The potential of lightweight low-energy houses with hybrid adaptable thermal storage

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The potential of lightweight low-energy houses with hybrid adaptable thermal storage: Comparing the performance of promising concepts

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ABSTRACT

The international community set clear goals regarding the reduction of CO₂ emissions and energy demand in the built environment. This drives research and building practice to search for solutions and new building concepts that contribute to achieving these goals. The work presented in this paper should be seen in that context. This research focuses on a building concept that makes use of the thermal energy storage capacity of materials and buildings. The concept combines the thermophysical benefits of low and high thermal mass buildings by adapting (on demand) to the most optimal thermal capacity. The main objective of this research is to identify if this so-called hybrid adaptable thermal energy storage (HATS) approach shows potential to reduce the energy demand of new lightweight residential buildings in the Netherlands and maintain or improve thermal comfort. This paper gives an overview of various HATS concepts and discusses the predicted performance of three HATS concepts. This research shows that the HATS approach is able to reduce the heating energy demand compared to a lightweight and heavyweight reference case. Furthermore, it shows that the HATS approach is able to improving thermal comfort compared to the lightweight reference case and maintain thermal comfort compared to the heavyweight reference case.

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1. Introduction

1.1. Reduction of energy use and CO₂ emissions

According to the International Energy Agency, the building sector must reduce its total CO₂ emissions by 60% in 2050 in order to limit global temperature rise to 2 °C [1]. Reduction of the use of fossil fuels in the built environment is an important step to meet these CO₂ emission goals. Therefore, the EU introduced the Energy Performance of Buildings Directive (EPBD) in 2002 [2]. The EPBD demands EU countries to reduce the energy use in buildings. This resulted in strict energy performance regulations. For example, the Dutch government introduced the EPC (energy performance coefficient) for new (residential) buildings to enforce energy saving measures; low EPC values correspond to highly energy efficient buildings. The EPC was set to 0.6 in 2011 and lowered to 0.4 in 2015, which forces building designers to use high levels of thermal insulation (R_c values of at least 3.5 m²K/W for floors, 4.5 m²K/W for walls and 6.0 m²K/W for the roof) and high energy efficient boilers. In addition, detached and semi-detached houses require solar

collectors to (pre)heat domestic hot water or ground source heat pumps [3]. The goal of the Dutch government is to reach energy neutral dwellings in 2020; therefore, the EPC will be set to 0.0 in 2020. This means that these future dwellings need to be very energy efficient. Moreover, a large portion of the remaining energy demand should be covered with renewable energy. These stricter energy requirements are a great challenge for the building industry.

The EPC focuses only on energy use in the operational phase of buildings, however the construction and demolition phase of buildings also contribute to the total energy use and CO₂ emission of buildings. To this purpose green building rating tools (e.g. BREEAM [4] and LEED [5]) are developed; these tools assess the sustainability of the whole building lifecycle. For instance, most of these tools also evaluate the reuse of building materials and management of waste materials at the construction site [6]. In the Netherlands, the use of these rating tools is not enforced by the building codes; nonetheless, their use is increasing among building designers. As a result, these designers need to reconsider conventional building concepts, since it might be more sustainable to use an alternative concept. Therefore, research and building practice are searching for solutions or new building concepts that contribute to achieving the mentioned energy and CO₂ emission goals.

The work presented in this paper should be seen in the same context. The work focuses on new building concepts that make use

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of the thermal energy storage capacity of materials and buildings. The scope of this research is narrowed down to solutions for residential houses in the Netherlands; the new building concept is discussed next.

1.2. Hybrid adaptable thermal energy storage

The thermal energy storage capacity of a building is closely related to the chosen material of the structural frame. Various materials can be used for the structural frame of a building; the most common materials are steel, wood, brick and concrete. Steel and wood are generally categorized as lightweight constructions with a construction weight of around 100 kg/m² floor surface area, while brick and concrete are categorized as heavyweight constructions with a weight of around 500 kg/m² floor surface area. From a thermophysical perspective the main difference between lightweight and heavyweight constructions is the difference in *effective thermal mass*; the effective thermal mass describes the effective thermal energy storage capacity of the materials used in a building. In general, buildings with lightweight constructions have a lower effective thermal mass than buildings with heavyweight constructions. This difference in effective thermal mass influences building performance regarding heating energy demand and thermal comfort:

- Buildings with low effective thermal mass show a fast response to temperature and heat flux excitations. This fast response shortens the pre-heating period of buildings compared to buildings with higher effective thermal mass. This results in lower heating energy demands when the building needs to be heated to a higher temperature. However, due to their fast response, buildings with low effective thermal mass are also sensitive to overheating. Though, it is possible to reduce this sensitivity through proper building design, e.g. blinds, overhangs.
- Buildings with high effective thermal mass show a slow response to temperature and heat flux excitations. This slow response delays and reduces peak temperatures, which reduces the risk of overheating. However, this also means that it requires more time to heat the building to a higher temperature, which results in higher heating energy demands when the building cools down due to intermittent building use.

