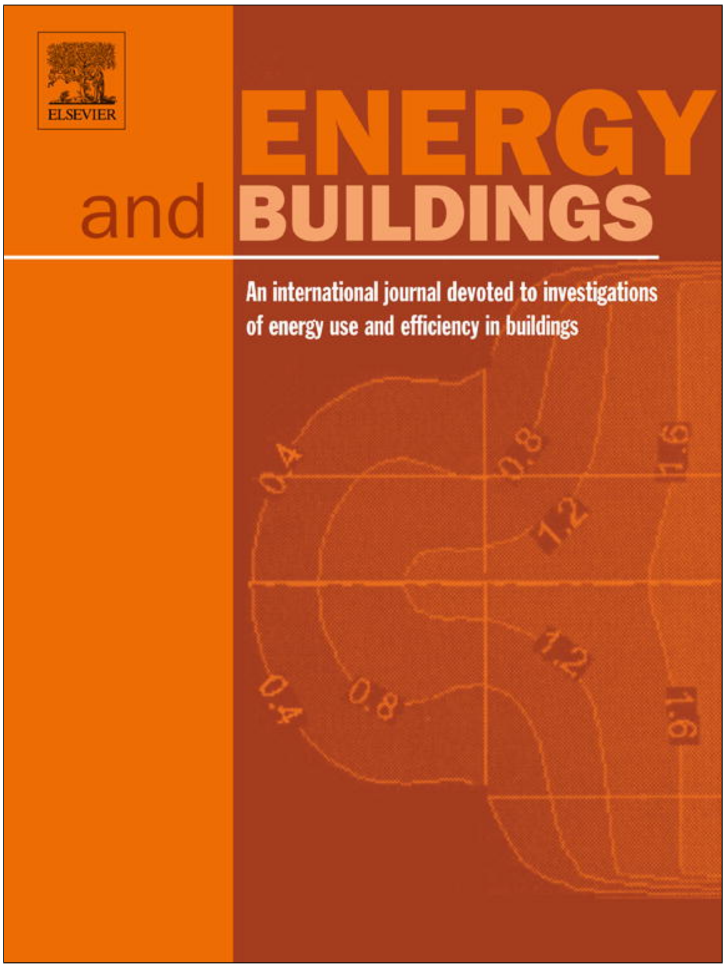

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A conceptual model that simulates the influence of thermal inertia in building structures

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ABSTRACT

The energy use for maintaining comfortable indoor temperatures are to a certain extent dependent on the thermal storage capacity of materials in contact with the indoor air. This article describes a conceptual model for investigating the effects of increasing the thermal storage capacity of building materials. A building is modeled as an exterior wall, an indoor air volume and a thermally heavy inner wall. The input of thermal energy (heating, solar) is also included, as is a varying external temperature. The result is shown in three-dimensional graphs with different output variables of interest as functions of volumetric heat capacity and thermal conductivity of the material in the heavy construction part (with a standard concrete as a reference). Output variables of interest are for example energy consumption, peak power consumption and thermal comfort parameters. Influence of factors such as the thickness of the interior wall, wall surface area, and the influence of free solar radiation can be tested. The aim is to present a minimal and thus fully comprehensible model that can be used as a qualitative tool to investigate the influence of thermal mass on building performance. The model was tested for a cold-climate case and the results show that passive energy storage through high thermal mass can significantly change the power consumption pattern, which can give significant benefits, while the total energy consumption in most cases is not much influenced.

1. Introduction

Optimization of buildings with regard to energy performance and thermal comfort can provide substantial environmental and economical benefits [1]. Thermally heavy buildings – buildings with a high heat capacity inside the thermal envelope – are often credited with a number of positive properties. Firstly, they are said to lower the energy consumption, for example by decreasing cooling needs in warm climates [2,3]. However, the addition of thermally heavy building parts does not always decrease energy consumption [4]; intermittently heated buildings like week-end cabins will for example have an increased heat consumption if the thermal mass is increased. Secondly, the power needs of a building may be lowered or shifted to times when there is a lower power demand, for example by shifting air-conditioning demands to off-peak periods [2] or to use night time cooling in warm climates [5]. Thirdly, thermally heavy buildings give more stable indoor temperatures, something that has been and is used in traditional and modern architecture in warm climates [6,7]. This has been investigated by, e.g., Fernández et al. [8] who divided buildings into different classes depending on their dampening of the external temperature variations.

