Exploring the optimal thermal mass to investigate the potential of a novel low-energy house concept

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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.

In this paper the potential of the novel HATS concept is investigated by determining the sensitivity of the optimal thermal mass of a building to the change of seasons and to changing occupancy patterns. The optimal thermal mass is defined as the quantity of the thermal mass that provides the best building performance (based on a trade-off between the building performance indicators). Building performance simulation and multi-objective optimization techniques are used to define the optimal thermal mass of a case study in the Netherlands.

Simulation results show that the optimal quantity of the thermal mass is sensitive to the change of seasons and occupancy patterns. This implies that the building performance will benefit from implementing HATS. Furthermore, the results show that using HATS reduces the heating energy demand of the case study with 26% and reduces weighted over- and underheating hours with 85%.

1. INTRODUCTION

National and international policies demand the reduction of energy use in the built environment. In the Netherlands 20% of the total energy use is consumed by households [Eurostat, 2007]; 65% of the energy is used for space heating and domestic hot water [Opstelten et al., 2007]. These figures indicate that reducing the heating energy demand of residential buildings will have a large impact on the total energy use of the country. While reducing the heating energy demand of residential buildings, comfort needs to be maintained or (rather) improved. To satisfy both objectives new building concepts and control strategies are needed.

In the Netherlands besides the recent energy and comfort requirements another factor can be identified that drives the need for innovative building concepts: the available land for construction of new buildings. In the Netherlands due to policies and an increasing population building estates are scarce and expensive. This leads to an increase in urban density and therefore in the need for lightweight constructions that can be used for e.g. top-up extensions of existing buildings. Steel frame constructions are ideal for this purpose. Moreover, 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).

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 behaviour (e.g. occupancy patterns), seasonal variations and future climate changes. The concept is not implemented in a building yet. In future papers we will discuss the technical implementation of the concept in detail.

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2. 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 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 [Walsh et al. 2006]. 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 [Balaras, 1995; Walsh et al., 2006; Kosny et al., 2001] 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 [De Vaan et al., 2009]. 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.

3. 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 [Dincer, 2002]. The TES methods are grouped in short term-storage (hourly, daily) and long-term storage (seasonal, yearly). Furthermore, the TES 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;
2. Latent storage, energy is stored in a medium by phase change (e.g. water/ice, paraffin, salt hydrates);
3. Thermochemical storage, energy is stored by thermo-chemical reactions (e.g. inorganic substances).

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 (with all advantages and disadvantages). To benefit from the advantages of both low and high thermal mass, the hybrid 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 (Figure 1). HATS can also consist of thermo-active building systems (TABS).
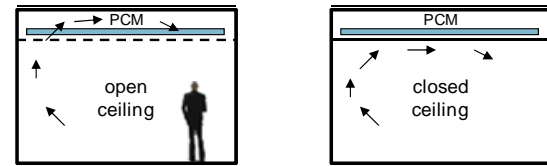

Figure 1: Example of a HATS concept using adaptable isolation of the PCM in the ceiling.

4. CASE STUDY AND PERFORMANCE INDICATORS

In cooperation with Corus Construction Centre, a building case study is defined to study the potential of implementing HATS. This potential is investigated by determining the sensitivity of the optimal quantity of the thermal mass of the case study to the change of seasons and to changing occupancy patterns. 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 described in the next paragraphs). Sensitivity of the optimal quantity of the thermal mass (in the rest of this paper referred to as 'the optimal thermal mass') to the seasons and occupancy patterns implies that the building performance will benefit from implementing HATS.

The case study is based on the residential houses of the Zonne-entrée project (Corus Star-Frame and Courage Architecten bna) in Apeldoorn, the Netherlands. The building is modeled and simulated in the building performance simulation tool ESP-r [Clarke, 2001] 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 (Figure 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 Figure 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 degrees (horizontal position). The slats are set to 80 degrees when the solar irradiance on the facade is higher than 300 W/m^2. Two user occupancy patterns are defined:

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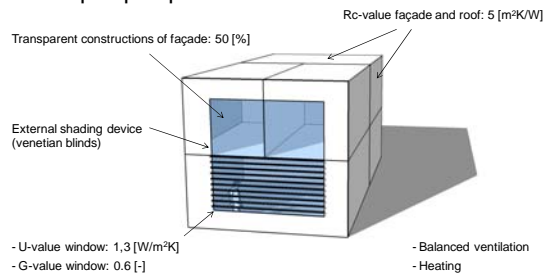2. Occupancy pattern 'day & evening': people present from 8h to 24h.

