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THERMAL INERTIA IN DWELLINGS: ADAPTING THERMOSTAT SCHEDULES IN RELATION TO THE BUILDING THERMAL MASS

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ABSTRACT

The thermal mass of building constructions and interior furnishing attributes to transient heat flow and storage effects. This paper explores the resulting impact on heating demand and suggested control strategies. Detailed multi-zone dynamic building simulations are carried out for a set of dwellings covering a range of construction types.
The thermal inertia not only affects the pace of heating up a building zone, but also the temperature set-back that can be attained with an intermittent heating regime. Furthermore, the thermal inertia has an influence on the surface temperatures inside the building, hence the comfort sensed by the occupants. The room thermostat control can compensate for these effects, e.g. by the timing of preheating the building or altering air temperature to compensate for distinct surface temperatures. Multiple such control strategies are explored in this study.
The simulation results underpin that the impacts of the thermal mass are generally rather limited. They range from an increase of 9.1% in yearly energy demand to a decrease of -3.6%, depending on the temperature control regimes implemented. In contrast to the monthly quasi-steady state calculations of EN ISO 13790, the dynamic simulations provide indications that lightweight constructions can be more energy efficient if proper temperature control strategies are put in place.

KEY WORDS: Thermal mass, dynamic simulations, inertia

1. INTRODUCTION

Two main strategies can be distinguished to improve building energy efficiency [1]. Active strategies encompass improvements to heating, ventilation and air conditioning systems and artificial lighting, whereas passive strategies involve improvements to the building envelope such as increasing thermal insulation and optimizing solar gains to lower the energy demand of a building. Increasing the thermal resistance of the building envelope by applying thermal insulation materials is generally considered as the most important factor to reduce the building energy demand, especially in heating dominated climates [2]. Apart from thermal insulation, the inclusion of high thermal mass is sometimes also advocated as an important energy saving measure for passive or low energy buildings [3].
In a transient situation, the thermal mass of a building can absorb, store and progressively release heat depending on the temperature difference with the immediate surroundings. The amount of heat stored depends on the density ρ and specific heat capacity c of the material, whereas the rate of heat exchange is influenced by the thermal conductivity λ of the material. By transient storage and release of heat in the thermal mass, the amplitude of heat fluxes can potentially be reduced and temperature fluctuations can be dampened and shifted in time.

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Many architectural design guidelines do not provide numerical evidence of the proclaimed impacts of thermal mass. In contrast to the beneficial effects often attributed to thermal inertia, some adverse effects can also be expected to occur in some cases [4]. The slow reaction of the building thermal mass could cause longer periods of occupant discomfort and longer preheating or precooling periods which will increase the overall energy demand [5–7]. Specific studies on the subject of thermal inertia display major differences in predicted impacts, amongst other due to differences in research methods, climatic conditions and the building usage considered [4,8,9] Many studies on thermal inertia are restricted to the analysis of individual building components. Furthermore, boundary conditions are often simplified, e.g. by assuming sinusoidal temperature fluctuations in standard EN ISO 13786:2007 [10]. In reality multiple heat fluxes such as solar gains, metabolic heat gains from occupants, convective heat transfer, etc. will mutually interact in real life buildings and generate much more intricate temperature profiles. Proper modelling of these interactions is crucial to understand the real transient performance of buildings and their composing construction elements in transient conditions.

In this paper, the focus is on residential buildings in a heating dominated climate. Most authors predict that buildings with increased thermal mass will have the lowest energy demand [8,10,11]. The savings are however small, e.g. for a set of Swedish residential buildings, Heier et al. calculate reductions in heating energy demand when replacing a lightweight structure with a concrete external wall ranging from 1 % for older buildings constructed in 1940, to 4-5 % for contemporary passive houses [12]. Some authors however oppose the general believe that houses with an increased thermal inertia will have a lower energy demand in a heating dominated climate. Kendrick et al. evaluated a typical three bedroom UK house, for which they conclude that increased thermal mass can lead to an increase of heating load of 5 to 8 % [7]. Karlsson concludes that there are cases in which thermal inertia is a clear disadvantage, for example for intermittently heated buildings [13]. CIBSE Guide F [14] suggests that less thermally massive buildings have shorter preheat periods and as a result will demand less heating energy.

