Numerical Analysis of the Impact of Thermal Inertia from the Furniture / Indoor Content and Phase Change Materials on the Building Energy Flexibility

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Abstract

Many numerical models for building energy simulation assume empty rooms and do not account for the indoor content of occupied buildings. Furnishing elements and indoor items have complicated shapes and are made of various materials. Therefore, most of the people prefer to ignore them. However, this simplification can be problematic for accurate calculation of the transient indoor temperature. This article firstly reviews different solutions to include the indoor content in building models and suggests typical values for its characteristics. Secondly, the paper presents the results of a numerical study investigating the influence of the different types of thermal inertia on buildings energy flexibility. Although the insulation level and thermal mass of a building envelope are the dominant parameters, it appears that indoor content cannot be neglected for lightweight structure building simulations. Finally, it is shown that the integration of phase change materials in wallboards or furniture elements can appreciably improve the energy flexibility of buildings.

Introduction

A significant deployment of renewable energy sources (RES) is foreseen in numerous European countries. The increasing share of intermittent RES may decouple instantaneous energy use and production, affecting the stability of the grids (Beurskens et al. 2011). In order to face this problem, recent projects are developing energy flexible technologies and demand-side management strategies to facilitate the operation of a smart grid system with high intermittent power penetration, (Mathiesen et al. 2015).

Buildings can bear flexible energy use to a certain extent. Moreover, the building sector is the largest energy end-user in many countries and can therefore play an important role in the management of the energy grid. Passive thermal energy storage (TES) in the indoor space was found to be a promising solution for building energy flexibility and more cost effective than heat accumulation water tanks (Hedegaard et al. 2012). Le Dréau and Heiselberg (2016) evaluated the potential of residential buildings for set point modulation in order to shift the energy use from high price to low price periods. It was shown that power modulation could be achieved without compromising the indoor thermal comfort: from a couple of hours for poorly insulated houses and up to 24 hours for well-insulated buildings.

This strategy relies on an accurate control of the transient building temperature. However, many of the current numerical models for building energy systems assume empty rooms and do not account for the internal content thermal inertia of objects like furniture. Such simplification is sufficient for energy calculations with constant set point but could be problematic for light buildings with dynamic set point modulation.

Some researchers emphasized the role of furniture in the indoor thermodynamics. Antonopoulos and Koronaki (2000) evaluated that furniture represented 7.4% of the total effective thermal capacitance of a typical Greek house, and can increase the building time constant and thermal delay by up to 15%. Wolisz et al. (2015) carried out a numerical analysis on the impact of modelling furniture and floor covering for building simulations with temperature set point modulation. The study showed that a fully equipped room can present a temperature increase time delay of more than 7 hours compared to an empty room. In the case of periodic set point control, the furnishing and floor covers can change the cool-down time by up to 2 hours.

In a first part, this article reviews different suggestions for the modelling of the furniture / indoor content thermal mass in building energy simulations. In a second part, the impact of different thermal inertia elements, and in particular the furniture / indoor content, is evaluated regarding short-term indoor heat storage for building energy flexibility.

Quantification and characterisation of the indoor content thermal mass

The amount of items in the indoor space can vary considerably in each room and building. No study or clear guidance concerning typical values for the furnishing / indoor content parameters in buildings could be found. It is therefore complicated to tackle the problem of indoor thermal mass modelling without having an idea of what are its physical properties. In order to address this issue, a simple survey has been performed on residential and single office buildings in Denmark (Johra and Heiselberg 2017). The quantification and characterisation of the building indoor content is a tedious task and only a study with a large sampling could pretend to provide statistically representative data. This is not the aim of this survey as it only proposes reasonable boundaries for the furniture / indoor content parameters based on systematic measurements of mass and dimensions of each piece of internal elements in 6 different bedrooms, 3 living rooms and 3 single office rooms.

One can see on Figure 1 that a reasonable range for the internal mass density in office and residential buildings would be 10–100 kg/m² of the net floor surface area (Johra and Heiselberg 2017). The few publications providing a value for internal content mass tend to over-estimate it compared to the results of the current survey (Raftery et al. 2014; Antonopoulos and Koronaki 2000).

