The Significance of Building Mass in Energy-Economizing

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Tiivistelmä

Rakenteiden massiivisuus vaikuttaa lämmitysenergian kulutukseen, kesäaikaisiin sisälämpötiloihin, rakennuksen jäähtymisnopeuteen ja vaadittavaan lämmitystehoon.

Omakoti- ja rivitaloissa keveiden rakenteiden korvaaminen raskailla rakenteilla vähentää lämmitysenergian kulutusta 3...10 %. Asuinkerrostaloissa, joiden välipohjat ovat raskaita, keveiden ulko- ja väliseinien korvaaminen raskailla rakenteilla vähentää lämmitysenergian kulutusta 1...4 %. Säästön suuruus riippuu rakennuksen sijainnista, ikkunoiden koosta ja suuntauksesta sekä sisälämpötilalle sallitusta vaihtelusta.

Summary

Building mass affects heating energy consumption, indoor temperatures in summer, the rate at which a building cools and the heating power required.

Replacing light structures in single-family and terrace houses with heavy structures reduces the heating energy consumption by 3...10 %. In apartment houses which have heavy floors, the replacement of light exterior and interior walls with heavy structures reduces the heating energy consumption by 1...4 %. The amount of energy saved depends on building location, the size and orientation of windows and permitted indoor temperature fluctuations.

1. INTRODUCTION

This paper is an abridged account of a treatise /1/ which examined the energy-economical significance of building mass in the design and choice of exterior and interior walls, floors and other structures.

The study was carried out by simulating the thermal behaviour of typical Finnish single-family, terrace and apartment houses using the TASE computer program /2,3/. Conclusions were drawn on the effect of building mass in different situations. The weather data used were those for Central Finland (see Appendix 1). Hourly weather data were employed for the calculations.

Building mass affects heating energy consumption, indoor temperatures in summer, the rate of cooling and the heating power required.

2. EFFECT OF BUILDING MASS ON HEATING ENERGY CONSUMPTION

2.1 Nature of effect of mass

In late winter, spring and autumn the strength of the solar radiation penetrating windows, coupled with interior heat loads, exceeds the heat losses which prevail at those times, causing a rise in indoor temperature even if heating is turned off. In light buildings indoor temperature reaches an unpleasantly high level since the heat storage capacity of their structures is small. Windows must be opened, leading to waste of free energy. In addition, high indoor temperature increases the heating energy consumption of a light building.

Indoor temperature rises more slowly in heavy buildings than in light ones since the surplus energy becomes stored in structures. Windows need not be opened, so that a surplus of free energy is saved up for a time it is needed (Figure 1).

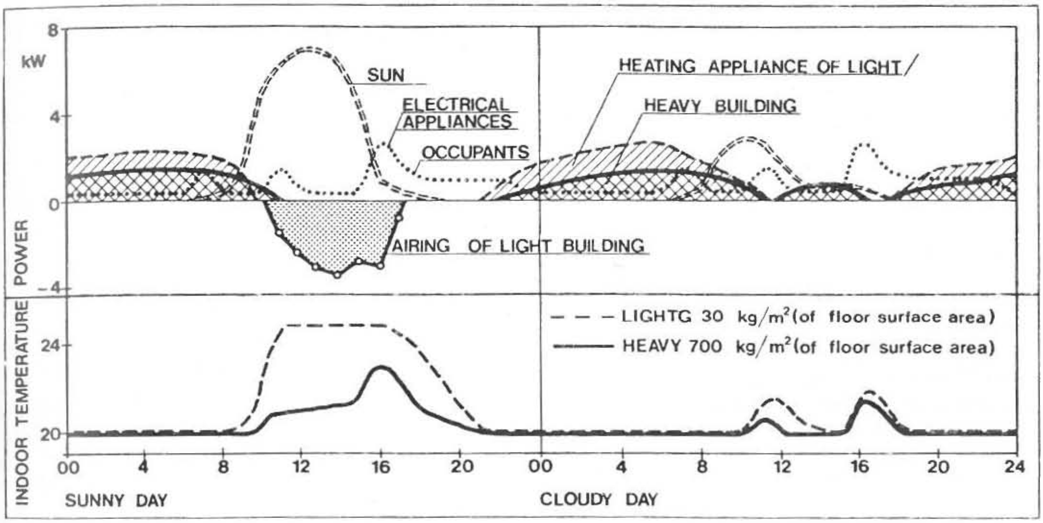


Figure 1. Production of heat, airing and indoor temperature in a light and heavy single-family house on two successive days in March. The floor area is 118 m^2, the volume 296 m^3, the surface area of the south window 10 m^2 and that of the north window 6 m^2. The interior mass of the light house is ca 30 kg/m^2 of floor surface area, and of the heavy house ca 700 kg/m^2.

