Computational performance prediction of an adaptable thermal storage concept

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Abstract
In the Netherlands and in other moderate climates, residential buildings with low thermal mass (e.g. steel frame constructions) demand less heating energy during intermittent use compared to high thermal mass buildings. This is caused by a shorter pre-heating period. Though, low thermal mass buildings are also sensitive to overheating problems. These problems can be alleviated by increasing the building’s thermal storage capacity with thermal energy storage systems or materials. However, this will also eliminate the benefit of a short pre-heating period. Therefore, we propose a concept that combines the benefits of buildings with low and high thermal mass by applying an adaptable thermal storage system to a lightweight building.

The proposed adaptable thermal storage concept consists of phase change materials (PCMs) as thermal storage medium placed above a thermally insulating ceiling. This ceiling can be opened or closed to influence airflow to the PCMs and thus thermally couple or decouple the PCMs from the room. In this paper we investigate the potential of this concept using computational building performance simulation.

To assess the true potential, it is necessary to optimize the design of the concept. Since the performance of the concept strongly depends on its operation, it is important to integrate optimal control strategies during the design optimization. We show how a model predictive controller and building scenario uncertainties are integrated in the design process. The simulation results show that the performance (regarding energy demand and thermal comfort) of the optimized design is higher than of the heavyweight and lightweight reference cases. This indicates a clear potential for the adaptable thermal storage concept.

Keywords – thermal storage; adaptable; lightweight; computational performance prediction; uncertainty analysis; performance robustness

1. Introduction
Lightweight steel frame constructions receive increasing interest as construction method for residential buildings, since these constructions are faster built and thus lower in costs compared to conventional concrete and masonry building constructions. Lightweight constructions typically lead to
buildings with low thermal mass; this low thermal mass shortens the pre-heating period compared to buildings with a higher thermal mass. During the heating season, this results in lower heating energy demands when the building is used intermittently (e.g. in residential buildings when people are working during the day). However, buildings with low thermal mass are also sensitive to overheating problems. It is possible to alleviate these problems by increasing the building’s thermal storage capacity. This can be achieved by applying thermal energy storage systems or materials to the building. Yet, by adding extra thermal storage to lightweight buildings, these buildings will show the same thermal behavior as heavyweight buildings, i.e., the benefit of a short pre-heating period is lost.

Therefore, Hoes et al. [1] propose a so-called Hybrid adaptable thermal storage (HATS) concept which is able to adapt to the most optimal storage capacity depending on weather conditions and building occupant behavior. Results of calculations with a simplified adaptable storage model show that for a case study building it is possible to reduce the energy demand by 35% compared to a conventional permanent high thermal mass building. Furthermore, the results show an increased thermal comfort compared to a low thermal mass building. These findings indicate that HATS concepts have the potential to increase building performance.

In this paper, in contrast to the earlier mentioned work, we investigate the potential performance of a specific HATS concept. The concept consists of phase change materials (PCMs) as thermal storage medium placed above a thermally insulating ceiling (described in more detail below). This study should be seen as a scoping study in which we want to determine if this concept shows enough potential to justify further studies, e.g., based on measurements in a mock-up building. Therefore, this work is solely based on computational building performance simulation.

2. Suspended ceiling and thermal energy storage

The HATS concept is based on a lightweight building with a suspended ceiling in each room. The ceiling is thermally insulating the living space from the cavity above the ceiling (1a and 1b in Fig. 1). In the cavity a thermal storage medium is placed (2 in Fig. 1); in this case study, we choose for phase change materials (PCMs). The PCMs are integrated in a baffle system (Fig. 2) which creates a large surface and thus will enhance the convective heat transfer between the air and the PCMs.