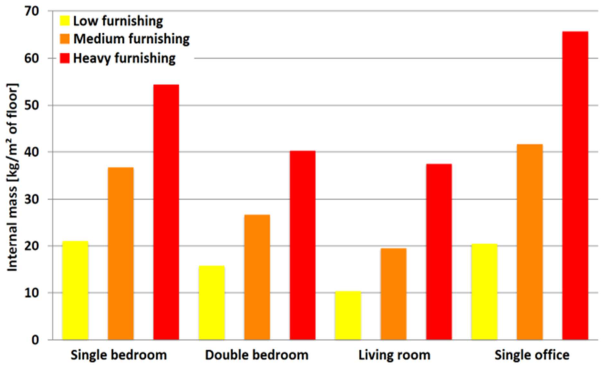

Figure 1: Internal mass of the building survey.

In addition, it has been found that most of the indoor content elements have a planar shape and can be classified into 4 distinct representative material categories.

Based on the results of the survey, suggestions for the thermo-physical properties of these 4 representative categories and an equivalent fictitious indoor content material are presented in Table 1 (Johra and Heiselberg 2017). They can be used to model the indoor content in building energy simulations as thin planar elements. In Table 1, the average value of each parameter is followed by its minimum and maximum limits in parentheses.

From these measurements and material assumptions, the effective thermal capacitance of each indoor element is calculated according to the standard method ISO 13786:2007. Their summation gives the total daily effective thermal inertia of each room's internal content.

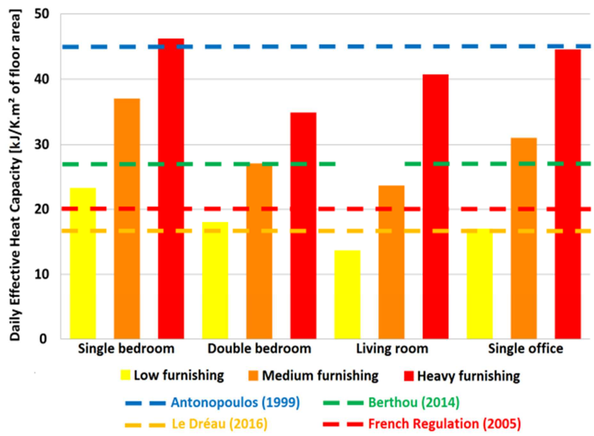

Figure 2: Daily effective heat capacity of indoor content / furniture thermal mass in buildings.

One can observe on Figure 2 that the results of the survey are in good agreement with the values found in different publications.

Modelling of the indoor content thermal mass for building energy simulations

The indoor content and furnishing elements often have complicated geometries with various types of material. The following section presents the different modelling technics found in publications attempting to represent the indoor thermodynamics in details.

Table 1: Properties of the representative indoor content material categories.

Material category	Room mass content (kg/m² floor area)	Surface area (m²/m² floor area)	Material density (kg/m³)	Material thermal conductivity (W/m.K)	Material specific heat capacity (J/kg.K)	Planar element thickness (cm)	Daily effective thermal inertia (kJ/K.m² floor area)
Light material	7 (0.5–14)	0.3 (0.1–0.6)	80 (20–140)	0.03	1400	10 (0.5–24)	3 (0.2–7)
Wood / plastic material	30 (8–80)	1.4 (0.5–2)	800 (400–1200)	0.2 (0.1–0.3)	1400	1.8 (1–5)	26 (9–45)
Concrete / glass material	1 (0.5–2)	0.03 (0.01–0.04)	2000 (1500–2500)	1.25 (0.5–2)	950	1 (0.2–2)	0.1 (0.05–0.2)
Metal material	2 (1–5)	0.02 (0.01–0.03)	8000	60	450	0.2 (0.1–0.3)	0.1 (0.05–0.4)
Equivalent indoor content material	40 (10–100)	1.8 (0.8–2.8)	600 (150–1500)	0.3 (0.1–0.5)	1400	4 (1–10)	30 (10–50)

First order thermal network building model

Simplified thermal network or resistance – capacitance (RC) models with the *xR1C* (x resistances and 1 capacitance) configuration aggregate all the effective thermal inertia of a thermal zone in a single capacitance. The latter includes the indoor air volume, interior walls, inner envelope walls and the furniture / indoor content effective thermal capacitance. This simplified model assumes that the entire thermal mass is perfectly isothermal with homogenous equivalent properties and constant thermal resistances. A *5R1C* model is described in the standard ISO 13790:2008.