This paper will investigate to what extent the heating schedule affects the relative contributions of thermal mass for the heating demand of residential buildings in a Belgian climate.

2. METHODOLOGY

Modelling the buildings and using a physics based formulation to describe the dynamic behaviour of heat conduction, storage and release, allows to analyse and compare many building variants without the limitations related to experimental measurement setups. This work relies on detailed dynamic building energy performance simulation (BEPS) that solve the differential algebraic equations for time dependent heat transport to model the thermal inertia effects in residential buildings.

2.1 Simulation model

Dynamic BEPS have evolved to a powerful instrument for building designers and academia and a myriad of integrated BEPS tools validated by BESTEST procedures and field tests are available nowadays. In this work, the EnergyPlus version 8.7.0.is used to model the energy performance of the buildings. The analysis covers the heating energy demand for a full year with a three minute time step. The optional Conduction Finite Difference model for opaque assemblies has been used, since this allows to explicitly simulate energy flows and temperatures at multiple nodes of a construction [15]. The model uses eight thermal zones, which corresponds to individual rooms: kitchen, living room, bathroom, 3 distinct bedrooms, an unheated attic and "auxiliary zone" containing corridor, storage space and stairs. Within a thermal zone, the air is supposed to be perfectly mixed and thus uniform in temperature. Further simplifications used in this BEPS model include the restriction to one-dimensional heat transfer in construction components, and a simplified model of the heating system, which does not take into account the thermal inertia of the hydronic system. The climate data from the 'International Weather for Energy Calculations' (IWEC) climate file for Uccle (Brussels, WMO Station 064510) have been used in all simulations.

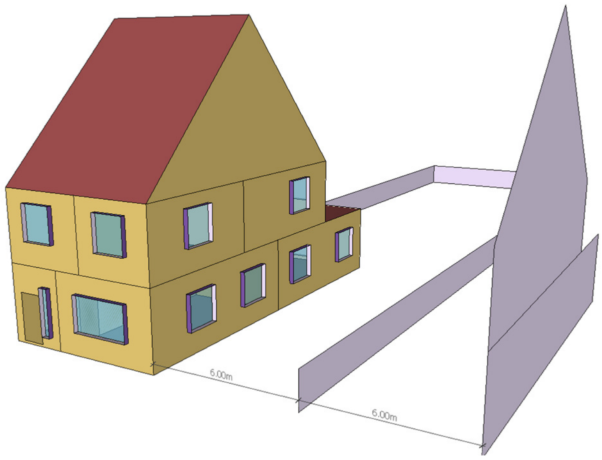

Fig. 1 Building geometry rendering, including external shadow casting objects and window reveals

2.2 Geometry

The building under consideration is a semi-detached dwelling with three bedrooms and a single bathroom. With a gross protected volume of 568.75 m³ and gross habitable floor area (excluding attic) of 200.14 m², the proposed design reflects an average newly constructed semi-detached dwelling in Flanders [16]. The partition walls which are common with the neighbours, are modelled to have adiabatic boundary conditions.

2.3 Constructions

A range of constructions is modelled for all internal and external walls and floors, corresponding to a heavyweight and lightweight building method. For the lightweight constructions timber frame walls, floors and roofs are defined. For the heavyweight constructions, limestone and concrete components are selected. Next to these, mixed construction types (e.g. limestone exterior, timber frame interior) and clay brick constructions have also been considered. The pitched roof composition is a lightweight timber frame construction for all cases. For the opaque external constructions, 5 variations of thermal resistance are defined: R1, R2, R3, R5 and R10. The layers are identical except for the thickness of the thermal insulation layers, which is varied so the one-dimensional total thermal resistance of all layers equals 1.0 m²K/W, 2.0 m²K/W, 3.0 m²K/W, 5.0 m²K/W respectively 10 m²K/W. The ground floor is modelled as a concrete slab in direct contact with the ground surface. Thermal bridging effects of building element connections have not been taken into account. Several variants of window sizing, window transmittance and solar heat gain coefficient (SHGC) are assumed, which are described in more detail in Verbeke (2017) [17].