Adaptation of the thermal storage capacity is made possible by opening or closing the ceiling. When the ceiling is opened air can flow to/through the PCM baffles exchanging thermal energy: the PCMs are thermally coupled to the room (1a in Fig. 1). When the ceiling is closed, the airflow is blocked and the PCMs are thermally insulated from the living space: the PCMs are thermally decoupled (1b in Fig. 1). A ceiling system with horizontal louvres (like in Fig. 3) might provide the required opening/closing functionality.
With this HATS concept each room can switch independently between a low and a high thermal storage capacity. The chosen PCM melting temperature has a strong influence on the concept’s performance; therefore, we need to optimize it to assess the concept’s true potential.

Next to the PCM melting temperature, the performance of the concept also depends on its operation, which, therefore, should be taken into account during the design optimization. When do we switch from a coupled state to a decoupled state? Furthermore, we also need to consider what should happen to the storage medium when it is decoupled. Depending on the ambient temperature the PCMs can be regenerated by flushing the cavity with outdoor air (3 in Fig. 1). This can be done using fans or natural ventilation. Of course, the use of fans will cost additional energy, but it might be more effective than natural ventilation. Furthermore, the ventilation rate in the living zone should be set. In total we can define up to 100 different daily control strategies based on all the possible combinations of coupling and ventilation settings. A controller is needed to find the optimal control strategy for each day.

The controller used in this study is described in section 5. In the next section the simulation model is discussed.


A simulation model of the HATS concept is made in the building performance simulation program ESP-r. The building is based on the steel
frame residential houses of the Zonne-entrée project (Tata Steel Star-Frame Solutions and Courage Architecten) in Apeldoorn (The Netherlands). The building consists of five zones with lightweight wall and floor constructions; more details are given in Fig. 4. In the ESP-r model only the two rooms on the ground floor are considered. Each of these rooms consists of two thermal zones: one zone for the living space and one zone for the cavity with the PCMs (Fig. 5). The ceiling is modeled as an adiabatic surface, thus there will be no heat flow through the ceiling. We assume that the air in both zones is fully mixed when the ceiling opens. An airflow network is used to provide the ability to model the various ventilation strategies. External blinds on the south façade are controlled based on indoor temperature and irradiation on the façade. An ideal controller is providing heating in the living space.

As a reference case, the same building is modeled with heavyweight constructions (masonry walls, heavyweight concrete floors), but without the cavity. The ventilation capacity and heating capacity is kept the same as for HATS concept. Fig. 6 shows the simulated air and surface temperatures of three summer days for this reference case and the HATS concept with coupled and decoupled thermal storage. The influence of the coupled thermal storage (solid red line) is clear on the first day (ambient temperatures over 30°C) with an air temperature difference of 2°C compared to the building with decoupled thermal storage (solid grey line).

Two performance indicators are defined to assess the building’s performance: the total primary energy use and the weighted discomfort hours.

Total primary energy use

The total primary energy use (E_{total}) is defined as the sum of the primary energy use for heating (E_{heating}) and for operating the fans (E_{fans}). The E_{heating} is calculated using the heating energy demand calculated by ESP-r and efficiency factors for the heating system. The following efficiency factors are used (based on [NEN7120]): for heat generation \( \eta_{generation} = 0.95 \), heat distribution \( \eta_{distribution} = 1.0 \) (no losses since we assume the heat distribution takes places within the thermal zone) and heat supply \( \eta_{supply} = 0.95 \). Heat is generated using natural gas; therefore no primary energy conversion factor is.
needed. The $E_{\text{fan}}$ is calculated based on the required ventilation rate, the total pressure difference over the fan calculated by ESP-r and a fan efficiency factor $\eta_{\text{fan}} = 0.5$. A primary conversion factor for electricity of 2.5 is used to calculate the $E_{\text{fan}}$, which is a typical conversion factor for electricity in the Netherlands [NEN7120].