Higher order thermal network building model

A RC network building model with more a realistic dynamic behaviour can be achieved by increasing the number of lumped capacitance nodes and dissociating the thermal mass elements with dissimilar thermal diffusivities. The indoor air volume and the construction elements can be separated to form a *xR2C* model. The RC network can be expended further to a *xR3C* or *xRyC* configuration (*x* resistances and *y* capacitances) by segregating the internal separation walls, the envelope walls and the heavy concrete floors or ceilings.
The furniture / indoor content effective thermal mass can then be integrated into these different lumped capacitances. Berthou et al. (2014) and TRNSYS type 56 models assume that items in the indoor zone are perfectly isothermal and in thermal equilibrium with the indoor air. The indoor content capacitance is therefore added to the one of the indoor air.
On the contrary, if it is assumed that the indoor content is not at the same temperature as the indoor air, the furniture / indoor content thermal mass can be merged with the one of the inner surface envelope walls or the interior partition walls (Berthou et al. 2014; Bacher and Madsen 2011). Moreover, the internal mass sub-system can be extended into a *2R2C* network to account for the temperature gradient in the equivalent element.

Distinct furniture / indoor content thermal mass capacitance

The thickness, thermal diffusivity and heat exchange coefficients of the furnishing elements may differ significantly from the ones of the wall inner surfaces. Therefore, a noticeable temperature difference could remain between the indoor content and the other building elements or the indoor air node. This would justify to model the indoor thermal mass with its own lumped capacitance.
The TRNSYS Type 56 model allows the inclusion of an additional fictitious furniture thermal mass node in the star network scheme for radiation and convection heat exchange calculations. The specific location of the internal mass is not required, but a proper equivalent surface area must be specified.
The ISO 13790:2008 standard provides a simplified formulation for the calculation of this equivalent indoor content surface area. Li et al. (2016) proposed a new method to transform the furniture items with irregular shape into a single lumped capacitance node with an appropriate effective area.
It should be kept in mind that the aggregation of the indoor objects into a single lumped capacitance is a non-geometrical heat balance calculation. Consequently, the correct assessment of solar radiation reaching the furniture node and the long-wave radiation heat exchanges with radiant surfaces can influence significantly the simulation results.

Equivalent virtual sphere model

The resistance – capacitance models represent the building system with a reduced number of nodes. Each of these node sub-systems is thus assumed to be isothermal. This assumption is acceptable if the Biot number of the element is smaller than 0.1. For plastic and wooden plates constituting most of the furnishing, this condition would imply elements thinner than 2 mm. However, most of the internal mass and furniture elements are thicker than 2 mm. Consequently, the indoor thermal mass cannot be considered isothermal and the lumped capacitance method should not be used to model it (Ma and Wang 2012).
To overcome this problem, Gao et al. (2000) and Zhou et al. (2011) suggested the virtual sphere method to model the internal mass. It aggregates different shapes of solid body into a single sphere with a radius equal to the characteristic length of the element. It is suitable for systems with Biot number in the range of 0 to 20, which is typically the case for the indoor content. Moreover, an effective convection heat transfer coefficient is introduced to account for the uneven distribution of indoor items' temperature. Nevertheless, this model does not currently include the radiation heat exchange.

Equivalent virtual planar element model

Antonopoulos and Koronaki (2000), Ma et al. (2012) and Wolisz et al. (2015) have chosen to concentrate the entire indoor content into a single equivalent planar element. This slab is made of an homogeneous material with constant properties which are representative of the items found in the indoor space. Because the length and width of the slab are much larger than its thickness, the conduction heat transfers and temperature distribution inside the element can be easily calculated with a one-dimensional finite difference or finite volume method formulation.
However, this equivalent slab element does not have a geometric representation in the thermal zone. Therefore, the presence of the planar element in the room is not taken into account for the calculation of internal solar distribution or long-wave heat exchange in between inner surfaces.
Energy Plus and IDA ICE software also allow the insertion of an equivalent furniture element as a fictitious one-dimensional multi-layer planar element which interacts solely with the air node by convection.