2.4 HVAC systems

The building is assumed to be equipped with a mechanical ventilation system with heat recovery unit, modelled as an EnergyPlus Constant Air Volume (CAV) system. The design air rates are calculated according to the specifications in Belgian standard NBN D50-001 [18]. The building envelope is assumed to be fairly airtight (0.04 ACH) and air exchanges between zones are represented by EnergyPlus 'Inter-zone mixing'-objects. Additional venting by opening of exterior windows or doors is assumed to only happen when there is a risk of overheating; so these actions will not affect the heating energy demand. This paper will focus on the energy demand and will not take into account different heat delivery or heat production systems. It is assumed the dwellings are heated by hydronic radiators. There are represented by the EnergyPlus radiant-convective baseboard system units. The radiant portion is assumed to represent 40 % of the total heat emitted by the system and the radiant heat exchanges with surrounding surfaces in a thermal zone have been explicitly modelled. Two variants are assessed in the simulations: an idealized system with unlimited power capacity versus capacity limited systems for which the timing of the thermostat schedules will be adapted.

2.5 Occupancy patterns and thermostat setpoints.

The building is modelled to be occupied by a family of two adults and two children. A realistic schedule for occupant activities and resulting room occupancy and internal heat gains is implemented [17]. Two variants of thermostat set point control are investigated: one variant with fixed temperature settings of 16°C in bedrooms and 21 °C in living areas, versus a variant in which the heating system is controlled by a thermostat with a temperature set-back regime. In this research, thermostats are assumed to control the temperature of each individual room. The comfort experienced by occupants will not solely be defined by the air temperature, but also by the surface temperatures which will cause radiant heat exchanges. The indoor surface temperatures vary over time, and are largely influenced by the thermal resistance of the components, indoor- and outdoor boundary conditions, and the thermal inertia of the constructions. The non-uniform distribution of surface temperatures in a room can also introduce a directional dependency, but this is left out of scope of this research. This simplification allows to represent the temperature 'felt' by an occupant as a weighted mean of air temperature and zone mean radiant temperature. In case of limited air speeds, the effects of air temperature and radiant temperatures can be equally weighted, resulting in the definition of the operative temperature Θ_{OP}:

$$\theta_{OP} = \frac{\theta_{air} + \theta_{MRT}}{2} \tag{1}$$

In reality, the thermostat control schedule implemented by occupants will to some extent be influenced by the thermal inertia and insulation characteristics of a building. In this paper, the thermostat control is based on the operative temperature experienced by the occupants, as opposed to the traditional control based on air temperature [19]. The benefit of this approach is that all variants are treated based on an equal comfort level. In case the actual room thermostat sensors only capture dry bulb air temperature, this would be a highly hypothetical control requiring continuous adjustments of air temperature to reach a predefined operative temperature. In reality however, many commercially available thermostats do not purely consider dry bulb air temperature, but rather an undefined mix of air and radiant temperatures, with possibly a component of surface temperature at the mounting place. This can result in the recording of a temperature which is closer to the operative temperature sensed by occupants than the dry-bulb air temperature [20].

3. RESULTS

Annual space heating consumption is calculated for 360 design variants of the semi-detached building with variations in envelope thermal insulation, construction type, glazing type and window size. For each of the design variants two thermostat regimes are compared: intermittent heating versus fixed temperature setpoints.

3.1 Overall results for idealized heating system

Fig. 2 displays the energy performance for a subset of the cases. For all cases under consideration, the difference in heating energy demand varies from a reduction of 7.5 % to an increase of 9.1 % of the annual heating energy, solely by changing the thermal mass (and diffusivity) of the constructions. The influence of the building thermal inertia is far less pronounced than the impact of other design parameters such as thermal insulation, window size and glazing properties.

This is also underpinned by a statistical analysis using Kendall's τ_b rank correlation (Table 1) which displays that the thermal insulation of the building envelope is – as one would expect – the most influencing parameter with a Kendall τ_b correlation coefficient = -0.808 and significance $p<0.001$ for a two-tailed test. The total heat capacity of the buildings structure has a very weak correlation with the energy demand and is not a statistically significant parameter for predicting the heating energy demand (τ_b =0.038, p=0.297).