**Weighted discomfort hours**

The weighted discomfort hours ($w\text{PPDhrs}$) are calculated based on the PPD. Each hour with a PPD$>\text{PPD}_{\text{limit}}$ is regarded as discomfort hour and weighted with the factor $\text{PPD}/\text{PPD}_{\text{limit}}$. The $\text{PPD}_{\text{limit}}$ is set to 10%, which is climate category B of NEN-ISO 7730. Regarding the calculation of the PMV/PPD, it is assumed that people in their own homes have a stronger tendency to change their clothing to reach their preferred comfort level than, e.g., in offices. Therefore, defining a fixed clothing (clo) value in the PMV/PPD equation for winter and summer is not realistic. Thus, per seasons an upper and a lower limit for the clothing (clo) value is defined, resulting in a bandwidth of acceptable temperatures as proposed in [2].

![Fig. 6: Simulated temperatures for three summer days (July 26-28, 1995) for the south orientated room. Shown are the air temperatures for the heavyweight building (solid black line), lightweight building (solid grey line) and for the zone with coupled thermal storage (solid red line). The dashed lines indicate the baffle surface temperatures.](image)

4. **Uncertainty analysis**

Since there are no measurements to validate the building model, it is important to perform an uncertainty analysis. For this purpose a Monte Carlo analysis is performed. The uncertainties considered in this analysis are divided into two groups [3]: *scenario* ‘uncertainties’ (e.g. the type of building occupants) and *thermophysical* uncertainties (e.g. uncertainties in material properties).
**Scenario uncertainties**

In an earlier study [1] we showed that HATS will show the greatest potential when in the building a temperature change occurs during the day. Without this temperature change, the heating energy demand for HATS is almost the same as for a heavyweight building. Therefore, an occupancy profile is defined in which the occupants are at work during weekdays and are at home during evenings using the rooms from 18h to 24h. The household consist of two people, which represent 33% of Dutch households in 2010 (www.statline.cbs.nl). Internal gains (e.g. by cooking or TV/computer use) are perfectly correlated to the occupancy profile, i.e. the internal heat gains are triggered when people are present, during absence the gains are reduced to a base load (‘slumber’ mode). Average internal gains of 2, 4 and 6 W/m² are used (based on NEN7120). These are average values of a detailed profile used in the simulation. For example, the kitchen is placed in zone B, so due to cooking activity high internal gains will occur there early in the evening.

The performance of the HATS concepts is studied for three weeks during the year selected from a Dutch reference year (NEN5060-B2-1%): a spring week with average temperatures (max. temperature 20°C), a warm summer week (max. temperature 32°C) and a cold winter week (min. temperature -10°C) in the Netherlands.

**Thermophysical uncertainties**

Distributions for the thermophysical material properties are based on values found in literature [4, 5, 6, 7], see Table 2. The distribution for the emissivity of the inside surfaces is N(0.9, 0.02) [4]. The solar absorptivity distribution for gypsum surfaces is N(0.4, 0.03) and for concrete surfaces is N(0.68, 0.04) [4]. For simplicity it is assumed that the material properties are constant during the simulation period, which is not true in reality, e.g. the material conductivity will be influenced by moisture, aging, etc.

**Table 2:** Materials properties and their distributions (dis.); N = normal distribution with μ and σ, U = uniform distribution with min. and max. values.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity [W·m⁻¹·K⁻¹]</th>
<th>Density [kg·m⁻³]</th>
<th>Specific heat capacity [J·kg⁻¹·K⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dis. μ or min. σ or max.</td>
<td>dis. μ or min. σ or max.</td>
<td>dis. μ or min. σ or max.</td>
</tr>
<tr>
<td>Air cavity</td>
<td>N 0,16 0,01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Concrete</td>
<td>N 1,4 0,11</td>
<td>N 2100 24</td>
<td>N 653 38</td>
</tr>
<tr>
<td>Concr. heavy</td>
<td>N 1,7 0,11</td>
<td>N 2400 24</td>
<td>N 1000 38</td>
</tr>
<tr>
<td>Gypsum</td>
<td>N 0,25 0,03</td>
<td>N 800 9</td>
<td>N 1090 86</td>
</tr>
<tr>
<td>Insulation</td>
<td>U 0,0341 0,0424</td>
<td>U 13,5 14,49</td>
<td>U 980 1020</td>
</tr>
<tr>
<td>Mansonry</td>
<td>N 0,84 0,14</td>
<td>N 1830 119</td>
<td>N 891 90</td>
</tr>
<tr>
<td>Wood panel</td>
<td>N 0,151 0,042</td>
<td>N 578 148</td>
<td>N 2162 646</td>
</tr>
</tbody>
</table>