A solution to reduce the risk of overheating in lightweight low thermal mass buildings is to increase the building's thermal energy storage capacity (from here on *effective thermal mass* is referred to as *thermal mass*). This can be done by adding thermal energy storage systems or materials to the building. This changes the thermophysical behavior of the building to that of a high thermal mass building, which also means that the benefit of a short pre-heating period is lost. Thus, to make use of the thermophysical benefits of low and high thermal mass buildings, buildings should be able to adapt (on demand) to the most optimal thermal mass. In the past, various studies investigated how to design and use thermal mass for thermal energy storage in buildings, e.g. [7,8]. However, in these studies the thermal mass is not made (fully) adaptable as meant above. This novel adaptable approach is the main topic of this research. Building concepts that use this approach are referred to as *adaptable thermal energy storage* concepts. The term *hybrid* is added to indicate the possibility of combining two or more of these concepts in one (hybrid) building concept. Therefore, the term *hybrid adaptable thermal storage* (HATS) concept is used in this work.

1.3. Lightweight building constructions

This research focuses on HATS concepts that can be used in combination with lightweight constructions. Lightweight constructions

are not commonly used for residential buildings in the Netherlands; heavyweight concrete and brick building constructions are traditionally the dominant construction method. However, according to various recent studies, lightweight constructions are an interesting alternative. In these studies, the environmental impact of lightweight and heavyweight structural materials for the whole building lifecycle is investigated using life cycle analysis (LCA). Cole [9] finds that wood and steel frame buildings use less energy and produce less CO₂ emissions during construction compared to concrete buildings. Xing et al. [10] compare steel frame buildings to concrete buildings and confirm Cole's findings for steel frame buildings. Other researchers suggest that the use of wood as construction material has the potential to reduce global CO₂ emissions [11,12]. Goverse et al. [13] argue that using wood as construction material for Dutch houses could reduce CO₂ emissions by almost 50% compared to traditional constructions. Vefago and Avellaneda [14] argue that the recyclability of wood and steel frame buildings is higher than concrete structures, which increases the sustainability of these building designs. In general, the findings of these LCA studies should be handled with care, since the results may be influenced by the building location and available resources. However, these studies clearly indicate that lightweight constructions should not be overlooked in the design process (certainly with the CO₂ emission goals in mind). This is also true for specific retrofitting cases, e.g. top-up extensions. Lightweight constructions can be used for these extensions without the need to change the building's foundations. In the Netherlands these sort of retrofitting methods are interesting due to high prices for building estates. Other specific buildings cases that are well suited for lightweight constructions are for example temporary and floating buildings.

1.4. Objectives and paper structure

The main objective of the work presented in this paper is to identify if the HATS approach shows potential to reduce the energy demand of new lightweight residential buildings in the Netherlands (with the 2020-goal in mind) and maintain or improve thermal comfort. The latter is important, since it is assumed that building occupants will not accept solutions that compromise thermal comfort. It is hypothesized that the HATS approach is able to reduce the energy demand and increase thermal comfort in lightweight Dutch residential buildings. The performance of the HATS approach is investigated using *computational building performance simulation*, i.e. using 'virtual buildings', and it should determine if the HATS approach shows enough potential to justify further study, e.g. by measurements in a mock-up.

This paper is structured as follows. Section 2 briefly introduces the results of a preliminary potential study of the HATS approach. Section 3 describes several HATS concepts and identifies which concepts are promising for Dutch residential buildings. Section 4 introduces a performance assessment methodology and the case studies used in this paper. Section 5 discusses the predicted performance of the three promising concepts compared to conventional lightweight and heavyweight buildings. Section 6 concludes this paper with a discussion of the results.

2. Preliminary potential study

A preliminary indication of the potential of the HATS approach is presented in two papers [15,16]. In the first paper a simplified adaptable thermal energy storage model is used. The model represents a fictitious, idealized adaptable thermal energy storage concept. The model switches between two extreme building cases (lightweight and heavyweight) and chooses the building variant with the lowest discomfort (primary criterium) and lowest

Fig. 1. Simulated results of the optimal effective thermal mass (5 kg/m^2 is lightweight, 50 kg/m^2 is mediumweight and 100 kg/m^2 is heavyweight) of a case study building with five zones (zone A, B, C, D and E) and an 'evening' occupancy pattern [16].

heating energy demand (secondary criterium) on a monthly, weekly or daily frequency. In the second paper optimization techniques are used to assess the optimal (effective) thermal mass of a case study building for each season. The optimal thermal mass of each room in the case study building is calculated for two occupancy patterns: 'evening' and 'day & evening' occupancy. It is assumed that if the optimal thermal mass changes per season, then this indicates that the adaptable thermal energy storage approach shows a certain potential. The main findings of both papers are summarized below:

- The results of the simplified adaptation model show that adaptable thermal energy storage provides the same level of thermal comfort during cold periods as a lightweight reference case, however, without the need for additional fan energy during warm periods. The results also show that adaptable thermal energy storage provides the same level of thermal comfort as a heavyweight reference case, but without the need for additional heating energy during start-up periods. Furthermore, the preliminary study shows that adaptable thermal energy storage increases the performance robustness regarding thermal comfort.
- The optimization results show that each room has a unique optimal thermal mass depending on its orientation, floor level and occupant scenario (Figs. 1 and 2). Furthermore, the optimal thermal mass shows to be sensitive to the change of seasons. This indicates that the adaptable thermal energy storage approach shows potential.
- The results show that the occupancy pattern has a strong influence on the potential of an adaptable storage capacity. A building which is used intermittently or during short periods will benefit from adaptable thermal energy storage. However, a building which is used during long and constant periods benefits less from adaptable thermal energy storage.