Concrete is the most common material that gives high thermal mass in buildings, and the present study concerns how the thermal properties of concrete will influence the thermal characteristics of a building. The aim is to investigate whether concrete with increased volumetric heat capacity and/or increased thermal conductivity can be useful in the construction industry. It is possible to increase both these properties by at least 50% [9], compared to standard concrete. For example can one exchange the ordinary rock aggregate with magnetite (iron ore) aggregate to increase the volumetric heat capacity, and add graphite to increase the thermal conductivity, but it is not known how beneficial this would be.

The influence of thermal mass on building performance is usually studied by calculations with analytical or numerical methods. Balaras [10] reviewed computational methods for thermal mass in buildings and found a host of different simplified methods using different ways to take thermal mass into account. Many of the used methods are simplified one-dimensional or network models that disregard aspects that are not of main interest [2,11,12]. For example did Li and Xu [11] disregard the heat flow through the thermal envelope in a study on the influence of thermal mass on night time ventilation. This was a valid approach as their aim was to investigate natural cooling in a warm climate.

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In the present study, the aim was to investigate the value of thermal mass in a cold climate where buildings are heated for most part of the year and where a substantial part of the heat losses in buildings are by heat conduction. We have therefore included heat losses through the thermal envelope, but disregarded ventilation. In a cold climate, the ventilation is only used to bring fresh air into the building, not to heat or cool it, and ventilation heat losses have been significantly reduced by modern ventilation systems with heat exchangers. The heat loss through ventilation is also approximately proportional to the heat loss through the thermal envelope, as the heat loss rates through both these routes are proportional to the temperature difference over the thermal envelope.

When analytical methods are used the cases studied have to be simplified so that they can be treated by available analytical tools. For example have Antonopoulous and Tzivanidis [13] and others described building thermal performance in terms of a thermal time constant, and Li and Xu [11] found that they could describe a building's thermal characteristics with three parameters: a time constant, a convective heat transfer number, and a parameter describing the effectiveness of the heat transfer inside the "virtual sphere" in which they concentrated all the thermal mass of a building. Such an approach can lead to a set of useful equations for the designer, but the analytical approach is limited in what can be modeled. We have therefore instead used a numerical approach in which we still use a simple model, but complement this with non-linear functions, for example how the cost of heating is influenced by a complex cost function. However, note that our models are still simplified models described by relatively few parameters.

The aim of this work was to investigate how the thermal properties of materials influence energy use, power demand, and comfort in a number of cases. The described model incorporates an inner concrete wall, whose thermal properties we change from the properties of normal concrete in the directions of higher volumetric heat capacity and higher thermal conductivity. The values used are based on a recent study of high heat capacity and high conductivity materials in concrete [9] (an alternative to this – that we do not investigate here – is to instead add phase change materials (PCM) [14,15]). The model described in this article makes it possible to quickly investigate the relative importance of material thermal properties in thermally heavy buildings, but it is a qualitative tool that should not be used for quantitative analysis. Its main use is to clarify factors in discussions about how to creatively design thermally heavy constructions.

2. The model

The one-dimensional model was programmed in MATLAB (Mathworks Inc., Natick, MA, USA). The building model consists of three parts: an external wall, the indoor air and an internal wall, see Fig. 1. The program works with an arbitrarily chosen internal air volume of 1 m^3. The wall surface area and other parameters are then related to this volume as these parameters are related in the type of building of interest.

In the presented model the main interest is the storage of sensible heat in the inner wall. The model has the following components (numbers given refer to Fig. 1):