Figure 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^{2}K/W]
6	Infiltration (q$_{infiltration;qv10;spec}$)	0,08	[dm^3/s p.m^2]
7	Heating setpoint occupied)	21	[°C]
8	Heating setpoint unoccupied	14	[°C]
9	Ventilation	1,0	[dm^3/s p.m^2]

4.1. Performance indicators

The performance of the building is assessed using two performance indicators: heating energy demand and the sum of the weighted over- and underheating hours. The heating energy demand is calculated for the whole building in kWh per season or per year (as indicated). The method used to calculate the summed weighted over- and underheating hours is described in the next paragraphs.

4.1.1. Thermal comfort

Thermal comfort is assessed by calculating the number of hours the temperature in a room will exceed a certain temperature limit. The level of thermal comfort and the temperature limits are calculated using the PMV (predicted mean vote) [Fanger, 1970]. The PMV is an index that predicts the mean value of the thermal votes of a large group of people. The level of thermal comfort is indicated on a 7-point thermal sensation scale (hot +3, warm +2, slightly warm +1, neutral 0, slightly cool -1, cool -2, cold -3). The PMV index is derived for steady-state conditions, but it can be applied in transient simulations provided that time-weighted averages of the variables from the previous (simulated) hour are applied [ISO, 2005].

The PMV method uses six environmental parameters to calculate the thermal sensation: (1) metabolic rate, (2) clothing, (3) air temperature, (4) mean radiant temperature, (5) air velocity and (6) air humidity. Since the HATS house is provided with a balanced mechanical ventilation system and automatic shading devices, the occupants

can *control* the indoor environment by altering the heating set-point temperature, (3) and (4), and the air velocity (5)(e.g. by increasing the ventilation rate or using a table fan). Also the occupants can *adjust themselves to* the environment by changing metabolic rate (1) and clothing (2).

Besides the PMV, the PPD (predicted percentage dissatisfied) is used to predict the percentages of people that are thermally dissatisfied [Fanger, 1970], i.e. people who feel uncomfortably warm or cold. The PPD value is derived from the PMV. The thermal indoor environment of the HATS house is assessed by using the comfort requirements of climate category C of [ISO, 2005]:

- -0,7 < PMV < +0,7
- PPD < 15%

In this study, the PMV and PPD are calculated with the simulated indoor temperatures, (3) and (4), and predefined values for the other parameters, (1), (5) and (6). The specifics for clothing (2) are discussed in the next paragraph. The time during which the actual (calculated) PMV exceeds the comfort boundaries, caused by too high, or too low, air and mean radiant temperatures (since the other parameters are fixed), is weighted with a factor which is a function of the PPD. The thermal comfort is calculated per room for every hour the room is occupied. In the end the weighted over- and underheating hours (WOH) of all zones are summed (WOH-Σ).

In the simulations we regard the metabolic rate as a fixed value of 70 W per square meter of body surface area, which represents a person in sedentary activity. The air velocity is 0,1 m/s, but in the summer months it is raised to 0,2 m/s. The relative humidity changes during the seasons: summer 70%, intermediate season 55% and winter 40%.

4.1.2. Implementation of adaptive clothing behavior

The above explained method allows us to reconsider the use of the (constant) clothing (2) values. For the purpose of this study, we developed and implemented an adaptive clothing approach for realistic calculation of the WOH-Σ. This adaptive approach is important since clothing behavior has a strong influence on the experienced indoor thermal environment [De Carli et al., 2006]. This is especially important for this study, because occupants in residential buildings easier adapt their clothing to the environment compared to office workers, who are more restricted to certain clothing codes depending on the corporate culture. The adaptive clothing behavior is accounted for by defining a low and a high clo-value. The low clo-value is used when calculating overheating hours and the high clo-value is used when calculating

underheating hours. It is impossible to discern the difference between over- and underheating hours, when only the PPD is used in the calculation, like in the Dutch GTO-method (gewogen temperatuuroverschrijding, in English, weighted temperature exceeding hours) [Rgd, 1999]. However, the difference can be discerned when using the PMV in the calculation. Using the PMV in the weighting method prevents that during a relatively cold summer day underheating hours are counted caused by a low clo-value, which in reality would not occur since the occupant will adapt to a higher clo-value.

