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Investigating the potential of a novel low-energy house concept with hybrid adaptable thermal storage

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ABSTRACT

In conventional buildings thermal mass is a permanent building characteristic depending on the building design. However, none of the permanent thermal mass concepts are optimal in all operational conditions. We propose a concept that combines the benefits of buildings with low and high thermal mass by applying hybrid adaptable thermal storage (HATS) systems and materials to a lightweight building. The HATS concept increases building performance and the robustness to changing user behavior, seasonal variations and future climate changes.

Building performance simulation is used to investigate the potential of the novel concept for reducing heating energy demand and increasing thermal comfort. Simulation results of a case study in the Netherlands show that the optimal quantity of the thermal mass is sensitive to the change of seasons. This implies that the building performance will benefit from implementing HATS. Furthermore, the potential of HATS is quantified using a simplified HATS model. Calculations show heating energy demand reductions of up to 35% and increased thermal comfort compared to conventional thermal mass concepts.

1. Introduction

In European countries legislation demands the reduction of energy use in the built environment (e.g. the Energy Performance of Buildings Directive, EPBD). This will result in very strict energy performance requirements for residential buildings in the near future. Furthermore, new requirements for residential buildings will be introduced. For example, the increasing demand in 'green rated' buildings (e.g. by BREEAM or LEED) will ensure that material use will be a more important design criterion during the design process. These stricter and new requirements will force the building designers to choose for less conventional solutions, since these requirements can only be met by applying new building concepts.

In this paper we propose and investigate the potential of a novel lightweight building concept that reduces the heating energy demand and increases thermal comfort. Furthermore, the concept will increase the robustness to changing user behavior (e.g. changing occupancy patterns), seasonal variations and future climate changes. In this paper we discuss the initial results of an ongoing research project.

2. Lightweight and heavyweight

Lightweight building constructions (e.g. steel or wood frame) show certain advantages over heavyweight building constructions (e.g. concrete). An important benefit is the reduced volume of construction materials. This reduces the energy necessary for the production and transportation of materials and reduces the quantity of waste materials. Thus, alleviating the environmental load of the building. Furthermore, lightweight constructions are suitable for retrofitting purposes, e.g. top-up extensions. In the Netherlands these sort of retrofitting methods receive increasing interest due to high prices for building estates. Steel frame constructions are a well-known lightweight construction method. Besides the mentioned advantages of lightweight buildings, steel frame buildings are lower in costs and faster built than the conventional concrete and masonry building constructions used in the Netherlands. However, lightweight constructions typically lead to buildings with low thermal mass and the accompanying risk of comfort problems (e.g. overheating).

3. Thermal mass

Thermal mass is the capability of a material to absorb and release heat; it is characterized by the volumetric heat capacity (quantity of heat storage in the material) and the thermal

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admittance (quantity of heat transfer from the material to air when subjected to cyclic variations in temperature) of the material. Materials with high heat capacity, moderate conductivity and high infra-red emissivity are most effective to use as thermal mass in buildings [1]. To make effective use of the thermal mass, the materials need to be placed on the inside of the insulated building envelope. Generally, concrete constructions will lead to heavyweight buildings with high thermal mass.

The general conception among Dutch building designers is that buildings with high thermal mass demand less heating energy and provide higher thermal comfort than buildings with low thermal mass. Several studies [1–3] indeed show this. However, a few other studies show that the positive influence of thermal mass on energy demand and thermal comfort should be nuanced because of the inertia of the thermal mass [4]. During specific operational conditions this inertia has a negative effect on energy demand and thermal comfort. During these conditions a fast responding building, i.e. a building with low(er) thermal mass, is preferred.

In conventional buildings thermal mass is a permanent building characteristic depending on the building design. However, as described above, none of the permanent thermal mass concepts are optimal during all operational conditions. We propose a concept that combines the benefits of buildings with low and high thermal mass by applying an adaptable thermal storage capacity to a lightweight building. The concept is described in the next section.