Air changes occur at the rate of 0,6/h and the heat recovery efficiency is 0,5. Air infiltration and wall conductance G_{tot} = 103 W/K+G_{floor}, G_{floor} = 45 W/K. Only those masses whose thermal resistance to the interior surface is smaller than 0,2 m^2K/W have been included with the interior mass. /1/.

2.2 Single-family house

In single-family houses the difference in heating energy consumption between the lighter and heavier alternative in mass is about 10 %. The customary light alternative incorporates, however, a heavy floor, so that if a light house is converted to a heavy house by replacing light structures with heavy ones there will be a saving of about 7 % in heating energy consumption (Figure 2).

Figure 2.
The effect of mass on the annual heating energy consumption of a customary single-family house with the following mass alternatives:

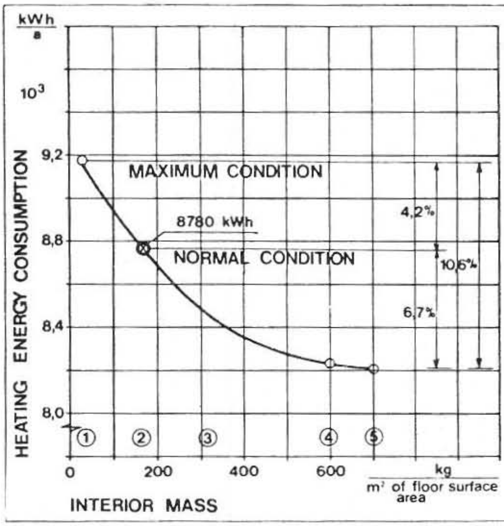
1≙ Interior mass 30 kg/m^2 of floor surface area with all structures light.

2≙ Interior mass 170 kg/m^2 of f.s.a. where floor is heavy and other structures light.

3≙ Interior mass 310 kg/m^2 of f.s.a. where floor and exterior walls are heavy and other structures light.

4≙ Interior mass 600 kg/m^2 of f.s.a. where floor, exterior walls and ceiling are heavy and other structures light.

5≙ Interior mass 700 kg/m^2 of f.s.a where floor, exterior walls, ceiling and interior walls are heavy.



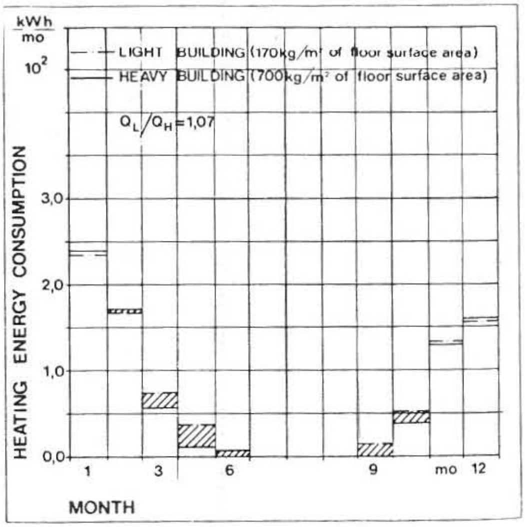
Other basic data as for Figure 1.

Savings in heating energy comsumption are achieved during sunny periods in spring and autumn (Figure 3).

Figure 3.
The heating energy comsumption of a light and heavy single-family house during different months. Basis of calculations same as for Figure 2, mass alternatives 2 and 5.

The heating energy consumption of a heavy house is distinctly smaller than that of a light one in late winter, spring and autumn. In March, for example, and increase in mass saves about 20 % of heating energy.

The mean temperature in March is -1,3 °C and the solar radiation entering from a south window 54 kWh/m^2. (Triple-glazed windows, $\tau_\perp$=0,65;$\tau_\perp$ = penetrating power of direct solar radiation when the radiation is perpendicular /1/.