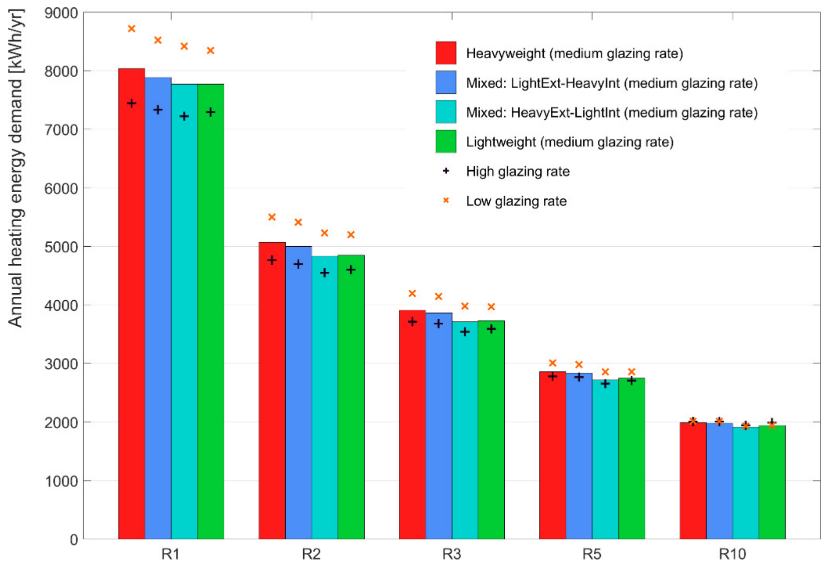

Fig. 2 Annual space heating demand in relation to thermal insulation, building thermal inertia and window size for buildings with standard double glazing and intermittent thermostat schedule.

Table 1 Statistical analysis of parameter correlations for annual space heating demand for north oriented semi-detached buildings, with intermittent heating schedule and idealized heating system (N=360).

Influencing Parameter	Kendall τb correlation coefficient	Statistical Significance p
Thermal resistance opaque envelope	-0.808	< 0.001
Glazing area * SGHC	-0.125	0.001
SHGC	-0.118	0.004
Total heat capacity C	0.038	0.297

3.2 Impact of heating schedules

For identical building designs, the effect of changing the intermittent heating schedule with temperature set-backs to a fixed temperature profile is tested using the multizone building simulations. On average, the heating schedule with fixed thermostat setpoints will result in an increase of 17.7 % in annual energy. This demonstrates that the thermostat set-backs can indeed be an effective energy saving measure. The results in Table 2 indicate that the relative savings of this intermittent regime are larger for poorly insulated homes; up to 33.5%. This can be attributed to the fact that in poorly insulated homes, the indoor temperature will show a much steeper decline after turning down the thermostat setpoint. In their well-insulated counterparts the temperature will remain close to the initial setpoint during an extended period, which results in comparatively higher shares of ventilation heat losses and less benefits from the temperature set-back. A similar logic with regard to the thermal inertia leads to the conclusion that the effects of temperature set-backs are more pronounced in lightweight buildings, which is also confirmed in the data of Table 2.

Table 2 Relative changes in heating energy demand when switching occupancy profile from intermittent heating to fixed temperature profiles for north oriented semi-detached buildings with standard double glazing

Inertia Type	Thermal resistance of building envelope					
	R1	R2	R3	R5	R10	Average
Heavyweight	+23.9%	+17.6%	+13.5%	+9.0%	+4.5%	+13.7%
Lightweight	+33.5%	+27.4%	+23.5%	+18.6%	+13.9%	+23.4%
Average	**+27.9%**	**+21.7%**	**+17.6%**	**+12.9%**	**+8.4%**	**+17.7%**

Fig. 3 displays the relative change in heating demand when changing the construction type of the building opaque components from heavy weight (lime stone and concrete) to variants with less thermal mass. In case the occupants apply a constant temperature profile, the heavyweight constructions are favoured. For intermittently heated buildings however, lightweight timber frame constructions will result in a lower heating energy demand. This analysis shows that some architectural design guidelines and international standards (such as the monthly method of EN ISO 13790 [21]) which attribute heating energy savings to heavy weight buildings are inadequate in case of strong intermittent building usage. For the residential buildings investigated, increasing thermal mass is not a robust energy saving measure: the effects will depend on the occupant behaviour, and are in any case rather limited.