4. Hybrid adaptable thermal storage materials and systems (HATS)

It is possible to increase the thermal storage capacity of buildings by applying thermal energy storage (TES) systems or materials. In literature various methods to store thermal energy are described [5]. The TES methods are grouped in short-term storage (hourly, daily) and long-term storage (seasonal, yearly). Furthermore, the methods can be classified into the following three categories:

1. Sensible storage, energy is added or subtracted to a medium with a continuous temperature change over time, e.g. water, concrete, active thermal slab [6].
2. Latent storage, energy is stored in a medium by phase change (e.g. water/ice, paraffin, salt hydrates) [7,8].
3. Thermochemical storage, energy is stored by thermo-chemical reactions (e.g. inorganic substances) [9].

Two or more TES methods can be combined into one hybrid thermal storage concept, e.g. phase change materials (PCM) in light concrete walls: latent + sensible storage.

From the thermal perspective, lightweight buildings with an extra thermal storage capacity behave the same as heavyweight buildings. To benefit from the advantages of both low and high thermal mass, the thermal storage capacity needs to be adaptable in time. We name this concept: hybrid adaptable thermal storage (HATS). An example of a HATS concept is a zone with PCM added to ceilings or walls that can be insulated from the building zone (Fig. 1). HATS can also consist of thermally activated building systems (TABS) [6].

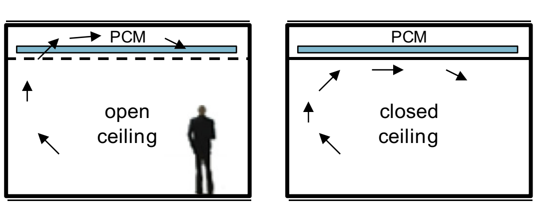

Fig. 1. Example of a HATS concept using adaptable isolation of the PCM in the ceiling.

5. Case study

In cooperation with Tata Steel Construction Centre, a building case study is defined to study the potential of HATS for reducing the heating energy demand and increasing thermal comfort. The case study is based on the residential houses of the Zonne-entrée project (Tata Steel Star-Frame and Courage Architecten bna) in Apeldoorn, the Netherlands. The building is modeled and simulated with the dynamic whole-building performance simulation tool ESP-r [10] using a weather file of the Dutch climate. The case study consists of five zones: zone A (south orientated) and B (north orientated) on the ground floor and zone C, D (south orientated) and E (north orientated) on the first floor (Fig. 2). The building is heated with an all-air system. The air temperature heating setpoints are set to 21 °C when the room is occupied and 14 °C when the room is not occupied; more details are given in Table 1 and Fig. 2. The south façade is provided with an external shading device (horizontal venetian blinds). During winter months the blinds are retracted making use of solar gains. During summer months the blinds are lowered with slats set to 0° (horizontal position). The slats are set to 80° when the solar irradiance on the façade is higher than 300 W/m^2. Two user occupancy patterns are defined:

1. Occupancy pattern 'evening': people present from 18 h to 24 h.
2. Occupancy pattern 'day & evening': people present from 8 h to 24 h.

5.1. Performance indicators

The performance of the building is assessed using two performance indicators: heating energy demand and summed weighted over- and underheating hours. The heating energy demand is calculated in kWh/m^2 per year. The over- and underheating hours (WOH-Σ) are weighted with a factor that is a function of the PPD [11].

6. Investigation of HATS potential

The potential benefit of implementing HATS is investigated by studying the optimal quantity of the thermal mass of the case study building. The optimal quantity of the thermal mass is defined as the quantity of the (permanent) thermal mass that provides the best building performance (based on a trade-off between the building performance indicators). Sensitivity of the optimal quantity of the thermal mass (in the rest of this paper referred to as 'the optimal mass') to the change of seasons implies that the building performance will benefit from implementing HATS.