- A 1 m^2 external wall has an overall heat transfer coefficient (U_e) of 0.2 W m^{-2} K^{-1}. This corresponds to about 20 cm insulation, which is less than what is used in for example the Nordic countries, but does here also include heat losses through windows and other less insulated building parts. The thermal mass of the wall corresponds to about 5 cm of standard concrete. The external wall is divided into three computational cells (1–3) into which both thermal resistance and heat capacity are equally divided.
- A 1 m^3 air volume with a heat capacity C_{air} corresponding to 1 m^3 air is modeled as a single body with complete mixing (4).
- An internal wall of concrete described by a thermal conductivity (λ), a volumetric heat capacity (c_v), a thickness (d), and a thermal surface transfer coefficient (α_i). The temperature profile in the internal wall is calculated numerically in one dimension using ten computational cells through the thickness (5–14). The back side of the internal wall is perfectly insulated (equal to an actual internal wall in a building having a thickness of 2d).
- To model the influence of thermal inertia it is important that the heating system allows temperature changes. We have in the present case used a simple on–off heating system with a heating power P_{HS} and a temperature hysteresis (see Fig. 2A). When the room temperature T_4 drops below a lower threshold value T_L, heating starts with a constant thermal power and continues until the room temperature has reached an upper threshold value T_H. In one case the heating system was arranged so that T_H and T_L changed to lower values if the external temperature was below −10 °C.
- The external temperature T_e is modeled as a daily sinusoidal oscillation between 0 and 10 °C. In one case we added a cold spell every fifth day by subtracting 20 K from the oscillation during 24 h (Fig. 2B).
- The model does not include any free heat from people and heat producing devices, but to investigate the possibility to prevent over-heating, we have in some cases added a high thermal input P_{sun} for a few hours during midday, typical of free solar heat (Fig. 2C).
- To model the increased cost of energy production at low temperatures, the cost of heating was in one case based on a heating tariff in which the energy price was a function of the external temperature in the following way: the price was constant down to +10 °C and then increased linearly with lowered temperatures below that level so that the price was doubled at −10 °C (Fig. 2D).

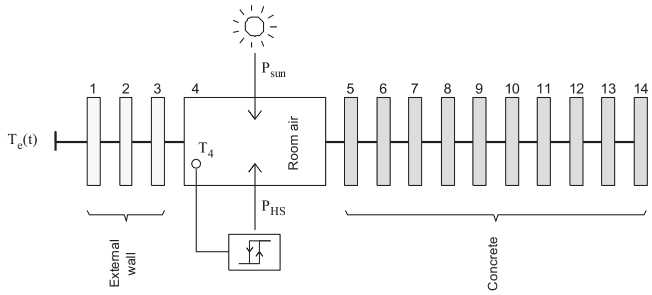

Fig. 1. The numerical thermal model. Each rectangle is a cell (a heat capacity) and the thick black lines are thermal connections (conductances) between the cells. From left to right there is the external temperature $T_e(t)$, the thermal envelope (1–3), the interior air (4), and an interior concrete wall (5–14) whose thickness and thermal properties are the main interest of the present study. A heating system (P_{HS}) and free solar heat (P_{sun}) supplies heat to the interior air.

Note that the model is described by only about 20 parameters and is therefore a small model. We have for example chosen to not include a ventilation system and in the "external wall" the whole building envelope is included. However, it is easy for a user to add and/or remove components as the model is small and transparent. In the present case the focus was on the effect of increasing the heat capacity and the thermal conductivity of the concrete in an inner wall.

The model is solved by explicit forward difference calculations. In this method each cell I in the calculations (1–14 in Fig. 1) is assigned a heat capacity C_I (J K^{-1}), and each pair of cells I and J

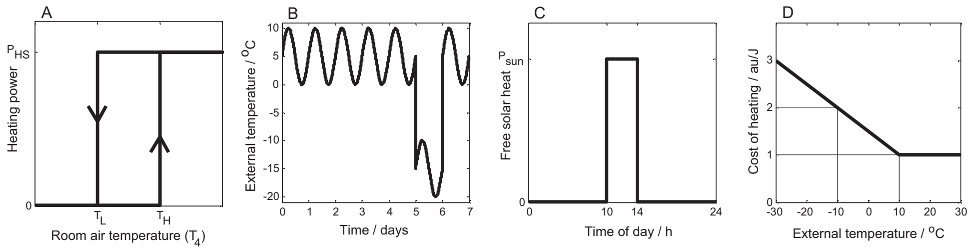

Fig. 2. Functions used in the simulations. (A) The heating of the room air was modeled as an on/off-heater with hysteresis. (B) The external temperature was a daily sinusoidal, to which in two cases was added a cold spell every fifth day. (C) Daily free heat was added to the room air at midday in two simulations. (D) In one simulation the cost of heat was modeled as increasing with decreasing external temperature (au/J = arbitrary units per joules of heat).