2.3 Apartment house

The floors of apartment houses in Finland are almost without exception heavy. Mass lowers the heating energy consumption in apartment houses by only 1...4 %. The greatest share of the savings is achieved by floor mass alone since the heat storage capacity of heavy floors is great compared with the surplus of free energy accumulating during the day (Figure 4).

Figure 4,
The effect of mass on the heating energy consumption of a unit in a customary apartment house with the following mass alternatives:

1º Interior mass 50 kg/m^2 of floor surface area with all structures light.

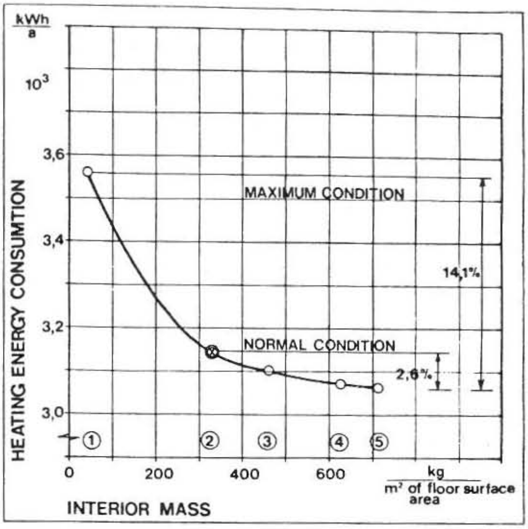
2º Interior mass 330 kg/m^2 of f.s.a. with heavy floors and other structures light.

3º Interior mass 460 kg/m^2 of f.s.a. with heavy floors and exterior walls (interior shell 16 cm of concrete) but other structures light.

4º Interior mass 630 kg/m^2 of f.s.a. with floors, exterior walls and supporting interior walls heavy and other structures light.

5º Interior mass 710 kg/m^2 of f.s.a where partition walls also are heavy.

The floor area of the unit is 60 m^2 and the volume 160 m^3. The area of the south window is 4 m^2 and that of the north window 2,4 m^2. Air changes occur at the average rate of 0,6/h. /1/.



2.4 Terrace house

An increase in mass lowers the heating energy consumption of a customary terrace house by about 9 %. The greatest benefit is got from the first heavy interior surfaces: adding mass to the upstairs floor lowers consumption by about 4 %, while adding mass to partition walls does not lower consumption at all if these walls are the last surfaces to have their mass increased (Figure 5).

Figure 5.
The effect of mass on the heating energy consumption of a customary terrace house with the following mass alternatives:

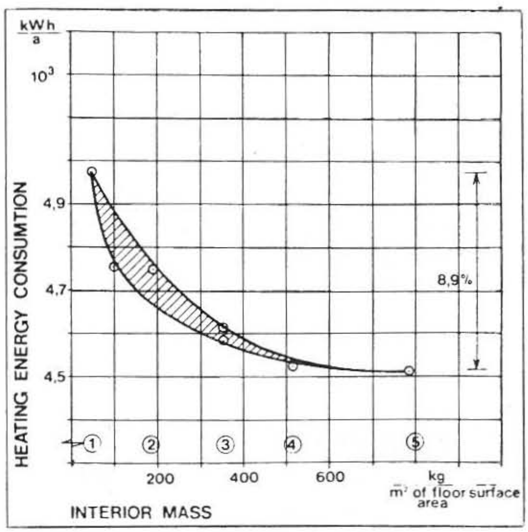
1º Interior mass 50 kg/m^2 of floor surface area.

2º Interior mass 190 kg/m^2 of f.s.a. where upstairs floor is heavy and other structures light.

3º Interior mass 360 kg/m^2 of f.s.a. where upstairs floor and supporting walls between houses are heavy and other structures light.

4º Interior mass 520 kg/m^2 of f.s.a. where upstairs floor, supporting interior walls and ceiling are heavy and other structures light.

5º Interior mass 780 kg/m^2 of f.s.a. where partition walls also are heavy.



The upstairs floor area is 60 m^2 and the volume 160 m^2. The area of the south and north windows is 3,2 m^2 each. Air changes occur at the average rate of 0,6/h. /1/.

3. FACTORS AFFECTING SIGNIFICANCE OF BUILDING MASS

The location and characteristics of buildings under construction vary considerably. To take this variance into consideration a sensitivity analysis was carried out using the following variables:

- location of building, orientation and size of windows
- ventilation rate
- indoor temperature fluctuations
- distribution of mass and the order in which heavy componenets are used
- surfacing materials covering heavy components.