The optimal thermal mass is investigated using the non-dominated sorting genetic algorithm II (NSGA-II) [12]. This is a well-known multi-objective optimization algorithm and has already been used in building performance simulation [13,14]. The optimization algorithm changes the thermal mass of the building by altering the density of the materials that are in contact with the indoor environment. The required density is calculated using the effective thermal mass method (in Dutch the Specifiek Werkzame Massa or SWM). The effective thermal mass is a simplified quantification of the thermal mass. It is defined as the mass of the thermal-active layers of the surfaces in a room divided by the total area of the surfaces, e.g. low thermal mass is 5 kg/m^2 (lightweight floors and walls), medium thermal mass is 50 kg/m^2

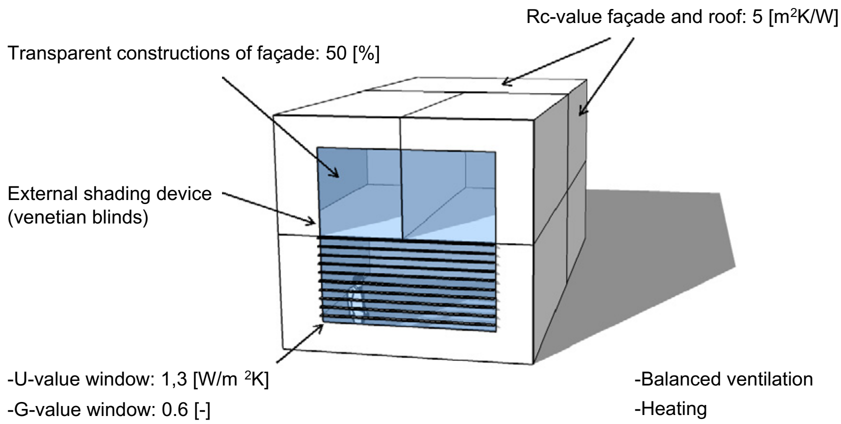

Fig. 2. Case study based on Zonne-entrée Apeldoorn, facing the south facade.

Table 1
Input parameters of base case study Zonne-entrée Apeldoorn.

	Input parameters	Value	Unit
1	Occupancy	Evening	(–)
2	Internal heat gains	4.0	(W/m^2)
3	Window type (U-value)	1.3	(W/m^2 K)
4	Window size	50	(%)
5	Thermal resistance façades	5	(m^2K/W)
6	Infiltration ($q_{infiltration;qv10;spec}$)	0.08	(dm^3/s per m^2)
7	Heating setpoint occupied	21	(°C)
8	Heating setpoint unoccupied	14	(°C)
9	Ventilation	1.0	(dm^3/s per m^2)

(concrete floors, lightweight walls) and high thermal mass is 100 kg/m^2 (heavy concrete floors and walls).

The optimal thermal mass is calculated per orientation and floor level (i.e. for zones 'A', 'B', 'C and D' and 'E') for every season using the occupancy pattern 'evening'. The thermal mass of the zones is varied between 5 kg/m^2 and 100 kg/m^2. The zones are thermally decoupled by an insulation layer in the partitioning constructions.

6.1. Results optimization thermal mass

Fig. 3 shows the optimal thermal mass per zone and per season. In spring and summer the zones on the first floor (C–E) require more thermal mass to prevent overheating than the zones on the ground floor (A and B). In winter this is also the case for zones C and D. This is caused by the external shading device which is not used in winter and thus causes direct solar radiation to enter the rooms. Together with the conduction through the (flat) roof this will cause overheating problems if the mass is too low. The relative low thermal masses of zones A and E compared to zones C and D are caused by differences in floor level and orientation: there is no conduction through the roof in zone A and there is no direct solar radiation in zone E.

6.2. Sensitivity of optimal thermal mass to the change of seasons

The influence of the seasons on the optimal thermal mass is shown in Fig. 3. Low thermal mass is required in winter and high thermal mass in summer. The influence can be quantified with the average relative change (ARC) of the optimal thermal mass during the seasons. The ARC is calculated per zone by dividing the optimal thermal mass per season with the average value of the optimal thermal mass for the whole year. A high ARC indicates a strong sensitivity of the optimal thermal mass to the seasons. The zones in this case study show high ARC values: zones A, B, C, D and E, respectively 83%, 88%, 54%, 54% and 90%.