that are thermally connected are connected by a thermal conductance k_{IJ} (W K^{-1}). In the explicit method the solution to a thermal problem is found by repeating two steps. First the heat flows q (W) between all connected cells are calculated:

$$q_{IJ} = k_{IJ}(T_I - T_J), \tag{1}$$

and then the resulting temperature changes in each cell is calculated:

$$T_I(t + \Delta t) = T_I(t) + \sum q_I \frac{\Delta t}{C_I}. \tag{2}$$

Here, Σq_I is the sum of all heat flows to cell I, and Δt (s) is the time step of the simulation. The thermal conductance between two cells is calculated as the conductance between the mid-points of the two cells:

$$\frac{1}{k_{IJ}} = \frac{d_I}{2\lambda_I A_I} + \frac{d_J}{2\lambda_J A_J} \tag{3}$$

Here, d (m) is the thickness and A (m^2) is the cross-sectional area of each cell. In the case of cells on the surface of a material, the surface mass transfer resistance α_J (W K^{-1} m^{-2}) (if there is one) takes the role of one of the terms in Eq. (3):

$$\frac{1}{k_{IJ}} = \frac{d_I}{2\lambda_I A_I} + \frac{1}{\alpha_J A_J} \tag{4}$$

Cell heat capacities are calculated by:

$$C_I = c_{v,I} A_I d_I \tag{5}$$

Here, $c_{v,I}$ (J/m^{-3} K) is the volumetric heat capacity.

The time step Δt (s) has to be chosen so that it does not exceed a critical time step at which the simulation becomes unstable. This is found from the following inequality:

$$\Delta t > \frac{C}{2k} \tag{6}$$

which represents the limiting case where temperature difference between two neighboring cells is evened out in one time step. Above this limit the amount of heat moved in each calculation step will cause the temperature difference between neighboring cells to shift sign on every simulation step, i.e., cause non-physical oscillations. The lowest critical time step calculated anywhere in a model is the critical time step of the whole model; often a slightly lower time step than this is used. In the present simulations a time step of 10 or 20 s was used.

The simulations were run for 20 days and the result from the whole simulation period is used to calculate the output variables described below. The initial temperature of the system was in all cases 20 °C.

When compared with analytical solutions, a disadvantage with this type of numerical simulation is that it is difficult to present the result (the program code) in a few lines; analytical formulations can be made much more compact. However, the numerical simulation gives a freedom to incorporate whatever one wants into the model without the restraint that comes with the need to be able to solve analytical formulations. It would, for example, have been difficult to include the heating with hysteresis, the cold spell, and the cost model that we have used in an analytical model.

Our interest here has been to study the effect of the thermal inertia of the inner wall on three parameters: (1) heat consumption; (2) peak power load and cost of heating; (3) comfort. For each of these cases a relevant output variable was constructed:

(1) Percent lowered heat consumption relative to the standard case. The energy stored in the internal wall at the end of the simulation relative to the stored heat at time zero was subtracted from the energy consumption.
(2) Cost of heating relative to the standard case. Two cost models were used: (a) constant cost per heat unit. (b) A cost model with increased cost per heat unit at lower temperatures (Fig. 2D).
(3) Comfort (or rather the lack of comfort) was quantified as the percentage of the time when the indoor temperature was above 24 °C.

The standard case was in all cases an internal wall thickness d = 0.1 m, a volumetric heat capacity c_v = 1.5 MJ m^{-3} K^{-1}, and a thermal conductivity λ = 2 W m^{-1} K^{-1}. These are normal values for a massive concrete wall. The simulations were run for two wall thicknesses (0.1 and 0.3 m) and all combinations of seven different thermal conductivities and seven different volumetric heat capacities. For both these parameters a range of values spanning from the values used in the standard case to twice those values were used. These values are typical of what one can achieve with, e.g., iron ore aggregate for increased heat capacity and graphite for increased thermal conductivity [9]. The result parameters are plotted against this 7 × 7 matrix.

Six different cases were studied:

(A) The heat consumption of a building with a daily period of free heating from the sun.
(B) The same case as A, but without free heating.
(C) The heat consumption of a building that is only heated in the weekends.
(D) The cost of heating a building during cold-spells when the cost of heat is differentiated so that it is more expensive when it is cold.
(E) The cost of heating a building during cold-spells when the cost of heat is constant.
(F) The thermal comfort when there is a significant free heat from the sun.