Fig. 2. Simulated results of the optimal effective thermal mass (5 kg/m^2 is lightweight, 50 kg/m^2 is mediumweight and 100 kg/m^2 is heavyweight) of a case study building with five zones (zone A, B, C, D and E) and a 'day & evening' occupancy pattern [16].

- The results show that the potential depends on the thermal resistance of the façade and roof. A sensitivity analysis with three R_c values (3, 5 and $8 \text{ m}^2\text{K/W}$) shows that the lowest thermal resistance results in the highest potential; this is caused by stronger indoor temperature fluctuations due to the lower thermal resistance.

Both methods used in the papers contain simplifications that influence the results, e.g. discharging effects of the storage medium in isolation are not considered. Nonetheless, the results indicate that the adaptable thermal energy storage approach shows potential, which justifies a more in depth investigation. Therefore, in this paper it is investigated how realistic adaptable thermal energy storage concepts could look like. Furthermore, the performance of three promising (and realistic) concepts is investigated. The performance of these concepts is assessed using advanced modeling methods which resolve the mentioned limitations of the simplified modeling methods used in the previous work.

3. Hybrid adaptable thermal storage

This section starts with a concise overview of thermal energy storage methods used in buildings. Then, it discusses how these methods can be used or made adaptable. This section concludes with the definition of four promising HATS concepts.

3.1. Thermal energy storage

Thermal energy storage methods that are used in buildings are extensively described in literature, e.g. [17,18], therefore only a short overview is given here. Generally, thermal energy storage (TES) is classified into three categories: sensible TES, latent TES and thermochemical TES. The storage methods in these categories can be grouped into short-term storage (hourly, daily) and long-term storage (seasonal, yearly). In this section, the methods are also differentiated depending on their potential integration in buildings. Two TES types are discerned:

- TES with a direct thermal coupling to the building's indoor environment, e.g. the storage medium is part of the building's structure;
- TES with an indirect thermal coupling to the building's indoor environment, e.g. the storage medium is placed in a thermally insulated container or is placed outside of the building. Generally, these TES methods result in systems that consist of a storage medium (e.g. water), a storage container (e.g. tank), an *injection/extraction device* to 'collect' thermal energy from the building and release thermal energy to the building (e.g. heat exchanger in the floor), a *transfer medium* (e.g. water) and a *distribution system* to transport the energy to and from the storage medium (e.g. pipes, valves and pumps).

3.1.1. Sensible thermal energy storage

Sensible TES methods store energy by changing the temperature of a storage medium. In the built environment commonly used materials for sensible TES are water, rock, bricks, concrete and soil. The storage medium can be a building element (e.g. floor, wall, ceiling) or part of a building element; these applications are referred to as sensible TES with a direct thermal coupling as mentioned above. In buildings, the term (*effective*) *thermal mass* is used to describe the thermal energy storage capacity of building elements. According to literature materials with high volumetric heat capacity, high thermal diffusivity, high thermal effusivity, moderate conductivity and high infra-red emissivity are most effective to use as thermal

Fig. 3. Thermal mass using water filled containers in Marsh House Two [21].

mass in buildings [7,8,19]. To make effective use of the thermal mass, the storage material should not be covered with other materials (i.e. not insulated) and convective heat transfer by means of airflow should be possible. Concrete and brick are commonly used to increase the thermal mass of a building, but there are also examples of buildings using water filled containers in wall constructions (Fig. 3); so-called water walls [20,21]. The sensible TES medium can also be placed in thermally insulated storage containers inside the building or the storage medium can be placed outside the building, e.g. in the ground (aquifer thermal energy storage or borehole thermal energy storage) or on the surface (solar ponds, rock beds); these applications are referred to as sensible TES with an indirect thermal coupling.

3.1.2. Latent thermal energy storage

It is also possible to store thermal energy in latent form using the phase change of materials. A material in solid phase will change to liquid phase when its temperature rises to the material's phase change temperature (melting temperature). During the phase change, the material will absorb energy and maintain a (nearly) constant temperature around phase change temperature. When the temperature decreases to the phase change temperature, the material changes back to solid phase and releases the stored energy. Materials used for storing energy in latent form, so-called phase change materials (PCMs), should have a high heat of fusion (specific melting enthalpy, the energy needed for the phase change per unit mass) and a phase change temperature within the operating temperature of the thermal system (for most building applications between 0 °C and 100 °C) [23,25]. Using the phase change of a material leads to a much higher thermal energy storage capacity per unit volume compared to storage in sensible form. For example, the energy stored in concrete for a 20 K temperature interval is $20 \times 0.84 = 17$ kJ/kg, while the phase change enthalpy of paraffins is 100–200 kJ/kg.