The results show that the optimal thermal mass is sensitive to the change of seasons, which implies that implementing an

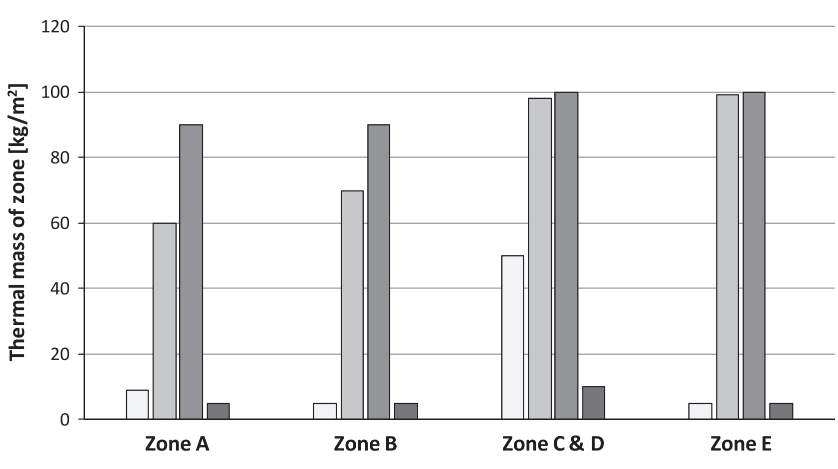

Fig. 3. Simulated optimal thermal mass for the case study with occupancy pattern 'evening'. The thermal mass is calculated using a simplified quantification method. The thermal mass is defined as the mass of the thermal-active layers of the surfaces in a room divided by the total area of the surfaces, e.g. low thermal mass is 5 kg/m^2 (lightweight floors and walls), medium thermal mass is 50 kg/m^2 (concrete floors, lightweight walls) and high thermal mass is 100 kg/m^2 (heavy concrete floors and walls).

adaptable thermal mass or an adaptable thermal storage capacity has potential to reduce heating energy demands and WOH-Σ. In [11] the optimization of thermal mass is described in more detail. It has been shown that the optimal thermal mass is also sensitive to occupancy patterns.

In the next sections the potential of HATS to reduce heating energy demands and WOH-Σ is quantified.

7. Quantification of HATS potential

The potential of HATS for this case study is quantified using a simplified HATS model. The HATS model assumes that it is possible to have a daily ideal switch between low thermal mass and high thermal mass. For this purpose two simulations of the case study are performed with an effective thermal mass of 5 kg/m^2 (lightweight) and 100 kg/m^2 (heavyweight). The HATS model selects the best thermal mass per room based on lowest energy demand or highest comfort. Thus, the model assumes an ideally controlled adaptable thermal mass, i.e. there is no delay in the system response and no effects of (re- or dis)charge of the thermal mass in isolation are considered. In reality the effects of (re- or dis)charge of the thermal mass in isolation will be influenced by the chosen HATS concept and control strategy.

Calculations are performed with an autonomous daily adaptable thermal mass per room. First, we show the results of zones B and C; next we show the summed results of all zones in the building.

7.1. Heating energy demand and comfort of zones B and C

Tables 2 and 3 show the heating energy demand for zones B and C per occupancy pattern (the heating energy demand compared to the simplified HATS model is shown in brackets). In some cases the differences between the simplified HATS model and the conventional permanent thermal masses are small, e.g. in zone B with occupancy pattern ‘evening’ the difference with the low thermal mass is 1%. In other cases the differences are bigger, e.g. in zone B with occupancy pattern ‘evening’ (from here on, the zone name will be followed by the used occupancy pattern, e.g. zone B ‘evening’) the difference with high thermal mass is 30%. A low percentage indicates that the simplified HATS model did not switch often between the two thermal masses. In case of zone B ‘evening’ this means that during the heating period most of the simulated days the low thermal mass is the most energy efficient; the adaptable thermal mass is not used to reduce the heating energy demand. For zone C ‘day & evening’ the high thermal mass is energy efficient during most of the heating period. Zone C ‘evening’ and zone B ‘day & evening’ use the capabilities of the adaptable mass during the heating period to reduce the heating energy demand, respectively with 17% and with 8% compared to low thermal mass and 23% and 8% compared to high thermal mass.