The parameters that define the six cases are listed in Table 1. It should be noted that the defining parameters are rather arbitrarily chosen and that the results should be seen as qualitative.

Table 1
Overview of the input parameters for the six simulation cases described in the text. When no value is given, the value for case A was used.

		Simulation case						
		A	B	C	D	E	F	
A_e	External wall area	1						m^2
A_i	Internal wall area	0.3						m^2
c_v	Internal wall volumetric heat capacity	1.5×10^6–3×10^6						$J/m^3 K$
d	Internal wall thickness	0.1 or 0.3						m
λ	Internal wall thermal conductivity	2–4						W/m K
C_{air}	Indoor air heat capacity	1200						$J K^{-1}$
T_e	External daily temperature sinusoidal 0–10 °C	Yes	Yes	Yes	Yes[A]	Yes[A]	Yes	°C
P_{sun}	Power from the sun between 10 h and 14 h	20	0	0	0	0	15[B]	W
P_{HS}	Power from the heating system	20	20	10[C]	4	4	4	W
T_L	Lowest allowed temperature	19	19	19.8	19.8[D]	19.8	19	°C
T_H	Highest allowed temperature	21	21	20.2	20.2[D]	20.2	21	°C
U_e	Heat transfer coefficient of insulation in external wall	0.2						$W/m^2 K$
	Thickness of external concrete slab	0.05						m
	Volumetric heat capacity of external concrete slab	1.5×10^6						$J/m^3 K$
	Thermal conductivity of external concrete slab	2						W/m K
α_i	Surface heat transfer coefficient of internal wall	10						$W/m^2 K$

A: these temperatures were lowered 20 K every fifth day (cold spell).
B: between 9 h and 15 h.
C: heating only on week-ends (days 6 and 7 of each week).
D: these temperatures were lowered 2 K when the external temperature was below −10 °C (combined with a differentiated heating tariff as described in the text).

3. Results

The results in Fig. 3 show how the heat consumption, cost (related to peak power loads) and comfort is related to the thermal properties of the inner wall in the model building for two wall thicknesses *d*. As is seen in the figures the influence of the thermal mass is quite different in the tested six cases. In three cases does high thermal inertia (thicker inner wall, higher volumetric heat capacity) give advantages (A, D and F); in two cases it does not much influence the result (B and E); and in one case (C) it is a clear disadvantage to have high thermal inertia. In no case does the thermal conductivity influence the results significantly (Fig. 3).

4. Discussion

The aim of the present article was to add to the discussion on the possible advantages with thermally heavy buildings in cold climates, and then especially the incorporation of materials with enhanced thermal properties. Working with the described model makes it possible to answer questions concerning the importance of high thermal inertia in buildings, such as:

- Will one always save heating energy by including an interior concrete wall in a building? The answer is no; there are cases when high thermal inertia is a clear disadvantage, for example for intermittently heated buildings (case C).
- Does the peak thermal power demand during cold-spells decrease in buildings with high interior thermal inertia? The answer to this question depends on how the heating is organized. In buildings with a tight control of indoor temperature one will not get much temperature changes in interior components and thus it does not make any difference whether, e.g., an inner wall is light of heavy (case E, where the cost is proportional to the consumed heat). However, if interior temperature is allowed to decrease significantly during cold-spells, the heating power can be reduced (during the cold-spell) if the building contains thermally heavy interior structures with stored heat.
- Will the heating bill be reduced if a building is “heavy”? The answer is that this depends on whether you can allow the temperature to swing – both up when there is free heat available, and down during cold-spells – and how your heating tariff is arranged. It is probable that significant economical savings will only be found when both the above criteria are favorable. One such instance is shown above as case D where the heating tariff severely punishes building owners that buy heat when the outdoor temperature is low. If one then can allow the indoor temperature to decrease slightly during a cold-spell in a building with high thermal inertia one can make significant savings by not buying heat during periods when the heat is expensive.
- Is the thermal indoor climate better in buildings with high thermal inertia? This question is complex, but it is true that the temperature variations will be lower in a thermally heavy building (case F).
- It is obvious that a high volumetric heat capacity leads to high thermal inertia, but is it important to also have a high thermal conductivity in the heavy construction part? The present simulations show that the thermal conductivity of a concrete structure is of secondary importance as, at least for temperature variations on the time scale of the order of a day, nearly the whole thickness of standard concrete walls will follow the room temperature variations, so an increased thermal conductivity is normally not an asset in this case. This can be illustrated by the following figures. Standard concrete has an approximate thermal diffusivity of $10^{-6}\,m^2\,s^{-1}$. If a concrete wall with a homogeneous temperature distribution is exposed to a temperature step on its surfaces, the time it takes for 90% of the heat to flow in or out of the wall to achieve a new stationary condition is 40 min, 2.5 h and 10 h for walls with thicknesses 10 cm, 20 cm and 40 cm (in the absence of surface mass transfer resistances like boundary layers or wallpapers). At least for the to two thinner walls, these times are short compared to the daily temperature variations. The thermal conductivity is then of secondary importance. However, the situation may be different when quick heat storage is important; for example to take care of intensive free solar heat during a few hours.