3.3 Capacity-limited heating system

The previous analysis was restricted to idealised heating systems with unlimited capacity. In reality, the power output will be limited and as a result a period of heating-up can be observed before the zone reaches it desired temperature as set by the thermostat. The duration of this period depends on multiple parameters, such as the installed capacities, the thermal insulation of the building envelope, the thermal mass of the constructions and the indoor and external temperatures of the zone and its neighbouring zones. In anticipation of this behaviour, the thermostat is programmed to start the heating prior to the actual occupation.

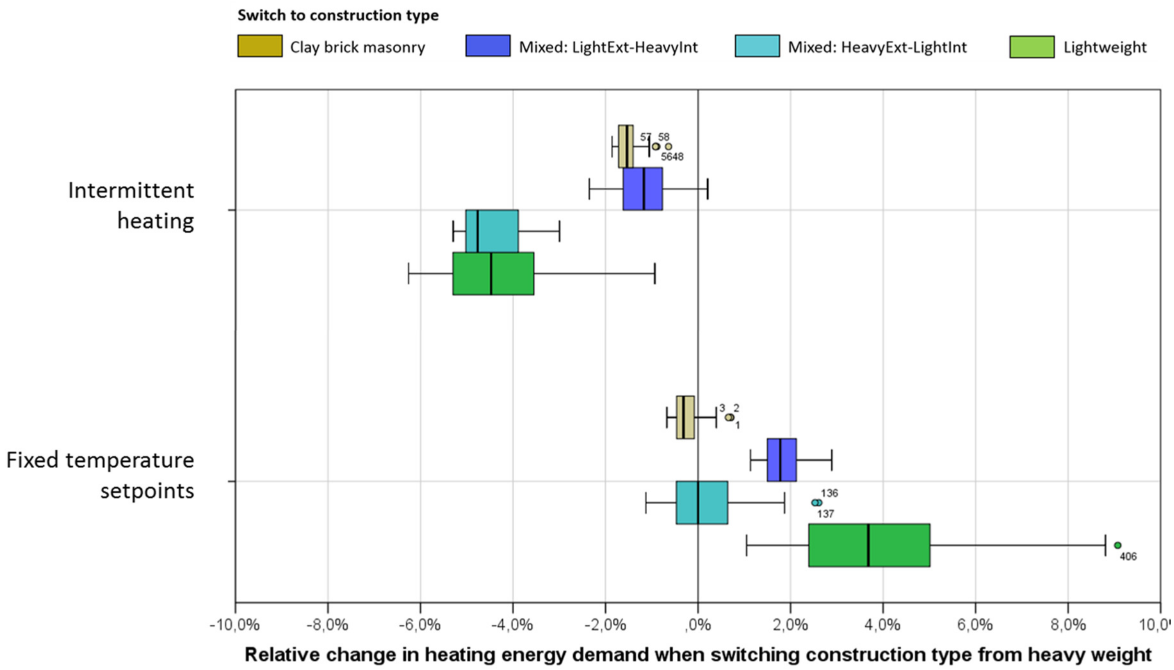

Fig. 3 Relative change in annual heating demand when switching construction type from heavy weight to different variants with less thermal inertia – in relation to distinct heating schedules.

Contemporary ‘smart’, or ‘self-learning’ thermostats will estimate the optimum timing based on analytics of former behaviour, sometimes enriched with weather data predictions or connections with smartphones or agendas of the occupants [22]. In this work however, a programmable thermostat with fixed daily or weekly schedules is considered. Although occupants could alter the settings when they deem fit, the literature reviews by Peffer et al. [23] and Meier et al. [24] indicate that only a small minority of occupants will actually undertake any action after initially setting the schedule. It is therefore assumed that the heating profile will be defined by one relatively cold winter day; which is chosen to correspond to the 98% percentile of the ambient temperature at 7 AM. For this design day, the time needed to reach the thermostat setpoint temperature is calculated from the EnergyPlus simulations and this timing is modelled to be implemented for all days of the heating season (see Fig. 4).