Tables 2 and 3 show the weighted over- and underheating hours (WOH) of zones B and C. For these zones using high thermal mass will always result in the lowest number of WOH: 0% difference with simplified HATS model. In other words, for these zones thermal comfort will not benefit from switching to low thermal mass.

The true potential of HATS can be studied by combining the results of the heating energy demand and the WOH. It is important to notice that in the Dutch climate the largest part of the heating energy demand is used in winter and most WOH will occur in summer. Therefore, the potential for HATS is high, if the results show that a different thermal mass is used for reducing the heating energy demand than for reducing the WOH (since this indicates a switch of the thermal mass during the year). Furthermore, the potential for HATS is also high when the adaptable thermal mass is used to reduce at least one of the two performance in>dicators.

The simulation results show that zone B ‘evening’ switches to low thermal mass to reduce the heating energy demand and switches to high thermal mass to reduce the WOH: the building performance is increased using HATS. Zone C ‘evening’ and zone B ‘day & evening’ use HATS to reduce the heating energy demand, while the WOH are reduced by switching to high thermal mass: the building performance is increased using HATS. Zone C ‘day & evening’ uses high thermal mass during most of the simulated time to reduce the heating energy demand and the WOH: the building performance is not significantly increased using HATS. From these results it can be concluded that HATS shows more potential with the occupancy pattern ‘evening’ than with ‘day & evening’.

7.2. Heating energy demand and comfort whole building

The heating energy demand and WOH per zone are summed to analyze the performance of the whole building. Results of the calculations show that the simplified HATS model reduces the heating energy demand by 6–27% compared to respectively the low and high thermal mass, while maintaining the comfort level of the high thermal mass (Table 4). The results show that especially the case with the ‘evening’ occupancy pattern benefits from HATS.

The results from this section show that the occupancy pattern has a strong influence on the potential of HATS. The influence of other parameters is investigated in the next section.

Table 2
Heating energy demand (kWh/m^2 per year) and summed weighted over- and underheating hours (WOH-Σ per year) of zone B.

Occupancy pattern	Heating energy demand			Weighted overheating hours		
	Low thermal mass (5 kg/m^2)	High thermal mass (100 kg/m^2)	Simplified HATS model	High thermal mass (100 kg/m^2)	Low thermal mass (5 kg/m^2)	Simplified HATS model
Evening	17.5 (+1%)	22.4 (+30%)	17.3	165 (+14,510%)	1 (+0%)	1
Day & evening	27.2 (+8%)	27.2 (+8%)	25.1	327 (+6111%)	5 (+0%)	5

Table 3
Heating energy demand (kWh/m^2 per year) and summed weighted over- and underheating hours (WOH-Σ per year) of zone C.

Occupancy pattern	Heating energy demand			Weighted overheating hours		
	Low thermal mass (5 kg/m^2)	High thermal mass (100 kg/m^2)	Simplified HATS model	High thermal mass (100 kg/m^2)	Low thermal mass (5 kg/m^2)	Simplified HATS model
Evening	13.2 (+14%)	14.2 (+23%)	11.6	101 (–)	0 (+0%)	0
Day & evening	19.9 (+57%)	13.0 (+3%)	12.6	737 (+1053%)	64 (+0%)	64

Table 4
Heating energy demand (kWh/m^2 per year) and summed weighted over- and underheating hours (WOH-Σ per year) of the whole building.