These general results concerning the influence of thermal mass agree with what has been found in previous studies. For example did Bloomfield and Fisk [16] in a study on daily intermittent heating (decreasing heating when a building like an office is not used) conclude that the additional thermal inertia of heavy-weight buildings do not offer any substantial energy savings in the case of daily intermittent heating (although intermittent heating strategies needs to be tailored to the thermal inertia of the building [16,17]). What one gains by not heating in one period is approximately lost when one has to heat more before people enter the building. It is thus not

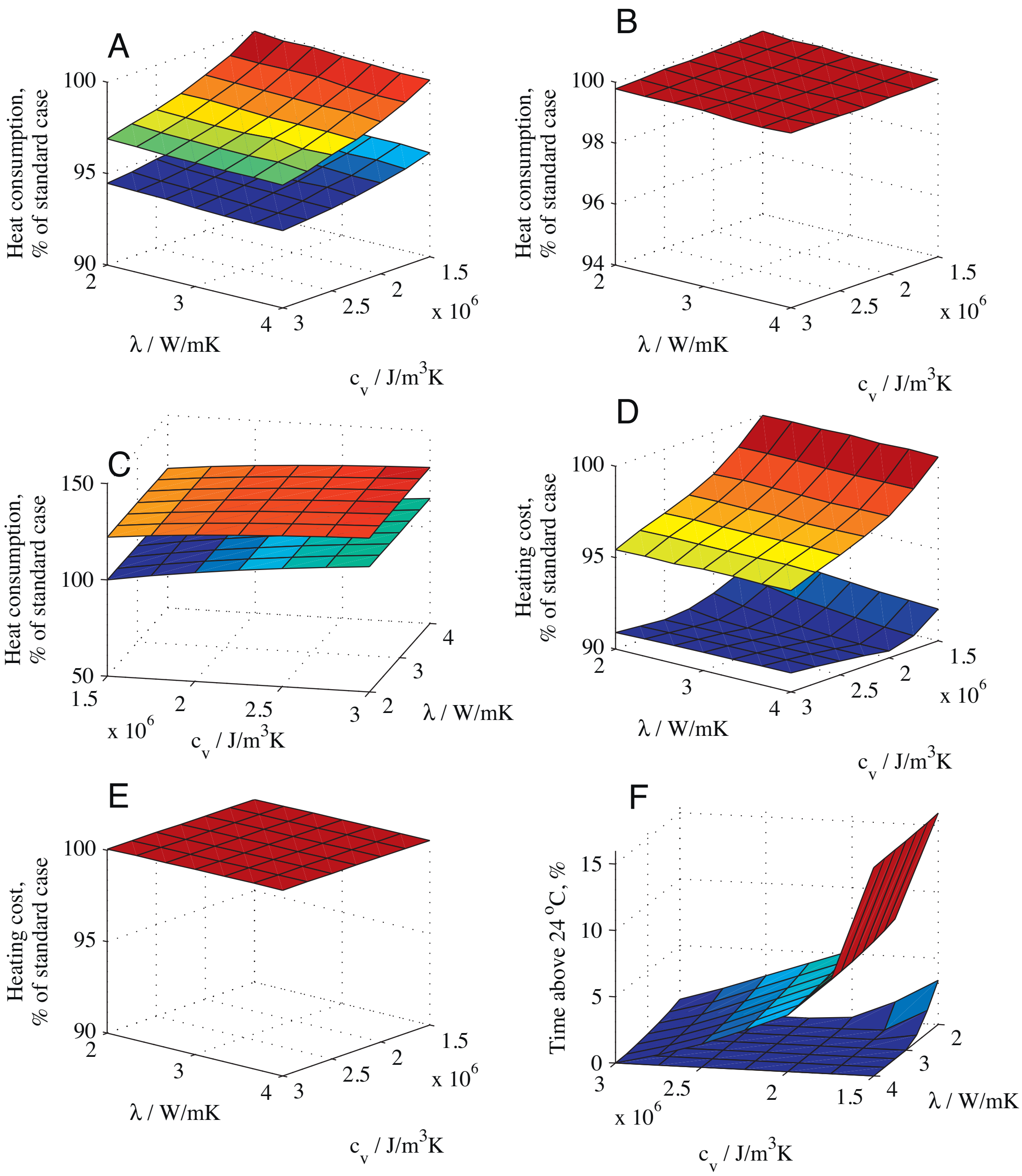

Fig. 3. The simulated results in the six cases described in Table 1 and the text. The top surface in each diagram is for a wall thickness of 0.1 m and the lower surface is for a wall thickness of 0.3 m (for (B) and (E) only one surface is shown as the two surfaces are almost identical). Note that the plots have been rotated differently in the heat capacity–thermal conductivity plane to more clearly show each result. The coloring differentiates different levels.

obvious that one will, e.g., save energy by increasing the thermal mass of a building. Statements like "The thermal mass of concrete in buildings [. . .] reduces heating energy consumption by 2–15%" [18] are not generally true. If positive effects will be achieved depends on many factors, like climatic conditions and acceptable indoor requirements, and it may be difficult to get only positive benefits from a high thermal mass; cf. Shao [4] who points out that "high thermal mass design could introduce conflicting requirements for winter heating and summer cooling".

Bellamy and Mackenzie [19] studied two test houses that were identical except for that one of the houses had a high thermal mass inside the external insulation. In their case the energy savings in a continuously heated house were strongly related to the reduction in ventilation requirements for cooling provided by heavy walls. They point out that "[s]imply replacing lightweight walls with heavy walls of equivalent *R*-value may increase or decrease the auxiliary heating requirements depending on the house design, climate and occupant behavior".

In general the thermal heaviness of a building can be quantified by the building's thermal time constant τ (s), which is defined by the ratio of the heat capacity inside the insulation and the thermal conductance of the envelope [2,13]. For our building model this will be:

$$\tau = \frac{A_i d c_v}{A_e U} \tag{7}$$