In the simulations the low clo-value is set to 0,3 which represent light summer clothing [ISO, 2005] and the high clo-value is set to 1,5 which represent warm winter clothing [ISO, 2005].

5. INVESTIGATION OF THE POTENTIAL OF HATS USING MULTI-OBJECTIVE OPTIMIZATION

The optimal thermal mass of the case study is investigated using multi-objective optimization algorithms. These algorithms are used to find the best (set of) solution(s) to a problem given a set of constraints. An optimization problem with two or more (conflicting) objectives that needs to be optimized simultaneously is called a multi-objective optimization problem (MOP) [Coello Coello, 2005]. In this project we are searching for the best compromise between heating energy demand and WOH-Σ. Because of the conflicting behavior of these objectives it is impossible to find one single best solution; instead a set of 'trade-offs' or good compromise solutions between the objectives is to be found. All solutions of this set are equally good and the solutions are all Pareto optimal (meaning that an increase of one objective would simultaneously lead to a decrease of the other objective). The set of Pareto optimal solutions is called the Pareto set. The plot of the objective functions of the Pareto set is called the Pareto front [Coello Coello, 2005]. It is rarely possible to compute the real Pareto set with the existing algorithms; instead the algorithms find approximations of the Pareto set.

The optimal thermal mass is investigated using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) [Deb et al., 2002]. This is a well-known algorithm and has already been used in building performance simulation [Emmerich et al., 2008, Hopfe, 2009]. The NSGA-II algorithm belongs to the group of genetic and evolutionary algorithms. These algorithms are population based, meaning that these algorithms use a set of search points (the population) instead of one point (path oriented) to search for optima.

The population is modified every generation using variation and selection of the individual solutions in the population (like biological evolution). The population makes it possible to find multiple Pareto optimal solutions in one single run of the optimization algorithm [Deb et al., 2002].

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

6. RESULTS OPTIMIZATION OF THERMAL MASS

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

6.1. Optimization thermal mass: occupancy pattern 'evening'

6.1.1. Optimal thermal mass whole year

In Figure 3 the approximated Pareto-front of the optimization of the thermal mass for the whole year with occupancy pattern 'evening' is shown. The approximated Pareto-front represents the Pareto set found by the algorithm. Figure 3 shows that the solutions are well-distributed along the Pareto-front. The solution with optimal comfort provides 32 WOH-Σ and a heating energy demand of 1945 kWh. The solution with optimal heating energy demand provides 1700 WOH-Σ (+5213% compared to the optimal comfort solution), but with a heating energy demand of 1354 kWh (-30% compared to the optimal comfort solution). These Pareto optimal solutions, and the others solutions presented in Figure 3, are equally good; we have to define a selection criterion to select one of the solutions. In this study we choose to limit the number of WOH-Σ to 200. This criterion discards a large part of the approximated Pareto-front; the computed solution closest to this criterion provides 150 WOH-Σ (+368% compared to the optimal comfort solution)

and a heating energy demand of 1808 kWh (+34% compared to the optimal heating energy demand solution). The discussed solutions are presented in Table 2. The selected trade-off solution represents the following thermal masses: zone A: 5 kg/m^2, zone B: 26 kg/m^2, zones C and D: 77 kg/m^2 and zone E: 97 kg/m^2.
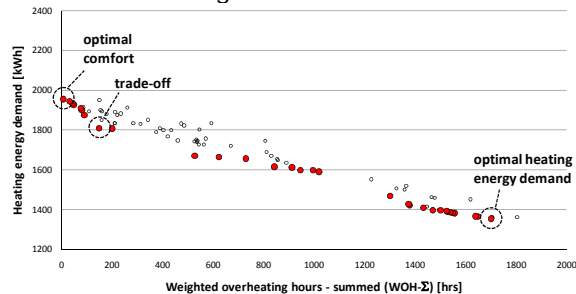

Figure 3: Results of the optimization of the thermal mass for the whole year using occupancy pattern 'evening'. Shown are the solutions of the last generations; the filled dots represent the Pareto optimal solutions.