Occupancy pattern	Heating energy demand			Weighted overheating hours		
	Low thermal mass (5 kg/m^2)	High thermal mass (100 kg/m^2)	Simplified HATS model	High thermal mass (100 kg/m^2)	Low thermal mass (5 kg/m^2)	Simplified HATS model
Evening	15.9 (+7%)	18.5 (+25%)	14.8	699 (+10,325%)	7 (+0%)	7
Day & evening	25.0 (+27%)	20.9 (+6%)	19.7	2850 (+1358%)	196 (+0%)	196

8. Exploring potential HATS using sensitivity analysis

The previous section showed the quantified potential of HATS for the case study building as it is designed by the architect. In this section we investigate if it is possible to increase the potential by modifying the original design. First, we define the parameters that influence the potential of HATS. These parameters are identified using the simplified HATS model and Monte Carlo Analysis with regression analysis (MCA) as sensitivity analysis (SA) method [15]. The influential parameters are used to construct realistic variants of the case study (base case). Next, per variant the potential is quantified using the simplified HATS model. The results are studied to define the maximum potential.

8.1. Input parameters

The values of the parameters used in the MCA are based on values used in practice (Table 5). The base values are based on the project description of the Zonne-entree project (Table 1). The minimal requirements are based on the Dutch building codes (Bouwbesluit). The high requirements are based on design rules of the Passive House in the Netherlands. In the MCA the occupancy is set to the 'evening' occupancy pattern based on the results of the previous section.

Table 5
Input parameters for the sensitivity analysis.

Input parameters	Base value	Value1	Value 2	Unit
Internal heat gains	4.0	2.0	6.0	(W/m^2)
Window type (U-value)	1.3	0.7	2.7	(W/m^{2}K)
Window size	50	25	90	(%)
Thermal resistance façades	5	3	8	(m^{2}K/W)
Infiltration	0.08	0.03	0.12	(dm^3/s per m^2)
Heating setpoint occupied	21	20	22	(°C)
Heating setpoint unoccupied	14	13	15	(°C)
Ventilation	1.0	0.8	1.2	(dm^3/s per m^2)

8.2. Results sensitivity analysis

The influence of the parameters on the heating energy demand and WOH-Σ are evaluated for the whole building. In Figs. 4 and 5 the results of the MCA are plotted for both performance indicators. Parameters that are not statistically significant in the regression analysis ($p > 0.05$) are printed strikedthrough in the graphs. The parameters are sorted from high influence (high values of the standardized regression coefficient) to low influence.

The parameters 'Heating setpoint occupied' and 'Thermal resistance façade and roof' are indicated as the two most influential parameters by the SA of the heating energy demand (with SRCs of 0.51 and 0.41). 'Window size' and 'Ventilation' are the most influential parameters according to the SA of the WOH-Σ (with SRCs of 0.52 and 0.24).

This top four of most influential parameters is used to construct a set of case study variants. The non-influential parameters are fixed to the base value; the influential parameters are varied between 'value 1' and 'value 2' from Table 6. The set of variants investigates the elementary effects and the interactions of the influential parameters on the performance of HATS.

8.3. Results of high potential variants

To assure a comfortable thermal indoor environment only the variants with a maximum of 200 WOH-Σ are regarded. Table 6 shows the results of the variants with the highest percentages improvement by the simplified HATS model on both performance indicators.

Variant 1 represents a building with a window size of 90% (value 2), thermal resistance of 3 m^{2}K/W (value 1), heating setpoint of 20 °C (value 1), ventilation rate of 1.2 dm/s per m^2 (value 2) and with the other parameters set to the base values. Variant 2 is the same as variant 1, but with a thermal resistance of 8 m^{2}K/W (value 2). The results show a maximum heating energy demand reduction of 35% and a maximum WOH-Σ reduction of 1295% (variant 1).

