*continued*)

Type of construction	Building annual cooling load (kWh)	Building annual heating load (kWh)	Additional expenditure required (C£)	Resulting life-cycle savings (C£)	Payback period (years)
Single wall, hollow brick 0.2 m and 0.02 m plaster on each side and **N–S Inclined roof**, 0.15 m heavy-weight concrete, 0.004 m asphalt for waterproofing, 0.05 m plaster and clay tile on top	24 750	7280	3245	7931	4.9
Single wall, hollow brick 0.2 m and 0.02 m plaster on each side and **E–W Inclined roof**, 0.15 m heavy-weight concrete, 0.004 m asphalt for waterproofing, 0.05 m plaster and clay tile on top	24 960	7257	3245	7848	4.9
Double-wall, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between and **flat insulated roof**, fair-faced 0.15 m heavy-weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminum paint of 0.55 solar absorptivity. (Case MB, Table 6)	21 710	3485	3479	10 378	4.3
Double-wall, 0.1 m hollow brick, 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between and **flat insulated roof, 0.05 m wood**, fair-faced 0.15 m heavy-weight concrete, **0.05 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity. (Case MG, Table 6)	22 035	3194	12 495	2901	13.2
Double-wall, 0.1 m hollow brick and 0.02 m plaster on each side and a layer of **0.05 m polystyrene insulation** in between and **flat insulated roof**, fair-faced 0.15 m heavy weight concrete, **0.10 m polystyrene insulation**, 0.07 m screed and 0.004 m asphalt covered with aluminium paint of 0.55 solar absorptivity. (Case MO, Table 6)	20 669	2705	3871	10 778	4.5

Table 9
Saving in C£ for cooling at 25 °C and heating at 21 °C for a 20-year period for various window-glazing types

Type of construction	Window type	Additional expenditure required (C£), compared to clear double-glazing (Case W1, Table 3)	Resulting life cycle savings (C£)	Payback period (years)
Single wall, no roof insulation	Reflective double glazing, bronze (Case W2, Table 3)	208	904	3
	Low-emissivity double glazing, bronze (Case W2, Table 3)	416	1368	3.8
50 mm roof and wall insulation plus 150 W extra lighting	Reflective double glazing, bronze (Case W2, Table 3)	208	1060	2.8
	Low-emissivity double glazing, bronze (Case W2, Table 3)	416	1478	3.8

Table 10
Saving in C£ for cooling at 25 °C and heating at 21 °C for a 20-year period for various overhang types

Type of construction	Overhang length	Type of construction and cost	Additional expenditure required (C£)	Resulting life cycle savings (C£)	Payback period (years)
Single wall, no roof insulation	1.5 m over windows	Concrete, C£30/m^2	1080	17.2	16.5
	1.5 m over windows	Other C£10/m^2	360	610	6
50 mm roof and wall insulation	1.5 m over windows	Concrete, C£30/m^2	1080	317	12.2
	1.5 m over windows	Other C£10/m^2	360	910	4.4

a reduction in the inside temperature by about 2 °C for one air change per hour, 3 °C for two air changes per hour and 7 °C for 11 air changes per hour. When maintaining the house at 21 °C in winter, there is no appreciable load reduction arising from ventilation. In summer, a reduction of the annual cooling load may be obtained if the ventilation rate is increased mechanically, to take advantage of the lower temperature of the outside air. A ventilation rate of nine air changes per hour leads to a maximum reduction in annual cooling load of 7.7% for maintaining the house at 25 °C. The effect depends on the construction type, with the better-insulated house saving a higher percentage. It is therefore recommended to use ventilation whenever the outside temperature is less than the house temperature at the maximum rate possible.

Window gains are an important factor and significant savings can result when low conductance and low transmittance window glazing is used. A saving in the annual cooling load of between 3050 and 5000 kWh can result depending on the construction and glazing type. The saving in annual cooling load for a well-insulated house may be as much as 24% when low-emissivity double-glazing windows are used.

Overhangs can result in savings of 2000–3000 kWh/year depending on the construction of the model house. Overhangs may have a length over windows of 1.5 m. In this way, about 7% of the annual cooling load can be saved for a house constructed from single walls with no roof insulation. These savings are about 19% for a house constructed with walls and roof both having 50 mm insulation.

The shape of the building affects the thermal load. The results show that the elongated house shows an increase in the annual heating load, which is between 8.2 and 26.7% depending on the construction type, relative to the model house of Shape 1. The annual heating load increase in this case is about 1000 kWh. Referring to orientation, the best position for a symmetrical house is to face the four cardinal points and for an elongated house to have its long side facing south in order to minimize the east wall area that has the biggest load contribution.

In respect to thermal mass, the analysis shows that increasing the wall and roof mass and utilizing night ventilation is not enough to lower the house temperature to acceptable limits during summer. Also the analysis shows that the roof is the most important structural element of the buildings in the Cypriot environment. The roof must offer a discharge time of 6 h or more and have a thermal conductivity of less than 0.48 W/mK in order to keep the loads to a minimum.

The life cycle cost analysis has shown that measures, that increase the roof insulation pay back in a short period of time, of between 3.5 and 5 years. However, measures taken to increase wall insulation pay back in a long period of time, of about 10 years. Low-emissivity double-glazing results in a short pay back period of 3–4 years, irrespective of the fact that useful solar radiation is also blocked during the cold days.

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