6.1.2. Optimal thermal mass per season

During the summer period no heating is necessary, so the multi-objective optimization problem is transformed into a single-objective optimization problem with minimizing the WOH-Σ as objective. The optimal solution provides 0 WOH-Σ (and a heating energy demand of 0 kWh) with thermal masses of 90 kg/m^2 for zones on the ground floor and 100 kg/m^2 for the zones on the first floor.

During spring overheating may occur and energy is needed to heat the building, so this period requires multi-objective optimization. In Figure 4 the approximated Pareto-front of the spring optimization is shown. In Table 3 three characteristic solutions are presented: a solution resulting in optimal comfort, a solution resulting in optimal heating energy demand and a trade-off solution. To select one of the solutions we use the results of the optimal thermal mass for the whole year as a reference for the yearly total heating energy demand (1808 kWh) and total WOH-Σ (150 hours); this reference is necessary to study the impact of the solutions for this season compared to the whole year. The three solutions show a minimum and maximum heating energy demand for spring of 9 kWh (optimal heating energy demand solution) and 14 kWh (optimal comfort solution), that is respectively 0,5% and 0,8% of the total reference heating energy demand. Regarding comfort the minimum and maximum WOH-Σ are 13 hours (optimal comfort solution) and 586 hours (optimal heating energy demand solution), or 8,6% and 390% of the reference WOH-Σ. The small difference in impact of the solutions on the total heating energy demand (0,5% and 0,8%) compared to the large differences in impact on total WOH-Σ (8,6% and 390%), makes it beneficial to choose for the optimal comfort solution.
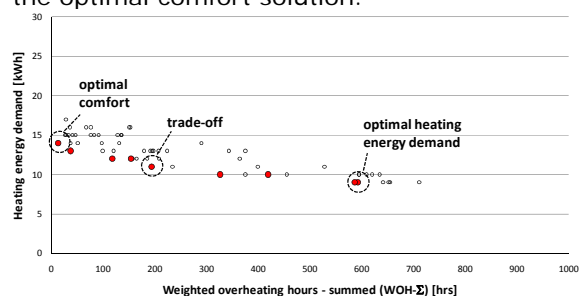

Figure 4: Results of the optimization of the thermal mass for spring using occupancy pattern 'evening'. Shown are the solutions of the last generations; the filled dots represent the Pareto optimal solutions.

The same procedure is used to select the most appropriate solution for winter and autumn. The selected solutions are presented in Table 4; the sum of WOH-Σ for the whole year is 23 hours and the sum of the total heating energy demand is 1330 kWh.

Table 2: Three solutions are shown of the optimization of the thermal mass per zone for the whole year: (1) optimal comfort (solution with lowest number of WOH-Σ), (2) optimal heating energy demand (solution with lowest heating energy demand) and (3) a trade-off solution (with selection criterion of WOH-Σ < 200 hours).

Solutions	Objectives		Thermal mass			
	Comfort (WOH-Σ)	Energy demand	Zone A	Zone B	Zone C & D	Zone E
	[hrs]	[kWh]	[kg/m^2]	[kg/m^2]	[kg/m^2]	[kg/m^2]
1. Optimal comfort	32	1945	76	99	75	66
2. Optimal heating energy demand	1700	1354	5	5	78	5
3. Trade-off (WOH-Σ< 200)	150	1808	5	26	77	97

Table 3: Three solutions are shown of the optimization of the thermal mass per zone for spring: (1) optimal comfort (solution with lowest number of WOH-Σ), (2) optimal heating energy demand (solution with lowest heating energy demand) and (3) a trade-off solution (with selection criterion of WOH-Σ < 200 hours).