For our standard case the time constant is 62 h; increasing the (half) wall thickness to 0.3 m gives 187 h; also using a material in the inner wall with doubled volumetric heat capacity gives 375 h. There are thus significant differences in how rapidly the modeled buildings will cool down if left in a cold climate without heating. The time constant is the time it takes for the temperature difference between inside and outside to drop to about 37% (e^{-1}) of its initial value; however, we cannot allow such a temperature drop in a cold climate. If we instead allow the temperature to drop from 20 to 15 °C when the external temperature is −20 °C, the temperature difference (inside–outside) will decrease to 87.5% of its initial value and this will always happen at about 13% of the time constant, i.e., at 8, 25 and 50 h after the heating of the buildings were discontinued. For the heaviest building this is a rather long time and if one allows the temperature to drop to 15 °C no heating is needed for two days even when the temperature is −20 °C outside. However, the reason that this building can function 50 h without heat supply is that it contains heat stored in the inner walls, and this heat has to be replenished after a cold-spell to get back to 20 °C. There is not much to be won in this case compared to a light building (in which the temperature is also allowed to drop to 15 °C) if one does not in one way or another take into account that it is more expensive to produce heat during cold-spells as the heating demand is then generally higher in the whole society. Heavy buildings are this perspective mainly an asset if their energy consumption is looked upon in a larger societal perspective.

An important question – apart from whether high internal heat capacity gives positive effects concerning energy, power or comfort – is whether high internal heat capacity is economical or not. We will not treat that issue here, but only remark that if the design of a building includes high heat capacity, this can often be used to gain positive effects. It is, however, probably much more difficult to economically add thermally heavy building components with the only aim of increasing the time constant of a building.

We conclude that also rather limited models can be useful for the conceptual understanding of how dynamic systems work. The described model can be further developed in different ways to account for other aspects, for example to include ventilation, thermally heavy parts of the external wall, or phase change materials.

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