Equivalent geometric planar element model

Raftery et al. (2014) developed and implemented into Energy Plus software an equivalent planar element model with a geometric representation and location inside the thermal zone. The slab is thus taken into account for the computation of the direct light beam reaching internal surfaces, diffuse solar repartition and radiant mean temperature. The long-wave radiation heat exchange can be calculated by radiosity method with correct view factors affected by the planar element in the middle of the room. Shading effect on the floor is modelled properly which adds a more realistic thermal behaviour to radiant systems.

Detailed explicit furniture model

The aforementioned indoor content modelling technics aggregate the items of the indoor space into a single equivalent element. This choice is justified by the complexity and the unknowns of what is inside an occupied building. Nonetheless, some numerical studies investigated the implications of the detailed modelling of furniture and indoor content with explicit locations in the building.

Athlaye et al. (2013) conducted an analysis with Radiance software and concluded that including details of interior partitions and furnishing has a significant impact on the indoor daylight conditions.

Bojic et al. (2002) and Horikiri et al. (2015) used CFD models of fully furnished ventilated rooms and showed that indoor items can create complex air flow patterns leading to local thermal discomfort.

Hand (2016) presented a library of pre-existing components such as office chairs, bookcases, light fittings, stairs or monitors, which can be easily integrated into ESP-r building models. These components have realistic geometries and thermos-physical properties. They can be positioned precisely in the indoor space. Exact solar distribution, shadowing and surface-to-surface view-factors can therefore be calculated for every surface in rooms with arbitrary complexity. Comparative simulations showed that the presence of indoor elements can have a significant impact on local discomfort due to their influence on local radiant temperature and radiant asymmetry. Moreover, it was found that additional thermal mass and lightweight pieces of furniture placed close to facades affect the heating and cooling demand profile of a building.

Current challenges for the indoor content modelling

A number of issues have to be addressed concerning the integration of simplified or complex modelling of the indoor content in buildings. Additional experimental investigations, such as the twin room tests conducted by Li et al. (2016), should be conducted to validate and improve the methodologies to aggregate complex items with various shapes and thermo-physical properties into simple equivalent elements. Great unknowns still remain regarding what typical amount of indoor thermal mass is present in buildings, what part of internal and solar gains are directly absorbed by these elements, what are the convection heat transfer conditions on their surfaces, how does furniture interact with radiant systems and how it influences the thermal comfort evaluation.

Building energy flexibility

The energy flexibility is often defined as the ability for a building to control its energy demand and generation according to local climate conditions, user needs and grid requirements. However, there is currently no agreement on an exact definition for the energy flexibility index and consequently no overview of the flexibility potential for the different types of building, Lopes et al. (2016). The on-going IEA EBC Annex Project 67 aims at defining precisely the energy flexibility concept and increasing knowledge on how building energy demand management can improve the operation of energy grids.

The rest of this article focuses on the capacity of a building to shift its heating energy use from high price periods to low price periods by the mean of indoor temperature set point modulation. One can see on the Figure 3 an example from the current numerical study of the heating energy shift induced by the heat storage strategy.

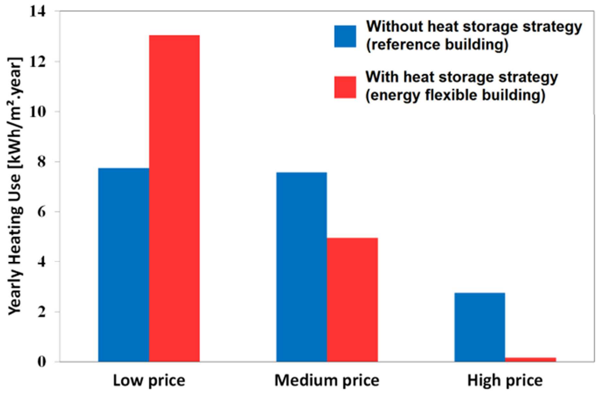

Figure 3: Variation of the yearly heating use profile for light structure passive house with heat storage strategy.