Solutions	Objectives		Thermal mass			
	Comfort (WOH-Σ)	Energy demand	Zone A	Zone B	Zone C & D	Zone E
	[hrs]	[kWh]	[kg/m^2]	[kg/m^2]	[kg/m^2]	[kg/m^2]
1. Optimal comfort	13	14	60	70	98	99
2. Optimal heating energy demand	586	9	5	9	18	6
3. Trade-off (WOH-Σ< 200)	194	11	6	75	80	13

Table 4: Results of the optimization per season for occupancy pattern 'evening'.

Optimization period	Objectives		Thermal mass			
	Comfort (WOH-Σ)	Energy demand	Zone A	Zone B	Zone C & D	Zone E
	[hrs]	[kWh]	[kg/m²]	[kg/m²]	[kg/m²]	[kg/m²]
Winter	4	704	9	5	50	5
Spring	13	14	60	70	98	99
Summer	0	0	90	90	100	100
Autumn	6	612	5	5	10	5
Total	23	1330				

6.1.3. Comparison of optimal thermal mass per year and per season

Figure 5 shows that the zones on the first floor (C, D and E) require a higher yearly thermal mass compared to the zones on the ground floor (A and B). This is caused by the extra heat gain these zones receive through conduction of solar irradiation on the flat roof of the building. The relatively low yearly thermal mass of zone A compared to B is a consequence of the trade-off decision between heating energy demand and comfort. This low thermal mass will produce overheating hours, but it lowers the yearly heating energy demand.
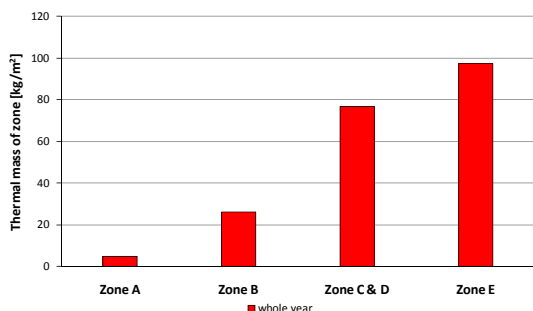

Figure 5: Optimal thermal mass per zone for the whole year using occupancy pattern 'evening'.

In summer for the seasonal optimal thermal mass, as for the yearly optimal thermal mass, the zones on the first floor require more thermal mass to prevent overheating than the zones on the ground floor (Figure 6). 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 roof this will cause overheating problems if the mass is too low. The relatively low thermal masses of zones A and E compared to zones C and D are caused by differences in floor level and orientation. In zones A and E, these differences result in elimination of the conduction through the roof or the direct solar radiation.

The results show that the optimal thermal mass changes per season (Figure 6). Comparing the performance of the sum of the seasonally changing optimal thermal masses for the whole year to the optimal thermal mass for the whole year shows a heating energy demand reduction of 26% (1330 kWh

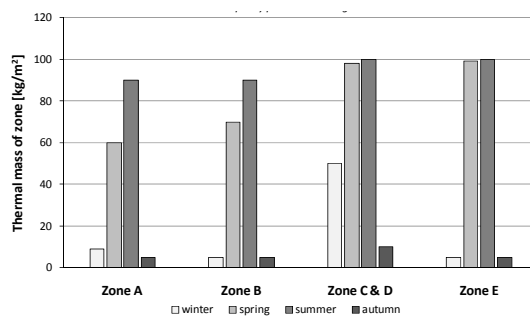to 1808 kWh) and a WOH-Σ reduction of 85% (23 hours to 150 hours).

Figure 6: Optimal thermal mass per zone for the seasons using occupancy pattern 'evening'.

6.2. Optimization thermal mass: occupancy pattern 'day & evening'

6.2.1. Optimal thermal mass whole year

Figure 7 shows the approximated Pareto front of the optimization using the occupancy pattern 'day & evening'. The selection criterion (of less than 200 WOH-Σ per year) results in a solution with a total WOH-Σ of 183 hours and a heating energy demand of 2147 kWh; the following thermal masses correspond with the solution: zone A: 88 kg/m², zone B: 67 kg/m², zones C and D: 98 kg/m² and zone E: 99 kg/m².
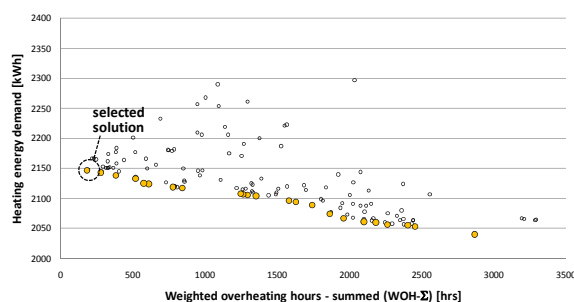