3.1 Location of single-family house and orientation of windows

The amount of solar radiation a house receives depends on its location. A house located on a south slope, the perimeter of an exposed area or such places receives the maximum amount of solar radiation. On the other hand, its environment may shield a house from much solar radiation it would otherwise receive. The location of a building within a sunny or shady place can be expressed using the horizon angle. The horizon angle is the angle formed by the horizontal plane and the upper edge of a visional obstruction.

The amount of beneficial radiation received depends primarily on the orientation of the windows. A south orientation brings about a decrease in the heating energy consumption, the size of which depends on the building mass and the location (Figure 6).

The energy-economical significance of building mass is greatest in a sunny location when the windows face south.

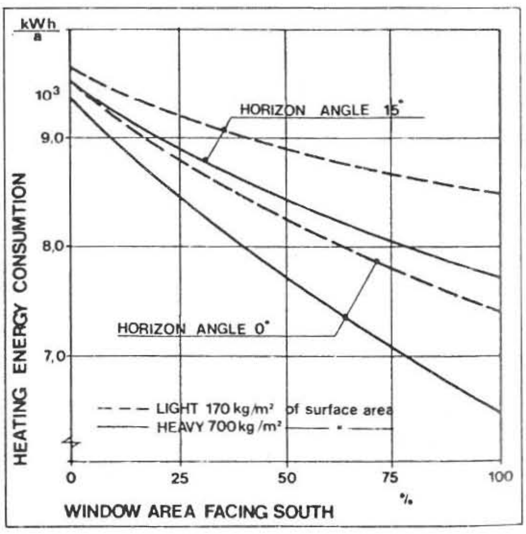


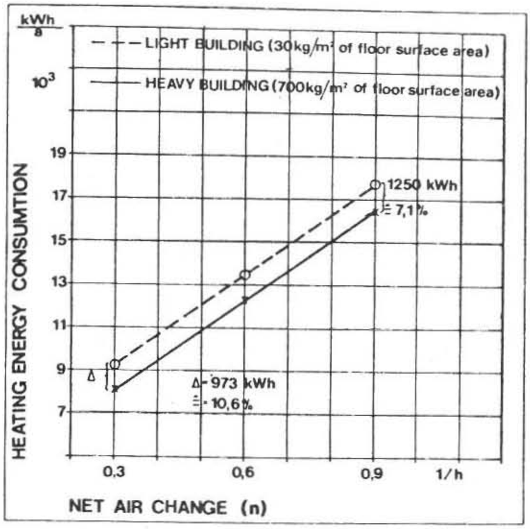
Figure 6.
The effect of window orientation, building mass and the horizon angle on the heating energy consumption of a single-family house. The figure compares the heating energy consumption of a light and a heavy single-family house, showing the dependence on window orientation and using two different horizon angles. The total surface area of the windows is 16 m^2. The horizontal axis shows the window surface area facing south in percentages of the total window surface area. The remaining windows face north. With the exception of the window orientation and the horizon angle, the calculations are based on the same data as for Figure 2. (In Figure 2 the horizon angle is 15 °C and the window surface area facing south 63 %). /4/.

3.2 Ventilation rate

A decrease in the ventilation rate brings about a definite drop in heating energy consumption (Figure 7).

As the ventilation rate decreases, the relative significance of building mass increases, but its absolute significance grows smaller (Figure 7).

Figure 7.
The effect of ventilation rate and building mass on the heating energy consumption of a single-family house. The ventilation rate has been expressed in net form. For example, when the ventilation rate is 0,6/h and the heat recovery efficiency 0,5, the net ventilation rate will be 0,3/h. With the exception of the ventilation rate, the basis for the calculations are the same as for Figure 2. (In Figure 2 the net ventilation rate is 0,3/h). /1/.



The increase in the relative effect when the ventilation rate decreases is due to the fact that, when the ventilation rate is small, the free energy available exceeds more easily heat losses than when the ventilation rate is great. The decrease in the absolute effect when the ventilation rate decreases is due to the shortening of the heating period.