The convective heat transfer correlations found in literature are all derived for specific cases, e.g. heating under a window or mechanical ventilation with a heated wall (a complete overview is given by [8]).
Beausoleil-Morrison [9] implemented an adaptive convection algorithm in ESP-r for which he defined various convection regimes. For each regime he defined which correlations to use for each surface. Furthermore, he specified which correlations to use when heating is turned on or off. However, none of the regimes match with our case study. Therefore, it is not possible to select one convection regime. Hence, various regimes are selected (Table 3). Each of the regimes is given an equal probability, i.e. a uniform distribution is assumed.

In literature various distributions for air tightness (infiltration) can be found [7,10,11]. We use the distribution given [11], since it is based on measurements performed in recently built buildings. The distribution is LogN(1.31, 0.96) in ACH with a 50 Pa pressure difference. In the ESP-r model air tightness is varied by changing the crack length value of a crack component in the airflow network.

Table 3: Convection regimes per ventilation strategy for each thermal zone as defined in [9]; uniform distributions (U) are assumed. The convection regimes make use of the correlations by Alamdari & Hammond (A3, B2, D), Khalifa & Marshall (B2, D), Fisher (C2) and the blended correlation by Beausoleil-Morrison (E).

<table>
<thead>
<tr>
<th>Thermal zone</th>
<th>Convection regimes per ventilation strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural ventilation</td>
</tr>
<tr>
<td>Living space</td>
<td>U</td>
</tr>
<tr>
<td>Cavity</td>
<td>U</td>
</tr>
</tbody>
</table>

Result thermophysical parameter uncertainty

As mentioned a Monte Carlo analysis (MCA) is used to assess the model’s uncertainty. The MCA is based on Latin Hypercube sampling using the distributions defined for thermophysical parameters. The appropriate sample size follows from a sensitivity analysis with different sample sizes and various runs for each sample size. The analysis shows that a sample size of 200 gives the same uncertainty range for the various runs and thus is considered sufficient for this case study. Here, only the results are shown for the sample size of 200. The MCAs are performed for the three levels of internal gains and for different PCMs (T_{melt} from 20 to 24°C). Results of the MCA for T_{melt} of 22°C are shown in Fig. 7. In the simulations the control strategy is fixed to coupled PCMs without night ventilation.

The box plots show E_{total} for the spring and winter week. For the spring week E_{total} shows a normal distribution with maximum relative standard deviation of 2.1% for the three uncertainty scenarios (see the boxplots). The maximum RSD for the winter week is 12.6%. The discomfort hours are not normally distributed. Therefore, the absolute range between the quantiles of 15% and 85% (ca. 1 sd difference from the mean) is used to describe the uncertainty. This range has a maximum of 0.3 hours for the three scenarios in spring and 3.6 hours for the winter week. The other PCMs show the same uncertainty range.
The uncertainties in $E_{\text{total}}$ for the spring week are relatively small compared to the winter week. This can be explained by the relatively large influence of the thermophysical parameters on $E_{\text{heating}}$ compared to their influence on $E_{\text{fan}}$ (which depends much stronger on the chosen ventilation strategy), and because 80% of $E_{\text{total}}$ is for heating in winter compared to 30% in spring.

5. Operating the HATS concept

As mentioned before, operation of the HATS concept will have a large impact on the performance, thus it is important to define an optimal control strategy. Since HATS concepts are slow responding due to their slow responding storage capacity, we need a controller which is able to anticipate on future events to assure optimal and robust performance. Model predictive controllers are capable of doing that by using models to predict future events. Therefore, to operate the HATS concept we use a model predictive controller (MPC).