Figure 7: Solutions of the last generations of the optimization of the thermal mass for the whole year using occupancy pattern 'day & evening'; the filled dots represent the Pareto optimal solutions.

6.2.2. Optimal thermal mass per season

The same procedure as described for the occupancy pattern 'evening' is used to select the optimal solutions per season for occupancy pattern 'day & evening'; Table 5 shows the selected optimal solutions. The sum of WOH–Σ for the whole year is 159 hours and the sum of the heating energy demand is 2070 kWh.

Table5: Results of the optimization per season for occupancy pattern 'day & evening'.

Optimization period	Objectives		Thermal mass			
	Comfort (WOH-Σ)	Energy demand	Zone A	Zone B	Zone C & D	Zone E
	[hrs]	[kWh]	[kg/m²]	[kg/m²]	[kg/m²]	[kg/m²]
Winter	0	1076	62	9	79	12
Spring	74	11	60	69	98	99
Summer	85	0	100	100	100	100
Autumn	0	983	63	5	49	12
Total	159	2070				

6.2.3. Comparison of optimal thermal mass per year and per season

Zone B demands the lowest thermal mass (Figure 8); this can be explained with the north orientation of the room and the position at ground level.
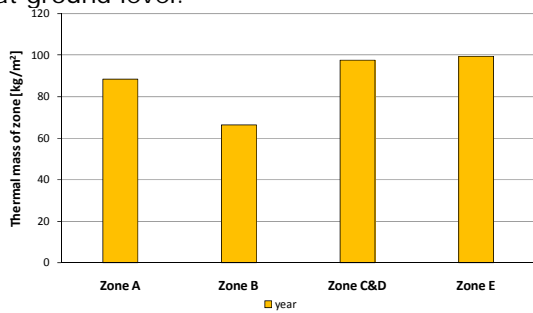

Figure 8: Optimal thermal mass per zone for the whole year using occupancy pattern 'day & evening'.

During winter the south orientated zones (A, C and D) require a high thermal mass (Figure 9); this can be explained with the relatively low position of the sun above the horizon in winter. Because of this, the south orientated zones receive a high amount of direct solar radiation and thus require a high thermal mass to prevent overheating. The extra thermal mass is also used to buffer thermal energy during the day and release this energy during the evening to reduce the heating energy demand.
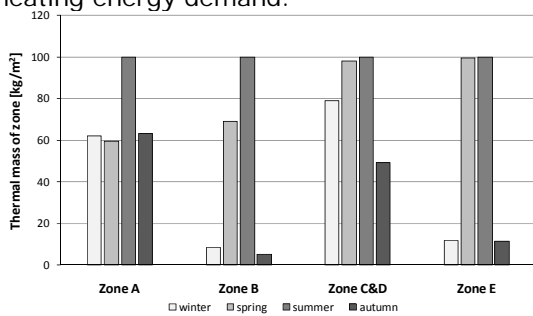

Figure 9: Optimal thermal mass per zone for the seasons using occupancy pattern 'day & evening'.

Comparing the performance of the seasonally changing optimal thermal mass for the whole year to the yearly optimal thermal mass shows a heating energy demand reduction of 4% (2070 kWh to 2147 kWh) and a WOH-Σ reduction of 13% (159 hours to 183 hours).