3.3 Indoor temperature fluctuations

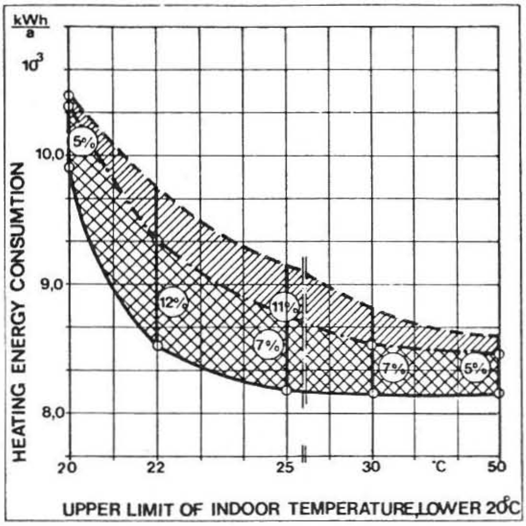
Even a small change in temperature causes heavy structures to store a comparatively large amount of heat. The heat stored in light structures is distinctly less. The heaviest single-family house used in the study (interior mass 700 kg/m^2 of floor surface area) stores 20 kWh of energy if the temperature of the interior mass changes an average of 1 ^{o}C. Under similar circumstances the lightest single-family house (interior mass 30 kg/m^2 of floor surface area) only stores 1,4 kWh of energy.

During a sunny day in spring a maximum of 40 kWh of heat is received through a 10 m^{2}south window. In addition, ca 7 kWh of heat is received at the same time from occupants and electrical appliances. There are simultaneous heat losses of 10...25 kWh depending on the difference between indoor and outdoor temperature. Consequently, in the above case the maximum surplus of free energy to be stored for later use will be 37 kWh.

On the basis of the rough calculation above it is clear that the indoor temperature fluctuation permitted is of great importance in studying the energy-economical significance of building mass.

According to studies on thermal comfort, indoor temperature may be allowed to fluctuate $\pm$2,5 ^{o}C from the optimal value if its rate of change is slower than 0,6 ^{o}C/h. /5/. Following this, 20 ^{o}C has been chosen as the lower limit of indoor temperature, and 25 ^{o}C as the upper limit. At the lower limit heating is commenced, and at the upper limit the ventilation rate is increased, for example by opening a window. The choice of the upper limit of indoor temperature clearly influences the difference in heating energy consumption of a light and heavy house (Figure 8).

Figure 8.
The heating energy consumption of a single-family house depending on its upper limit of indoor temperature and mass. Otherwise the basic data is as for Figure 2.
(In Figure 2 the upper limit of indoor temperature is assumed to be 25 °C and the lower limit 20 °C).



3.4 Distribution of mass and the order in which heavy components are used

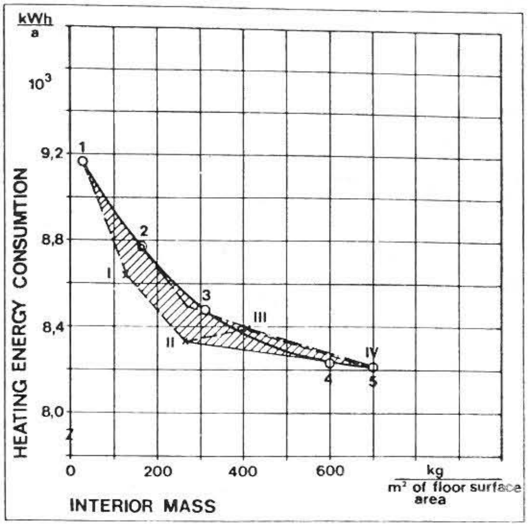
From the point of view of their effect, the heavy components in a building can be distributed in two different places: either on the indoor or outdoor side of the insulation. Heavy components on the outdoor side of the insulation influence very little the heating energy consumption of a building since they readily adopt exterior temperatures.

Heavy components on the indoor side of the insulation (interior mass) have a considerable influence on the energy-economy of buildings since surplus energy is stored in this mass.

The surplus free energy accumulating in daytime is at best quite small if the heat storage capacity of building mass is considered (cp 3.3 above). For this reason, when mass is increased the greatest benefit is derived from the first heavy interior surfaces.

For example, if the interior walls are the first mass-increasing interior surfaces in a single-family house, the heating energy consumption drops about 5,8 %. However, if the mass of interior walls is increased in a house in which all other structures are already heavy, the benefit derived from the mass of the interior walls is only 0,3 % of the annual heating energy consumption (Figure 9).