The performance of heat storage in the indoor environment highly depends on the amount of building thermal mass which can be activated and the efficiency of the envelope. The current study emphasizes the impact of the envelope thermal mass and additional thermal mass such as furniture and phase change material (PCM) on the energy flexibility capacity.

Methodology

Numerical model of the building case study

A MATLAB-Simulink multi-zone building model of a typical Danish single family house has been created within the framework of the EnovHeat project. It is used here to investigate the influence of detached houses' characteristics on their capacity to shift in time heating use under Danish weather conditions (Denmark Design Reference Year 2013). Envelope performance, construction thermal mass, heating system and additional indoor thermal mass parameters are varied to generate 48 different study cases. Two different classes of insulation are considered (low insulation house from the 80's and high insulation passive house) with three levels of envelope thermal mass each (light structure: 30

Wh/K.m², medium structure: 55 Wh/K.m², heavy structure: 100 Wh/K.m²). In addition to the empty room cases, three kinds of additional internal thermal mass are modelled (furniture / indoor content, PCM integrated in furniture elements and PCM wallboards placed on inner walls and ceilings). Two types of heating system are tested (radiators and water based under-floor heating).

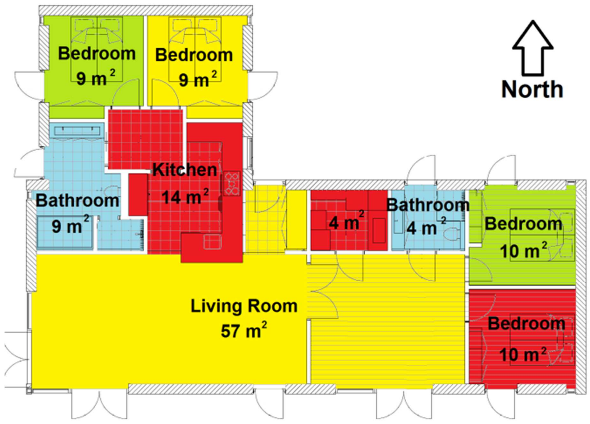

Figure 4: Scheme of the house case study: a typical 150 m² single family house in Denmark.

The furniture / indoor content is represented as a fictitious equivalent planar element and modelled with a one-dimensional implicit finite control volume formulation. The mass of each element is 60 kg/m² of the room's floor surface area concentrated in a 4.7 cm thick slab. The equivalent homogeneous material of the element is chosen to be with a density of 715 kg/m³, a thermal conductivity of 0.3 W/m.K and a specific heat capacity of 1400 J/kg.K. It is assumed that 50% of the internal radiative heating gains and solar radiation are absorbed by the surfaces of the planar elements.

The PCM wallboards are modelled with an enthalpy formulation coupled to a one-dimensional implicit finite control volume model. The 1.5 cm thick PCM slab elements are considered made of Energain®. The latter is a common commercial product composed of 60 w% micro-encapsulated paraffin incorporated into 40 w% polyethylene matrix. The material is set to be with a melting temperature of 22 °C, a total latent heat of fusion of 120 kJ/kg, a density of 1000 kg/m³, a thermal conductivity ranging from 0.18 to 0.22 W/m.K and a specific heat capacity of 2000 J/kg.K.

Furniture with integrated PCM are represented by a PCM wallboard element attached on one side of a fictitious equivalent furniture planar element.

The building numerical model has been validated with a BESTEST procedure. Each sub-component of the building model has been validated against commercial software (COMSOL Multiphysics and BSim) or experimental test data.

Validation test results and detailed description of the building model and its sub-components can be found in a DCE technical report (Johra and Heiselberg 2016).

Heat storage control strategy

The main objective of developing energy flexible buildings in a smart grid system is to allow the integration of a larger share of intermittent RES. The electricity spot price is a good indicator of the availability of RES in Denmark. Consequently, a price control strategy based on the 2009 Danish electricity spot price is used for this study.

As shown on Figure 5, the indoor temperature set point is increased to 24 °C when the electricity price is low to accumulate thermal energy. When the electricity price is high, the temperature set point is decreased to 20 °C to save thermal energy. If the electricity price is within the medium price range, the temperature set point is maintained at 22 °C.