Encapsulated PCMs can be used to increase the thermal capacity of building materials and elements, like plaster, concrete or gypsum boards [24,26]. Therefore, the applications discussed for sensible TES can be 'flavored' with PCMs. By using PCMs, it is possible to decrease the total system's weight, while maintaining its thermal energy storage performance. This weight reduction makes it possible to keep the total building's mass lightweight, which is ideal for, e.g., retrofitting purposes or top-up building extensions. PCMs can also be used to increase the thermal capacity of heat and cold storage units [18,27]. Microencapsulated PCMs can also be dispersed in a fluid [28–30]. These phase change slurries (PCS) can be used as a thermal energy storage medium or as a heat transfer fluid to replace conventional heat transfer fluids, like water, in heating and cooling applications.

3.1.3. Thermochemical storage

Sensible and latent TES systems lose energy over time, which is a disadvantage for long-term storage purposes. Thermochemical storage does not have this problem and shows negligible heat losses, making these systems suitable for long-term storage. Thermochemical storage is based on sorption phenomena. Sorption storage systems use a reversible reaction to store and release energy in materials. Research in finding the most appropriate materials is ongoing [31,32]. According to Zondag et al. [31] it is a challenge to design thermochemical reactors on a household scale; however, first prototypes have been built. Because of the size and complexity of the systems, these are all indirect thermally coupled to the building's indoor environment.

3.2. Adaptation of thermal energy storage

The discussed TES methods are able to influence the level of thermal comfort in a building and the required energy to reach this thermal comfort. For example, TES can be used to store excess thermal energy (e.g. solar gains or internal gains) to reduce peak temperatures and limit overheating. It can also be used to store excess thermal energy and use it later to reduce the heating energy demand. However, in case there is no excess thermal energy and the building needs to warm up (e.g. during cold cloudy days), then the heating energy supplied by the heating system should not be stored. Since storage of this energy slows down the building's response to the heating system, this might lead to discomfort when a quick response is required. Furthermore, if the stored energy is not used (e.g. when the building is only used for a short period), then the heating energy is wasted, increasing the total energy use of the building.

The following discusses how TES methods can be used to achieve the goal of high thermal comfort and low energy demands. The idea is to influence the building's thermal environment by adjusting the amount of thermal energy that the TES method stores or releases. There are various ways to do this, which is explained using the following heat balance. This heat balance gives the temperature change of a storage medium, e.g. a heavy concrete wall, over time:

$$C \cdot \frac{dT}{dt} = \varphi_{conv} + \varphi_{cond} + \varphi_{rad} + \varphi_{inj} \quad [W] \quad (1)$$

with temperature T in [K], time t in seconds, heat flows φ (convection, conduction and injection) in [W] and heat capacity C in [J/K]. This heat balance presents two general principles to influence the amount of stored energy:

1. Change the physical storage capacity of the storage medium, i.e. change C .
2. Influence the energy transfer to and from the storage medium, i.e. change the heat flows φ .

Both *adaptation principles* can be applied to direct and indirect thermally coupled TES methods, however the implementation and the ease of implementing the principles will be different. From here on the concepts that can be used to perform adaptation are called *adaptation mechanisms*. In literature several examples of adaptation mechanisms can be found, however those examples are never described in the context of adaptable thermal storage as defined in this paper. The next paragraphs give an overview of various adaptation mechanisms (found in literature).

3.2.1. Change heat storage capacity

The storage medium's heat storage capacity C is given by $C = m \cdot c$, in which m is the storage medium's mass in kg and c is the medium's specific heat capacity in J/(kg.K). Thus, there are two ways to change

the storage capacity: change the medium's mass or change its specific heat capacity. The possibility of implementing those depends on the type of storage medium. For example, when fluids are used as storage medium in a tank, it is relatively easy to change the mass of the fluid in the tank by removing or adding fluid from/to the tank. For solids it is more difficult or practically not feasible to (re)move a part of the storage medium, e.g., when the solid is part of the building construction.

3.2.2. Influence heat transfer

TES methods with an indirect thermal coupling are coupled to the building by means of a *distribution system*, which consists of pipes and ducts through which a transfer medium (e.g. water, PCS or air) flows. This *distribution system* makes it relatively easy using conventional techniques to control the energy transfer to the storage medium. For example, it is possible to control the flow rate or temperature of the transfer medium to the storage medium using valves and pumps. TES methods with a direct thermal coupling lack a *distribution system*. This makes it more difficult to control the stored energy. However, it is possible to influence heat transfer to the storage medium by influencing at least one of the three heat transfer mechanisms (convection, conduction, radiation). Below, various adaptation mechanisms are introduced for each heat transfer mechanism. These mechanisms can also be used to influence heat transfer to the *injection/extraction device* of the indirect coupled TES methods.

3.2.2.1. Convection. Convective heat transfer can be influenced by using fans to increase (or support) the airflow. Forced convection in combination with night ventilation significantly increases the cooling capacity of the thermal mass. Geros et al. [33] showed that for a high thermal mass building, the internal temperature during the next day can be reduced by 3 °C when using night ventilation. Webb et al. [34] propose the idea of a biomimetic façade based on animal fur. The 'fur' consists of artificial fibers of which the angle with the façade can be altered. According to their models this artificial 'fur' is able to influence convective heat transfer at the façade.