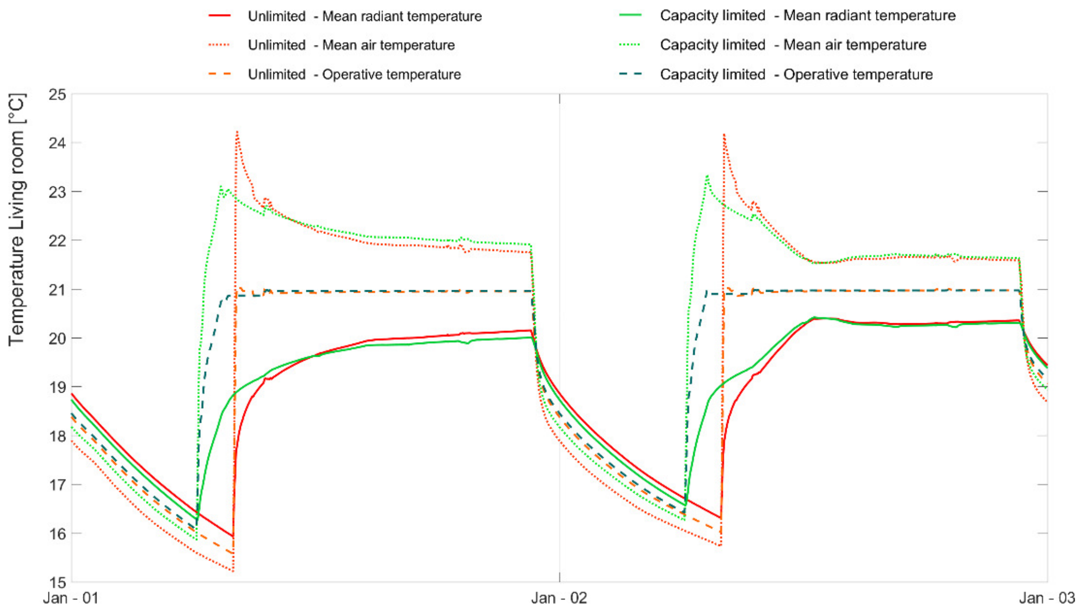

Fig. 4 Time series data for capacity limited HVAC system with early start-up versus unlimited power (semi-detached heavyweight dwelling with R5 insulation, standard double glazing and medium glazed area)

For most cases, the lightweight constructions are found to require a longer pre-heating period compared to the heavyweight constructions. This might seem contradictory, but can be explained from the fact that the temperature set-back that is achieved in the constructions with less thermal inertia is much larger. Once the desired operative temperature is reached, the remaining power demand is however lower in case of lightweight constructions. Overall, this culminates in a net reduction of the annual heating energy demand for constructions with low thermal inertia and intermittent heating profiles. For well insulated buildings, the relative changes in annual heating energy demand become even less pronounced compared to the simulations with idealised heating systems (see Table 3).

Table 3 Relative changes in heating energy demand when replacing heavy weight construction with lightweight timber frame construction for semi-detached buildings with standard double glazing

	Envelope thermal resistance				
	R1	**R2**	**R3**	**R5**	**R10**
Intermittent heating schedule	-3.3%	-4.5%	-4.4%	-3.7%	-2.3%
Intermittent heating schedule + capacity limit and preheat	-7.5%	-5.3%	-3.5%	-1.4%	-0.2%

4. CONCLUSIONS

Multi-zone dynamic energy performance simulations reveal that the effect of thermal mass on heating energy demand is not straightforward. For intermittently heated buildings, lightweight constructions yield a lower annual space heating demand compared to their heavy weight counterparts. The potential savings are relatively small with a 3.37% reduction on average. If more realistic assumptions on heating system sizing are taken into account, the differences become even less apparent, since the lightweight constructions are subject to larger temperature swings which can necessitate switching on the heating system earlier. In case of fixed thermostat set points without temperature set-backs, a slight preference for more thermal mass is found. Overall it is concluded that the impact of thermal inertia on heating energy demand is relatively small, and comes only second to other design parameters such as window-to-wall-ratio, thermal insulation, and glazing properties.

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