Model predictive controller and disturbances

The controller is implemented in the simulation environment proposed in [12] consisting of ESP-r as building simulation tool, Matlab as the MPC and BCVTB as middleware for data exchange between the two programs. As in [12] the building model in the MPC is based on the same ESP-r building model as the ‘real’ building. So to simulate a MPC under realistic conditions, we have to take disturbances into account.

In this study we introduce disturbances in weather predictions and user behavior. These disturbances depend on the selected uncertainty scenario, e.g. the arrival times show variations around 18h based on the selected ‘evening’ occupancy scenario. In Table 4 the disturbances related to the uncertainty scenarios are shown. Using these disturbances max. 90 disturbance scenarios can be made ($10 \times 3 \times 3$). Since not all simulation...
periods show the same sensitivity to the disturbances, the number of disturbance scenarios can vary for the different simulation periods. For example in summer the performance indicators showed to be very sensitive to the occupancy, while for spring this was not the case. Therefore, only one occupancy disturbance scenario is used for spring (to reduce computational time), while more scenarios are used for summer.

Table 4: Disturbances in the MPC controller. The parameters marked with an asterisk (*) depend on the chosen uncertainty scenario.

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Distr.</th>
<th>Values</th>
<th>Units, remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy profile</td>
<td>arrival and departure times*</td>
<td>D</td>
<td>[1:10]</td>
<td>ten occupancy series generated with markov chains [13]</td>
</tr>
<tr>
<td></td>
<td>ventilation rate when occupied</td>
<td>D</td>
<td>[1:3]</td>
<td>low, med, high ventilation rate (party mode)</td>
</tr>
<tr>
<td>Simulation week</td>
<td>daily weather uncertainty*</td>
<td>D</td>
<td>[1:3]</td>
<td>three weather predictions based on the nearest neighbour method [12]</td>
</tr>
</tbody>
</table>

The MPC’s optimization horizon length describes how far the controller will look into the future, e.g. 1, 2 or 3 days. The controller searches for the optimal control sequence for this optimization horizon. In this project each day is represented with one control signal, e.g., ‘close the ceiling and use natural ventilation’ or ‘open the ceiling’. The controller is set to minimize both (conflicting) performance indicators.

6. Exploring the design space

The building performance is calculated for two reference cases, the heavyweight building and the lightweight building with only ‘decoupled’ control options, and for the lightweight building with all control options (HATS). Note that all cases have the same capacity for heating and ventilation. For a range of melting temperatures (20-24°C) the MPC controller is used to calculate the performance indicators per zone for the three weeks.

Optimization horizon length

The controller’s optimization horizon length will influence the performance of the controller. Therefore, the optimal horizon length is investigated for each week and $T_{\text{melt}}$ by varying it from 1 to 3 days. In summer the controller shows the best performance (lowest discomfort and energy demand) with an optimization horizon of 2 days. For the spring and winter week a horizon of 1 day shows the best results. This difference in optimal horizon length is influenced by the uncertainty in the weather predictions. For a week with large uncertainties in the weather predictions (e.g. in spring and autumn), it gets harder to find an optimal control sequence when the horizon length increases (due to propagation of the uncertainties). In such a case it is better to reduce the horizon length.
Results various melting temperatures

Fig. 8 shows the results per melting temperature using the optimal horizon length for each week. These results are used to select the optimal T_{melt} per room (since the rooms are thermally decoupled). For the user scenario of 4 W/m² this results in an optimal T_{melt} of 22°C for zone A and 22°C for zone B. The user scenarios of 2 and 6 W/m² are also investigated, however these scenarios did not change the optimal T_{melt}.