3.2.2.2. Conduction. Conductive heat transfer to the storage medium can be controlled by installing an interface construction in front of the storage medium. The interface construction can be used to thermally insulate the storage medium from the room when it is not needed and vice versa. Ideally, this interface would consist of an insulation material which is able to switch between states of low and high conductivity. The idea of such a dynamic insulation material (DIM) is proposed in literature [35,36] as a building material of the future (beyond the state-of-the-art). Next to this fictive material, various existing concepts are found in literature. Some of these concepts are used for the façade, however, the same principles can be used indoors.

Thermodiodes are devices based on the thermosyphon effect and allow the heat to flow in only one direction [37]. Chun and Chen [38] propose a bi-directional thermodiode, which makes it possible to direct the heat flow to the wall during a summer day and reverse the heat flow when the stored energy is needed. Rylewski [39] proposes a system based on the same principle, but with a different implementation. Al-Nimr et al. [40] propose a 'smart insulation' system for walls which is also based on fluids. Their system consists of two gaps filled with fluids and a movable partition between the gaps. The fluid in the first gap has a high conductivity, while the other fluid has low conductivity. Both layers are connected to small tanks and a control system, which makes it possible to control the amount of fluid in either of the gaps. The partition is free to move to either side of the gap, depending on the driving force of the fluids. Thus, by controlling the amount of both fluids, it is also possible to control the thermal resistance of the whole wall construction.

Another dynamic system is the 'switchable insulation' proposed by Horn et al. [41]. Their system changes the thermal conductivity by using a metal hydride to change the H₂-gas pressure within a panel. They show with simulations that the conductivity can be changed by about a factor of 50. Burdajewicz et al. [42] describe an interface for the external façade with movable/rotating insulation panels.

3.2.2.3. Radiation. Radiant heat transfer can be controlled by blocking radiation to the storage medium with an interface device. For example by using traditional systems like blinds or curtains. However, a more advanced switchable or 'smart' glazing system can also be used, e.g. thermochromic glazing [43,44] or electrochromic glazing [45], which are able to change the optical properties of the glass, e.g. from low to high reflectivity (in the infra-red range).

Another method is to change the storage medium surface's short-wave (solar) absorption or long-wave emissivity coefficients. A simple method is to cover the storage medium or the interface to the medium with reflecting curtains or blinds. A more advanced method is the use of coatings that respond to their thermal environment by changing their absorptivity or emissivity. Thermochromic coatings/paints change the solar absorptivity, for a large part in the visible spectrum. These materials change reversibly from darker colors to lighter colors with rising temperatures caused by a thermally reversible transformation of the molecular structure of the color pigments [46,47]. Agrawal and Loverme [48] propose the concept of a variable emissivity coating. These coatings are based on the same principles as the thermochromic materials mentioned above. However, the emissivity changes only in the infra-red range (wavelengths in the range of about 8 to 14 µm). Therefore, no visible color change will occur. Two types of coatings are used: type 1, which increases its emissivity with increasing temperature and type 2, which decreases its emissivity with increasing temperature.

It needs to be mentioned that influencing one of the heat transfer mechanisms will also influence the other mechanisms, e.g. by lowering the convective heat transfer, the surface temperature will increase and thus the surface radiant heat transfer will increase. These effects are important to take into account when assessing the overall efficiency of the adaptation principle.

3.2.3. Overview of adaptation mechanisms

Table 1 provides an overview of the adaptation mechanisms that are discussed above and other mechanisms found in literature. The following characteristics are used to describe the mechanisms:

- **Adaptation principle:** This property describes the adaptation principle that is used: *variable heat storage capacity* or *heat transfer intervention*.
- **Heat transfer mechanism:** If the adaptation principle is *heat transfer intervention* then this property describes the heat transfer mechanism that is mainly used to perform adaptation: *conduction*, *convection* or *radiation*.
- **Operation:** Two properties related to the operation of the mechanisms are defined: *operation type* and the available *operation modes*.
 - Operation type describes how the mechanism is operated: *active* or *passive* operation. *Active* operation means that the mechanism is part of a larger system containing sensors and a controller; the controller actuates the adaptation mechanism based on sensed control variables. *Passive* operation means that the mechanism actuates itself without the help of external sensors or controllers.
 - Operation modes indicate how many system states the mechanism can provide. For example, a system that can be turned *on* or *off* has two *discrete* states. A system can also have more states in between or it can be *continuous*.

Table 1
Overview of adaptation mechanisms and their properties.