7. POTENTIAL FOR HATS

7.1. Sensitivity of optimal thermal mass to occupancy patterns

The influence of the occupancy pattern on the optimal thermal mass is visible from the absolute differences of the optimal thermal mass between the two occupancy patterns (Figure 10 and 11). For this case study a higher thermal mass is preferred for the 'day & evening' occupancy pattern, than for the 'evening' occupancy pattern (Table 4 and 5).
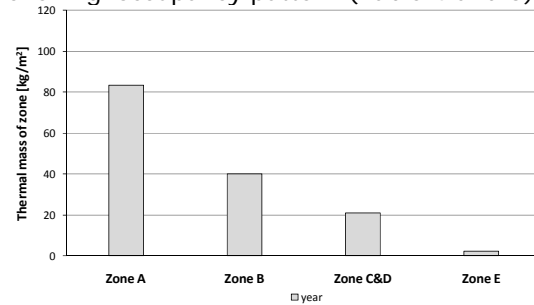

Figure 10: Absolute differences between the optimal thermal masses for the whole year of both occupancy patterns.
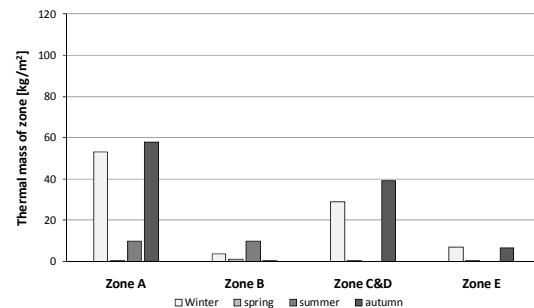

Figure 11: Absolute differences between the optimal thermal masses per season of both occupancy patterns.

7.2. Sensitivity of optimal thermal mass to seasons

The influence of the seasons on the optimal thermal mass is visible from Figure 6 and 9. Low thermal mass is required in winter and high thermal mass in summer. The influence can be quantified with the average relative change of the optimal thermal mass during the seasons (relative to the average value of the optimal thermal masses during the seasons for the specific zone, Figure 12). A high average relative change (ARC) indicates a strong sensitivity of the optimal thermal mass to the seasons and thus potential for implementing HATS. All zones with the 'evening' occupancy pattern show high ARC values: zones A, B, C, D and E

respectively 83%, 88%, 54%, 54% and 90%. The ARC for the 'day & evening' occupancy pattern shows a larger spread between the zones. Zones B and E have a relatively high ARC of 85% and 79% compared to zones A, C and D with values of 20%, 22% and 22%.
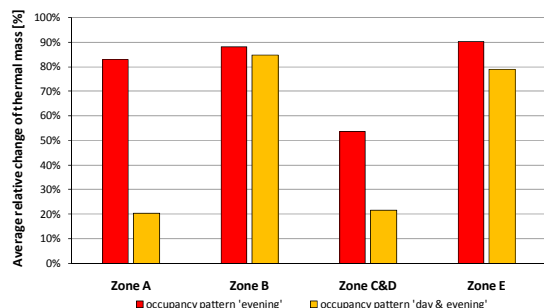

Figure 12: Average relative change of optimal thermal mass during the seasons; high values indicate a potential for HATS.

7.3. Performance of adaptable thermal mass

The adaptable thermal mass shows a heating energy demand reduction of 26% and a WOH-Σ reduction of 85% for the 'evening' occupancy pattern, and a heating energy demand reduction of 4% and a WOH-Σ reduction of 13% for 'day & evening' occupancy pattern. These results show that the occupancy pattern has a strong influence on the performance of the HATS concepts.

In [Hoes et al., 2010] the potential of HATS is quantified in more detail using a simplified HATS model.

8. CONCLUSIONS

In this paper the potential of the novel HATS concept is investigated by determining the sensitivity of the optimal thermal mass of a building to the change of seasons and to changing occupancy patterns. The optimal thermal mass is defined as the quantity of the thermal mass that provides the best building performance (based on a trade-off between the building performance indicators).

The results show that the optimal quantity of the thermal mass is sensitive to changing occupancy patterns and the change of seasons, which implies that the building performance will benefit from implementing HATS. Furthermore, the occupancy pattern shows a strong influence on the optimal quantity of the thermal mass and on the performance of the HATS concepts. This indicates that user behavior modeling will be important for the performance simulation of HATS concepts.

The presented results are calculated 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 various HATS concepts will be defined and modeled. The performance of these concepts will be optimized using innovative control algorithms based on multi-objective optimization with receding time horizons.

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