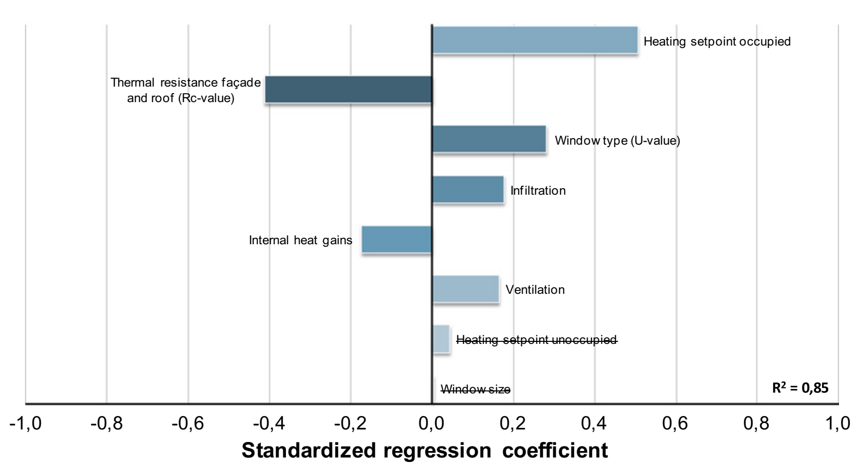

Fig. 4. Results of the sensitivity analysis (MCA) with the simplified HATS model for heating energy demand of the whole building.

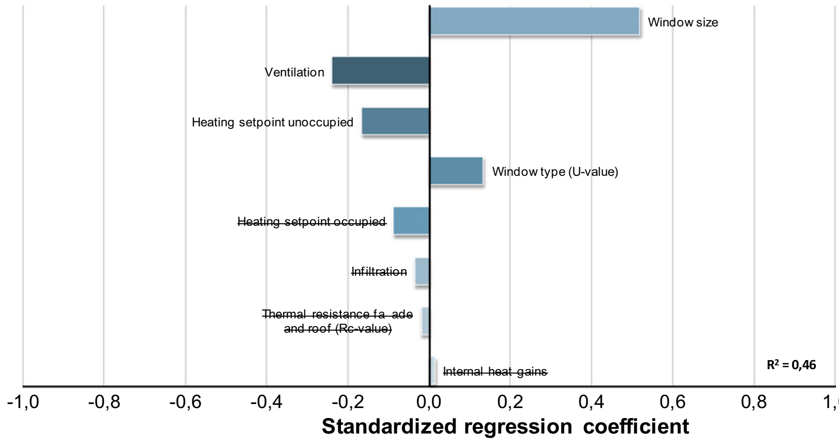

Fig. 5. Results of the sensitivity analysis (MCA) with the simplified HATS model for WOH-Σ of the whole building.

Table 6
Heating energy demand (kWh/m^2 per year) and weighted overheating hours (WOH-Σ per year) of the whole building; percentage difference with simplified HATS is shown in brackets.

	Heating energy demand			Weighted overheating hours		
	Low thermal mass (5 kg/m^2)	High thermal mass (100 kg/m^2)	Simplified HATS model	Low thermal mass (5 kg/m^2)	High thermal mass (100 kg/m^2)	Simplified HATS model
Variant 1	14.1 (+9%)	17.4 (+35%)	12.9	2059 (+1295%)	149 (+1%)	148
Variant 2	8.5 (+15%)	9.7 (+31%)	7.4	1844 (+1076%)	157 (+0%)	157

9. Conclusion

Building performance simulation is used to investigate the potential of the novel HATS concept for reducing heating energy demand and increasing thermal comfort. The results of the optimization of the thermal mass show that the optimal quantity of the thermal mass is sensitive to the change of seasons, which implies that implementing HATS has potential to reduce heating energy demands and WOH-Σ of the case study. Results of calculations with a simplified HATS model show that for this case study the HATS concept is able to reduce the energy demand with a maximum of 35% compared to a conventional permanent high thermal mass concept. Furthermore, the HATS concept is able to reduce the summed weighted over- and underheating hours with a maximum of 1295% compared to a conventional permanent low thermal mass concept.

The presented results are simulated for the Dutch climate; however the HATS concept will show the same potential in other moderate climates that show a distinct temperature difference between the seasons. Future work is needed to investigate the potential in other (than moderate) climates.

In the future of this project realistic HATS concepts will be defined and modeled. The performance of these concepts will depend on the applied control strategies. To assure optimal performance it is necessary to develop new control methods. These methods will define the most optimal control strategy by using models that predict the thermal behavior of the building and the relevant disturbances (e.g. user behavior and weather conditions), so-called Model Predictive Controls (MPC).

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