	Name	Adaptation principle	Heat transfer mechanism	Operation type	Availability	Complexity [1 = low, 5 = high]
1.	Fans and valves	Heat transfer intervention	Convection	Active	Available, conventional technology	1
2.	Biomimetic façade based on animal fur [34]	Heat transfer intervention	Convection	Active	Difficult implementation, research phase	4
3.	Variable emissivity coating [48]	Heat transfer intervention	Radiation	Passive	Research phase	1
4.	Switchable glazing [43–45]	Heat transfer intervention	Radiation	Active	Commercially available	2
5.	Rotating stripes with highly absorptive and highly reflective side [49]	Heat transfer intervention	Radiation	Active	Feasible, simple technology	3
6.	Blinds, Curtains, Shading	Heat transfer intervention	Radiation	Active	Available, conventional technology	2
7.	Dynamic insulation material (DIM) [35,36]	Heat transfer intervention	Conduction	Active	Promising idea, early research phase	2
8.	Smart insulation using two fluids with different conductivities [40]	Heat transfer intervention	Conduction	Active	Complex system, research phase	5
9.	Switchable insulation using metal hydride in panel [41]	Heat transfer intervention	Conduction	Active	Complex system, research phase	5
10.	Movable insulation	Heat transfer intervention	Conduction	Active	Feasible, simple technology	2
11.	Bi-directional thermodiode [38]	Heat transfer intervention	Conduction	Active	Feasible, research phase	4
12.	Variable liquid mass	Variable capacity	–	Active	Feasible, simple technology	2
13.	Pressurized chamber with PCM [49]	Variable capacity	–	Active	Complex system, research phase	4
14.	Water tank with pivoted partition [49]	Variable capacity	–	Active	Feasible, simple technology	3
15.	Movable storage medium	Variable capacity	–	Active	Feasible, complex implementation	5
16.	Phase change materials [23–26]	Variable (apparent) capacity	–	Passive	Commercially available	1

- **Compatible storage medium:** This property describes the various storage mediums that are compatible with the mechanism. Not all adaptation mechanisms can be combined with all types of thermal energy storage (sensible, latent, thermo-chemical) or types of storage mediums (water, concrete, etc.).
- **Availability:** This property describes the availability of each mechanism. Some mechanisms are based on existing technologies or commercially available products and materials, while other mechanisms depend on materials or products that are still under research and development.
- **Complexity:** This property gives an estimated quantitative score of the relative number of system components and control variables. This property also indicates the feasibility of implementing the mechanism in a building.

PCMs are also listed as adaptation mechanisms. Basically, PCMs can be seen as a TES method with an *apparent* variable heat capacity, since the actual (latent) heat capacity of the materials is not changed.

3.3. Design considerations

An adaptable thermal energy storage concept consists of a TES method enhanced with an adaptation mechanism. As mentioned in the Introduction, the concepts are called *hybrid* to indicate the possibility of combining more than one TES method, or more than one adaptation mechanism in one concept. The following discusses several issues to consider when choosing between the TES methods and adaptation mechanisms:

- Choosing an appropriate TES method for a building depends on many factors, among others the building design (e.g. space availability, orientation, location, retrofitting or new building), building type, building use (e.g. comfort requirements, required storage capacity) and investment costs. For instance, consider the case of a renovation project which makes use of a top-up extension. Heavyweight TES methods like heavy storage walls (water or concrete) or storage tanks are probably not feasible due to weight constraints. For these buildings it is better to choose PCM

based methods or water carrying pipes in building constructions (TABS). New buildings show more flexibility since these can be dimensioned such that the weight of heavier storage methods can be supported.

- Choosing an adaptation mechanism for the chosen TES method does not only depend on the performance of the mechanism but also on the building design at room level, e.g. orientation, location of the storage medium (e.g. curtains or rotating strips are not practical on the floor), space availability (e.g. size of the mechanism, compare the size of a variable emissivity coating to a thermodiode). Selection can be based on the overview given in Table 1.
- The implementation of an adaptation mechanism depends on the chosen TES method. The following describes how the discussed adaptation mechanisms can be used to achieve adaptation of direct and indirect coupled TES:
 - *Direct coupled TES:* Adaptation mechanisms 1 to 11 from Table 1 can be used on the interface of the storage medium and 12 to 16 on the storage medium itself (Fig. 4).
 - *Indirect coupled TES:* mechanisms 1 to 11 from Table 1 can be used on the injection/extraction device, conventional techniques (like valves and pumps) can be used on the distribution system and mechanisms 12 to 15 on the storage medium itself (Fig. 5).

3.4. Promising concepts

The previous findings are used to define three promising HATS concepts. The goal is to model and study the performance of these concepts in detail (in contrast with the simplified adaptation models discussed in Section 2). The concepts are defined based on the following considerations. First, it is intended to investigate a wide range of adaptation mechanisms, therefore, lightweight and heavyweight TES methods are considered. Furthermore, at least one mechanism per mode of heat transfer is chosen. The complexity and feasibility of the adaptation mechanisms is used as the selection criterion between the available mechanisms. The least complex and most feasible mechanisms are preferred. Based

Fig. 4. Adaptation mechanisms for direct thermal coupled TES (e.g. a storage wall). Some mechanisms alter the storage medium directly (e.g. altering the storage capacity), other mechanisms use an interface device in front of the actual storage medium to influence heat transfer. The numbers corresponding to the appropriate adaptation mechanisms from Table 1 are shown between brackets.