Low price and a high price limits are defined for each hour as the lowest and highest quartile of the hourly electricity market price over the last 14 days.

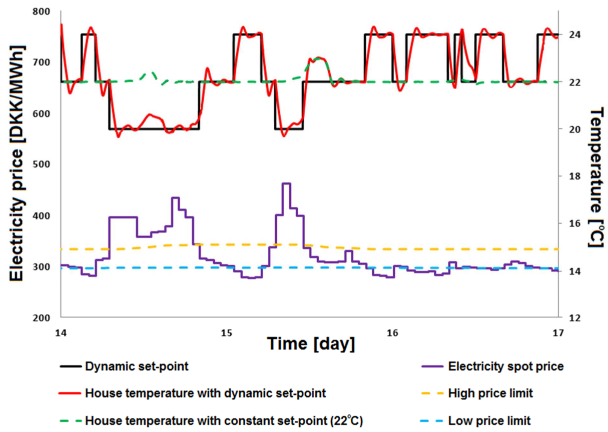

Figure 5: Temperature set point modulation with price control for a low insulation and light structure house.

Building energy flexibility index

Similarly to Le Dréau and Heiselberg (2016), the energy flexibility of a building is defined here as its capacity to reduce heating need during medium and high electricity price periods by storing heat during low electricity price periods (see example on Figure 3). The flexibility index is then calculated with equation (1).

$$F = \left[\left(1 - \frac{\%High}{\%High_{ref}}\right) + \left(1 - \frac{\%Medium}{\%Medium_{ref}}\right)\right] \times \frac{100}{2} \qquad (1)$$

$\%High$ and $\%Medium$ are the percentages of the yearly thermal energy used during high and medium price periods respectively when set point modulation with price control is activated. Similarly, $\%High_{ref}$.and $\%Medium_{ref}$ account for the reference case which does not have any heating storage strategy.

If the energy usage repartition with heat accumulation is the same as the reference case, the flexibility index is zero. If the energy share of high and medium price period increases, the flexibility index is negative. If all the energy share of the high price period is shifted to the low price period, the flexibility index is 50%. If all the energy share of the high and medium period is shifted to the low price period, the flexibility index reaches the maximum value of 100%.

Results

A total of 48 different building scenarios were simulated with the same weather conditions and heat accumulation strategy: two different insulation levels, three different classes of envelope thermal mass, two types of heating system (radiators and under-floor heating) and four different configurations of additional thermal mass (empty room, furniture / indoor content, furniture with PCM, PCM wallboards). The building cases equipped with convective radiators and no TES strategy are taken as references for the calculation of the energy flexibility index.

During the entire heating period, the indoor operative temperature is maintained between 20 °C and 24 °C. This temperature span corresponds to a normal level of thermal comfort with less than 10% of dissatisfied occupants (ISO 7730). Moreover, the time variation of the house temperature is always kept below the thermal comfort limit of 2.1 K/h (ASHRAE Standard 55 - 2004).

Figure 6 illustrates the increase of the building energy flexibility in function of its total effective thermal mass including the thermal mass of the envelope and the indoor content. It appears that activated thermal mass, regardless of its nature and location, contributes to increase the total storage capacity and therefore the energy shifting ability of the building. However, the impact of this parameter is smaller for low energy buildings compared to houses with poor envelope performance. Above 80 Wh/K.m² of total daily effective thermal mass, low energy buildings reach the maximum flexibility potential: there is no more energy to shift in time. It is therefore useless to increase the thermal mass of these buildings further more.

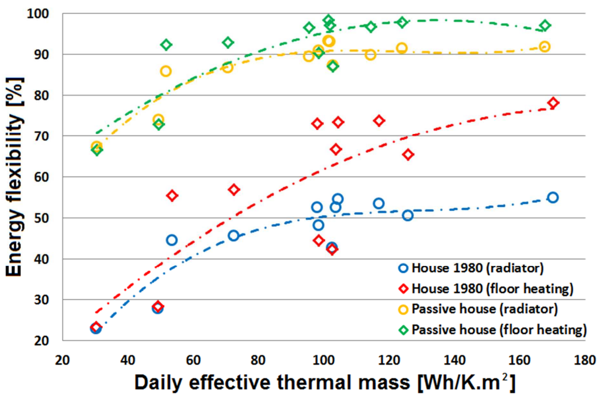

Figure 6: Effect of building effective thermal mass on energy flexibility.