Figure 9.
The effect of mass distribution and the order in which heavy components are used on the heating energy consumption of a single-family house.



The order of heavy components in the basic alternative:

1. All structures light; interior mass 30 kg/m^2 of floor surface area
2. Heavy floor, other structures light; interior mass 170 kg/m^2 of f.s.a.
3. Floor and exterior walls heavy, other structures light; interior mass 310 kg/m^2 of f.s.a.
4. Floor, exterior walls and ceiling heavy; other structures light; interior mass 600 kg/m^2 of f.s.a.
5. Floor, exterior walls, ceiling and interior walls heavy; interior mass 700 kg/m^2 of f.s.a.

One other replacement order of heavy components:

I Partition walls heavy, other structures light; interior mass 130 kg/m^2 of floor surface area

II Partition and exterior walls heavy, other structures light; interior mass 270 kg/m^2 of f.s.a.

III Partition and exterior walls and floor heavy, other structures light; interior mass 410 kg/m^2 of f.s.a. 1)

IV Ceiling heavy also; interior mass 700 kg/m^2 of f.s.a.

Solar radiation entering a building through the windows first strikes the floor, whence it is transferred to the other surfaces in a room by reflection, as long-wave heat radiation and convection. The convection heat naturally raises the temperature of the air in the room. The location of mass in a place sensitive to radiation is beneficial, but its impact on the benefit conferred by mass is not, however, a deciding factor (Figure 9). This is because the temperature differences of room surfaces remain relatively small due to the effect of reflection, long-wave heat radiation and convection.

1) Note: Lowering the thermal resistance of the floor surfacing layer increases heat loss through the floor.

3.5 Interior surfacing materials

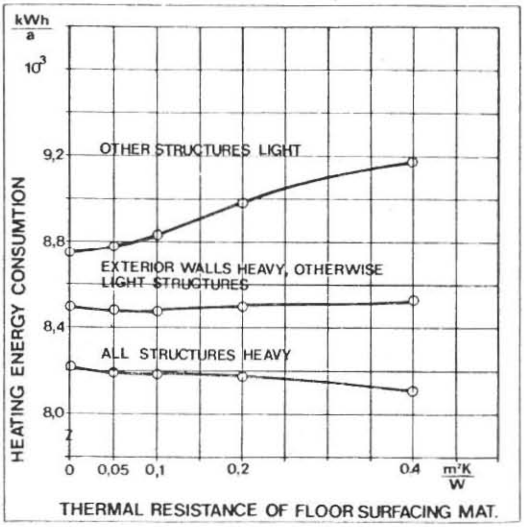
Surfacing materials covering heavy components on the indoor side of the heat insulation slow down the storing in structures of surplus heat entering a building.

In a light single-family house (interior mass 170 kg/m^2 of floor surface area) in which the floor is the only heavy surface, surfacing the floor with heat insulation material increases the heating energy consumption of a building (Figure 10 top line in graph).

In a single-family house having heavy exterior walls in addition to a heavy floor, the effect of surfacing the latter is negligible because the decrease in heat losses through this floor is equal to the benefit deriving from the floor mass (Figure 10, middle line in graph).

In a single-family house in which all surfaces are heavy, surfacing the floor is beneficial because in this case the decrease in the heat losses through the floor is greater than the benefit deriving from the floor mass (Figure 10, bottom line in graph).

Figure 10.
The effect of the thermal resistance of floor surfacing on the heating energy consumption of a single-family house where the mass of other structures varies. The floor consists of a 6 cm thick reinforced concrete slab over a 10 cm thick insulation layer. With the exception of the thermal resistance of the floor surfacing material, the basis for the calculations is the same as for Figure 2. (In Figure 2 the thermal resistance of the floor surfacing material is 0,05 m^{2}K/W). /1/



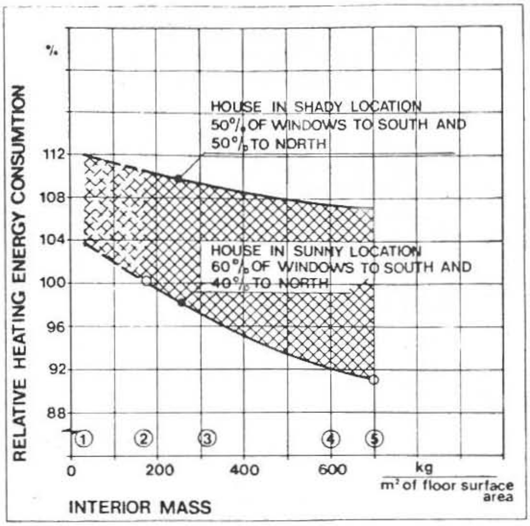
3.6 Joint effects

From the practical point of view, the most important variables in the sensitivity analysis are location and window orientation.