Fig. 5. Adaptation mechanisms for indirect thermal coupled TES (e.g. TABS in the wall and a storage tank). The numbers corresponding to the appropriate adaptation mechanisms from Table 1 are shown between brackets.

on these considerations the following adaptable thermal energy storage concepts are defined:

- Concept 1: Lightweight wall and ceiling constructions with PCMs.
- Concept 2: High thermal storage wall with variable emissivity and absorptivity coating.
- Concept 3: High thermal storage wall with dynamic insulation or movable insulation.

Concepts 1 and 2 are considered as passive adaptable thermal energy storage concepts (no active control is required), while concept 3 is considered as active adaptable thermal energy storage (control is required). The performance of concepts 1, 2 and 3 (illustrated in Fig. 6a–c) are discussed in the next sections.

4. Performance assessment: Case study building and uncertainties

The performance of each HATS concept depends on several design parameters. For example consider concept 1, the chosen PCM melting temperature greatly influences the performance. Therefore, it is necessary to optimize the designs of the concepts to

make a fair performance comparison possible. This section introduces the performance assessment methodology. Furthermore, it describes a case study building for which the HATS concepts are optimized.

4.1. Building performance simulation

As mentioned in the Introduction the performance is investigated using computational building performance simulation; the whole-building performance simulation tool ESP-r [51] is used in this research. Simulation of concepts 2 and 3 required code development and code modifications to the ESP-r program; this is not described in this paper due to space limitations, more details can be found in [50]. A simulation time step of 5 minutes is used in all simulations. All simulations in this research are performed for a full year.

4.1.1. Uncertainty analysis

Generally three sources of uncertainty are discerned in building performance simulation: *modeling* uncertainties, *numerical* uncertainties and *input* uncertainties [54]. In this research it is assumed that model uncertainties will not influence the results, i.e. the physical model is correctly chosen, and that numerical uncertainties are negligible, i.e. the discretization model and time steps are also correctly chosen. Only *input* uncertainties are considered. Monte Carlo analysis in combination with Latin Hypercube sampling [55] is used to investigate the uncertainty of the model's output due to the uncertainties in the building specific parameters, e.g. thermophysical material properties and infiltration rate, and the convective heat transfer coefficients. The assumed distributions for these uncertain parameters are described in Section 4.3. The results of the Monte Carlo analysis (MCA) are used to define a confidence interval (uncertainty range) for the model output.

4.1.2. Design optimization

For each concept a set of design solutions (variations of the design parameters) are evaluated. The results are presented in

Fig. 6. (a) Lightweight wall and ceiling constructions with PCMs. Change apparent heat capacity. (b) High thermal storage wall with variable emissivity and absorptivity coating. Influence: radiation. (c) High thermal storage wall with movable or dynamic insulation. Influence: conduction.

Fig. 7. Schematic of the results of design optimization. Each dot represents a building design; the dashed boxes show the uncertainty range of three distinct solution.

scatter plot with two performance indicators on the axes (heating energy demand and discomfort hours); an example is shown in Fig. 7. Since the performance indicators are conflicting (the decrease of one indicator leads to an increase of the other indicator), the scatter plot shows a Pareto front consisting of the non-dominated design solutions. In the scatter plot, the uncertainty range (two standard deviations) of both performance indicators is shown for several distinct design solutions (best comfort solution, best energy solution and a trade-off solution). The performance of the solutions within the uncertainty range of a distinct solution are considered equal to the performance of that distinct solution. Therefore, those design solutions are also discussed in the result analysis. Finally the performance of the three distinct design solutions are compared for all the HATS concepts.

The next sections describe the case study building, the performance indicators and the input uncertainties that are taken into account.

4.2. Case study building

This case study building consists of five zones (Fig. 8): a living space (zone A, south orientated) and a kitchen (zone B, north orientated) on the ground floor, and two bedrooms and a study room (zone C and D, south orientated and zone E, north orientated) on the first floor. The north and south façades consist of large (identical sized) windows. The south façade has an external shading

device (horizontal venetian blinds). The floor, external walls and roof constructions have R_c values of $5 \text{ m}^2\text{K/W}$, which is higher for floor and walls than the current Dutch buildings codes ($3.5 \text{ m}^2\text{K/W}$ for floors and $4.5 \text{ m}^2\text{K/W}$ for walls). It is not anticipated that the building codes will demand much higher R_c -values in the future (e.g. passive house standards), since it is expected that buildings with such high R_c -values will be sensitive to overheating, while the energy benefits of the extra thermal insulation are small. The windows have U -values of $1.1 \text{ W/m}^2\text{K}$, which is a higher performance than the requirements in the current Dutch building codes ($1.65 \text{ W/m}^2\text{K}$).

The building is ventilated with a balanced mechanical ventilation system. The temperature set points are 21°C for an occupied house and 14°C for when the house is not occupied. No mechanical cooling is available in the building. The performance of each HATS concept is compared to the performance of a lightweight (low thermal mass) and a heavyweight (high thermal mass) variant of the case study building. The lightweight reference building consists of lightweight wall, floor and ceiling constructions. The partition walls consist of gypsum board (12 mm) – insulation (50 mm) – gypsum board (12 mm). The external walls consist (from the outside to the inside) of wood panel (20 mm) – air cavity (30 mm) – insulation (185 mm) – gypsum board (12 mm). The floor constructions consist of concrete (150 mm). The heavyweight reference building consists of partition walls made of brick (100 mm), external walls consisting of brick (100 mm) – air cavity (30 mm) – insulation (180 mm) – brick (100 mm) and floors made of concrete (200 mm). The lightweight and a heavyweight variants of the case study building are identical except for the wall, floor and ceiling constructions.