In Table 5 the results for the optimal combination of T_{melt}'s are shown in more detail:
• Spring week (Table 5): for both zones the HATS control sequence is identical to the lightweight control sequence, which results in an E_{total} of 136 kWhrs compared to 148 kWhrs for the heavyweight building (8% difference). All cases show thermal discomfort of 0 wPPDhrs.
• Summer week (Table 5): HATS chooses mainly for a heavyweight approach except for one lightweight day for zone B. This sequence results in a mean energy demand of 167 kWhrs for all cases. However, HATS gives slightly lower comfort compared to the heavyweight building (6 to 0 wPPDhrs)(Fig. 9). The lightweight building shows the highest discomfort with 90 wPPDhrs.
• Winter week (Table 5): HATS chooses mainly for a lightweight approach except for one heavyweight day for zone B, for both zones this leads to 0 wPPDhrs for zone A and B (Fig. 10), and the lowest E_{total} with 388 kWhrs compared to 443 kWhrs for heavyweight. The heavyweight case shows 52.7 discomfort hours for zone A and B compared to HATS due to under cooling (not enough heating capacity).

These results show that the HATS building makes use of the optimal thermophysical behavior depending on the uncertainty scenarios. This leads to higher thermal comfort and reduced energy demands compared to both reference cases.
Fig. 9: Results PCM22 zone A for summer week; comparison of HATS to non-adaptable buildings for summer (90% prob. range).

Fig. 10: Results PCM22 zone B for winter week; comparison of HATS to non-adaptable buildings for winter (90% prob. range).

Table 5: Results of the HATS model with PCM22 the model predictive controller (summed mean values of both zones).

<table>
<thead>
<tr>
<th></th>
<th>Total energy use [kWh]</th>
<th>Thermal comfort [wPPDhrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heavy</td>
<td>Light</td>
</tr>
<tr>
<td>Spring week</td>
<td>148</td>
<td>137</td>
</tr>
<tr>
<td>Summer week</td>
<td>167</td>
<td>167</td>
</tr>
<tr>
<td>Winter week</td>
<td>443</td>
<td>388</td>
</tr>
<tr>
<td>Three weeks summed</td>
<td>759</td>
<td>692</td>
</tr>
</tbody>
</table>

7. Discussion

Fig. 8 shows that for the simulated weeks the energy demand does not differ among the PCM cases and the lightweight reference case. This indicates that during the heating periods the phase change of the PCMs is not used for daytime energy storage, e.g. to store solar gains during sunny days. This is clear from the chosen control sequences for spring and for zone A in winter; yet, zone B is coupled for one day in winter. For that day, however, the baffle surface temperature did not reach $T_{\text{melt}}$. The design can be adapted to store more energy (for heating demand reduction) by selecting a lower $T_{\text{melt}}$ above the ceiling (e.g. 18°C) for sunny winter day storage (which can be decoupled when it is not needed) and a higher $T_{\text{melt}}$ in the walls of the living zone for summer comfort (e.g. 24°C).

The performance of the reference cases can be improved by increasing the heating capacity (for the heavyweight case) and the ventilation capacity (for the lightweight case); however, this will increase the total energy use of both cases. It is calculated that the under cooling of the heavyweight building can be reduced by doubling the heating capacity, which will results in a 20% increase of the heating energy demand.

8. Conclusion

This HATS concept shows a higher performance compared to the fixed thermal mass reference cases. For the three simulated weeks the total energy use for heating and fans is decreased with 9% compared to the heavyweight
reference case. Moreover, thermal comfort is increased to 7.6 weighted discomfort hours compared to 91.0 hours for the lightweight case (overheating) and 52.7 hours for the heavyweight case (under cooling). The latter indicates that to achieve the same level of thermal comfort as in the HATS building, it is necessary to increase the ventilation capacity for the lightweight case and the heating capacity for the heavyweight case, which will increase the total energy use of both reference cases.

The performance of the concept is sensitive to the selected PCM melting temperatures. Therefore, it is important to investigate the optimal melting temperature for each design when applying this concept in real buildings.

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