Moreover, the insulation level seems to play a dominant role in the improvement of the building energy flexibility compared to its thermal inertia. Indeed, only poorly insulated house cases with a very large heating storage capacity and under-floor heating system are able to reach the same flexibility potential as passive houses.

Finally, the type of heat emitter has a limited effect on the building energy flexibility. Nevertheless, under-floor heating can improve the activation of the thermal mass of poorly insulated houses and noticeably improve their energy flexibility.

One can see on Figure 7 the impact of the different types of additional thermal mass on the building energy flexibility potential. The empty room building cases with no PCM are used as reference.

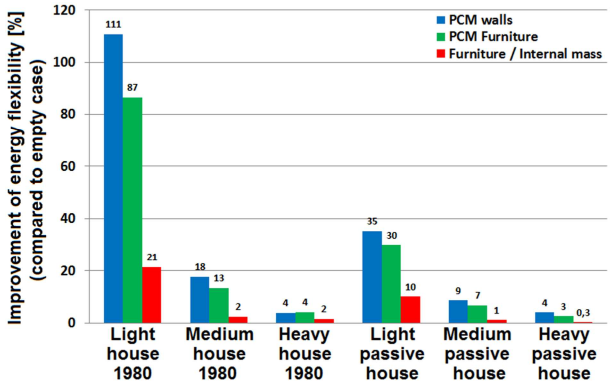

Figure 7: Influence of internal thermal mass on energy flexibility for houses equipped with radiators.

The results indicate that PCM integrated in wallboards or furniture elements can significantly improve the energy flexibility potential of low insulation light structure buildings. However, the benefit is lower for well-insulated dwellings and very limited in the case of medium and heavy structure buildings. Because of their low thermal conductivity, PCM wallboards positioned on inner surfaces of thermal zones tend to screen the activation of the thermal mass underneath them. It thus nullifies the storage capacity of the structural elements which is counterproductive in the case of heavy construction elements such as masonries.

In the case of houses with large effective thermal mass, the share of additional thermal inertia of indoor items and furniture is very small. Therefore, the impact of the latter on the building energy flexibility index appears to be almost negligible. Nevertheless, the influence of the furniture / indoor content for the light structure buildings should be taken into account.

Conclusion

This article presented a numerical study assessing the influence of different building parameters (effective thermal mass, insulation level and type of heating emitter) on the heating energy flexibility potential of a single family house in Denmark.

The energy flexibility index is here defined as the capacity of the building to shift its heating use from high and medium electricity price periods to low electricity price periods by the mean of temperature set point modulation.

Although the effective thermal mass of a building determines its maximum energy storage capacity, results indicate that the envelope performance is the most important parameter concerning the ability of a house to shift heating use. Under-floor heating systems present better performance in that matter, especially for low insulation level buildings. It is therefore more interesting to improve the building envelope and storage efficiency rather than increasing its thermal inertia or changing heating systems.

Nevertheless, the integration of phase change materials in wallboards or furniture elements appears to be a good solution to increase the effective thermal mass of lightweight structure buildings and consequently significantly improve their energy flexibility potential. It should be noted that PCM wallboards should not be employed in heavy masonry constructions because they screen the thermal mass activation underneath them and do not provide more heat capacity than thick concrete walls.

Finally, it has been clearly shown that the empty room assumption is not valid for the simulation of low thermal mass buildings with dynamic indoor temperature set point. The indoor content of such buildings can change the assessment of its energy flexibility by up to 21%. The modelling of the indoor content is therefore significant for detailed and realistic building simulations. This should be a taken as a motivation to explore further the different modelling technics reviewed in this article. More theoretical and experimental investigations should be performed to have a better knowledge of what is present inside occupied buildings and how these objects interact with the rest of the building thermal systems.

Acknowledgement

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