The replacement of light structures with heavy ones in a single-family house whose floors are heavy lowers the heating energy consumption by 3...10 %, depending on the size and orientation of the windows and the location of the building (Figure 11).

Figure 11.
The effect of mass on the annual heating consumption of a single-family house having the following mass alternatives:

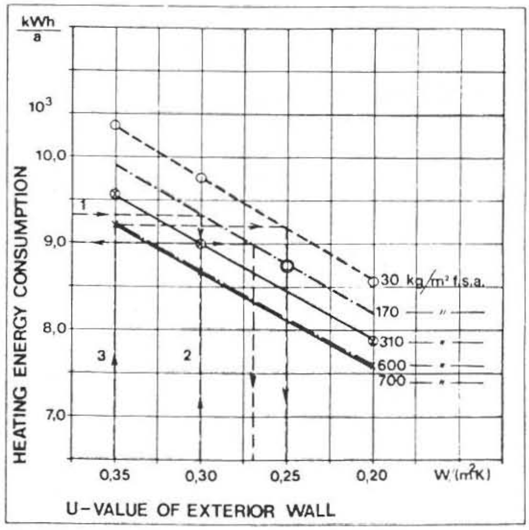
1ª Interior mass 30 kg/m² of floor surface area with all structures light.
2ª Interior mass 170 kg/m² of f.s.a., the floor is heavy (thermal resistance of surfacing material=0,05 m²K/W) and other structures are light.
3ª Interior mass 310 kg/m² of f.s.a., the floor and exterior walls are heavy and other structures are light.
4ª Interior mass 600 kg/m² of f.s.a., the floor, exterior walls and ceiling are heavy and other structures light.
5ª Interior mass 700 kg/m² of f.s.a., the floor, exterior walls, ceiling and partition walls are heavy.



4. MASS AND COEFFICIENT OF THERMAL TRANSMITTANCE OF EXTERIOR WALL OF A SINGLE-FAMILY HOUSE

Improving the U-value of the exterior wall of a single-family house from 0,35 to 0,20 W/m²K reduces the annual heating energy consumption of the house studied by about 17 %. On the other hand, increasing the interior mass of the house from 30 kg/m² to 700 kg/m² of floor surface area lowers the annual heating energy consumption of the house in question by 11 % (Figure 12).

Figure 12.
The effect of the U-value of the exterior wall on the heating energy consumption of a single-family house with different mass alternatives. With the exception of the U-value of the exterior wall, the calculations are based on the same data as for Figure 2. (In Figure 2 the U-value of the exterior wall was assumed as 0,25 W/m²K).



In making economical decisions the alternatives to be compared might for example be the following:

Example 1. The U-value of the exterior wall has been chosen as 0,30 W/m²K. The house already has a heavy floor (interior mass 170 kg/m² of floor surface area; a typical Finnish house). If in this case heavy facades (8 cm of concrete on indoor side of insulation layer) were chosen instead of light ones, the annual heating energy consumption of the building would decrease by 3,7 % (9350 → 9000 kWh/a).

Example 2. One wishes to know how much better the U-value of the light facade in the foregoing situation would have to be in order for the annual heating energy consumption of buildings equipped with a light and heavy facade ($k=0{,}30$ W/m^{2}K) to be the same. It is clear from the figure that the U-value of the light facade must be 0,27 W/m^{2}K.

Example 3. One wishes to know how much better the exterior walls of a completely light house must be in order for the heating energy consumption of a light and heavy single-family house to be the same. It is clear from the figure that the U-value of the exterior wall of the light house must be 0,25 W/m^{2}K if the U-value of the exterior wall of the heavy house is 0,35 W/m^{2}K.

5. EFFECT OF MASS ON THE INDOOR TEMPERATURE OF A SINGLE-FAMILY HOUSE IN SUMMER

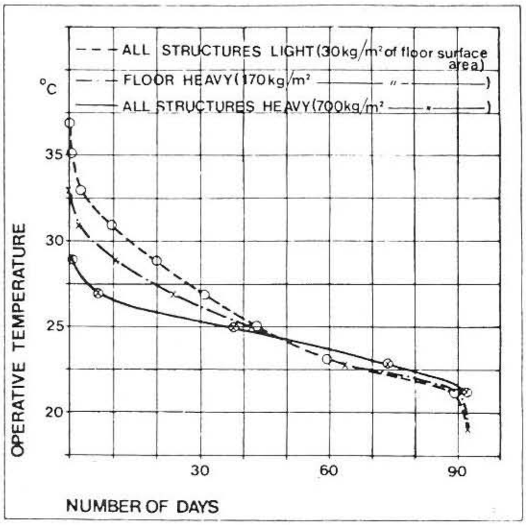
The tightness of houses built in the future and the orientation of windows towards the south poses a certain problem: too high indoor temperatures in summer. Indoor temperatures can be lowered by increasing ventilation, by preventing solar radiation from entering via windows and by increasing building mass.

Increasing the mass of structures lowers indoor temperatures because the heat loads produced during the day by the sun, electrical appliances and occupants are in part stored in heavy structures while, on the other hand, the indoor temperature of a light building often becomes unpleasantly high. During the night structures can be cooled using night air, thus preparing them to absorb the next day's heat loads (Figure 13).

Figure 13.
The stability of the operative temperatures of a single-family house depending on building mass. (June, July, August). Rate of air changes 1,0/h. Air taken from shady place. Triple-glazed windows fitted with Venetian blinds; blinds at angle of 45 °.
τ_L = 0,2 (=penetrating power of solar radiation).
Orientation: - southwards 10 m^2
- northwards 6 m^2

When the operative temperature falls, the temperature of both surfaces and room air is considered as this gives a better picture of indoor conditions than taking the room air alone.

With the exception of air change and window shielding, the calculations are based on the same data as for Figure 2.



6. EFFECT OF MASS ON COOLING RATE AND REQUIRED HEATING POWER

When heating breaks down, a heavy building remains usable longer than a light one because the stored energy keeps a heavy building warm longer than in a light one. For example, when heating breaks down at 20 °C below zero, a heavy building remains usable for over 24 hours while, on the other hand, the indoor temperature of a light building falls to below 10 °C in 5...8 hours.

Mass lowers the required heating power by about 10 % providing that indoor temperature is allowed to fall 2 °C during the severest cold periods and that heating appliances are precisely sized. In such cases the energy stored in structures lowers the power requirements of a heavy building compared to a light one.

7. CONCLUSIONS

With the continuous improvement in the standard of energy economy in buildings, the relative role of free energy in satisfying heating requirements is becoming more and more significant. The exterior and partition walls of a building, windows and heating and ventilation systems form a whole in which the mutually complimenting factors have a decisive effect on each other. When the effect of the characteristics of the different factors on the energy economy of buildings is examined, this reciprocal influence must generally be acknowledged. Building mass is one such characteristic.

Building mass affects the heating energy consumption, the summer indoor temperature, the cooling rate and the required heating power of buildings, so that it must be considered when making economical decisions.

Sources

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/5/ Gonzales, R., Berglund, L., Efficacy of Temperature and Humidity Ramps in Energy Conservation, ASHRAE Journal, June 1979 s. 34...41.

Appendix 1.Wheather data for Central Finland, a rough indication

		Mean temperature °C	Degree Days °C d		Solar radiation on horizontal plane kWh/m^2 mo	
		T_{out}	DD_{17}	DD_{20}	Direct	Diffuse
1	January	-12,3	1026	1131	1,6	4,7
2	February	-11,5	797	881	12,0	12,2
3	Mars	-1,3	512	596	19,4	27,9
4	April	+0,9	452	536	43,5	46,1
5	May	+6,0	356	446	71,5	78,0
6	June	+13,8	29	38	101,9	59,8
7	July	+15,7	-	-	70,7	66,7
8	August	+14,3	29	44	84,6	68,6
9	September	+8,9	226	307	28,8	33,9
10	Oktober	+5,8	305	383	13,5	18,9
11	November	-0,5	553	639	3,5	7,6
12	December	-4,7	666	769	0,4	2,6
	WHOLE YEAR	+2,9	4951	5770	451	427