Occupancy is modeled using predefined occupancy profiles. Based on the results of the preliminary potential study (Section 2), an evening occupancy profile is defined (intermittent use). The profile describes two occupants who are at work during weekdays and at home during evenings (from 18 h) to early in the morning (8 h); early in the morning and during the evening the occupants require the ground floor rooms to be heated to 21°C . Per room profiles are defined to model the internal gains (caused by cooking, TV/computer use, lighting). For example, early in the evening high internal gains will occur in the kitchen, zone B (see Fig. 8), due to cooking activity. The average internal heat gains are 4 W/m^2 based on the Dutch standard NEN7120 [52]. The Dutch building code demands a minimum ventilation rate of $0.9 \text{ dm}^3/\text{s}$ per m^2 . This value is used as the ventilation rate when the building is not occupied. In case the building is occupied a ventilation rate of $1.2 \text{ dm}^3/\text{s}$ per m^2 is assumed. The Dutch climate reference year for energy simulations is used in this study (as defined in the Dutch standard NEN5060 [53]).

Fig. 8. Geometry of the case study building with several building characteristics. Facing the south façade.

Table 2

Thermophysical properties and uncertainties. Two distributions (dis.) are assumed: normal distribution (N) with μ and σ , and discrete uniform distribution (U) with minimum and maximum values.

Material	Thermal conductivity [W/mK]			Density [kg/m ³]			Specific heat capacity [J/kgK]		
	dis.	μ or min.	σ or max.	dis.	μ or min.	σ or max.	dis.	μ or min.	σ or max.
Air cavity	N	0.16	0.01	–	–	–	–	–	–
Brick	N	0.84	0.06	N	1830	20	N	891	13
Concrete	N	1.4	0.11	N	2100	24	N	653	38
Gypsum board	N	0.25	0.03	N	800	9	N	1090	86
Insulation	U	0.0341	0.0424	U	13.5	14.5	U	980	1020
Wood panel	N	0.151	0.042	N	578	9	N	2162	335

4.3. Performance indicators

Two performance indicators are investigated: heating energy demand per year (in kWh) and weighted thermal discomfort hours per year. The discomfort hours are based on the calculated PPD per hour (PPD_{hour}); the PPD comfort limit is defined as 10%. Occupied hours with $PPD_{\text{hour}} > PPD_{\text{limit}}$ are considered as discomfort hours. These hours are multiplied with a weighting factor defined as $PPD_{\text{hour}}/PPD_{\text{limit}}$.

4.4. Uncertainties in model input

4.4.1. Material properties

Table 2 shows the thermophysical properties and the assumed uncertainty distributions for the building materials. The uncertainty distributions are based on values found in literature [56–59]. For most materials, a normal distribution (N) is assumed; the properties of the insulation material are described with a discrete uniform distribution (U). The emissivity of the inside surfaces is normally distributed with a mean value of 0.9 and a standard deviation of 0.02; written as $N(0.9, 0.02)$. The solar absorptivity for gypsum surfaces is $N(0.4, 0.03)$ and for concrete surfaces is $N(0.68, 0.04)$. 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.).

4.4.2. Infiltration

An infiltration rate of 0.12 ACH for building types such as the case study building ('residential', 'detached', 'flat roof', 'built after 2005') is suggested by the Dutch standard NEN8088-1 [60]. Macdonald [59] shows that a normal distribution is able to describe the distribution of infiltration rates (despite the fact that a log-normal distribution fits the data better): the standard deviation is 1/3 of the mean value and the mean value is approximately 1/3 of the maximum value. For the case study, an infiltration rate of $N(0.12, 0.04)$ is defined with a maximum at 0.36 ACH.

4.4.3. Convective heat transfer correlations

The convective heat transfer correlations for internal surfaces found in literature are derived for specific cases, e.g. heating under a window or mechanical ventilation with a heated wall. A complete overview of the correlations used in building simulation is given by Beausoleil-Morrison [61] and Peeters et al. [62]. Beausoleil-Morrison 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. For the case study building, the following three regimes are chosen as defined by Beausoleil-Morrison [61]. Regime A which represents a flow with buoyancy as the driving force (the default ESP-r setting), regime D with a fan as the driving force (mechanical) and regime E which represents a mixed flow (mechanical and buoyant forces). Each of the regimes is given an equal probability,

i.e., a discrete uniform distribution is assumed. The convective heat transfer correlation for external surfaces given by McAdams is used in the building model; this is the default correlation in ESP-r [51].

5. Performance assessment: Predicted performance of promising adaptable thermal storage concepts

This section presents the predicted performance of the promising HATS concepts 1, 2 and 3 (as defined in Section 3.4). Discussion of the results focuses on the two ground floor rooms: living room (zone A) and kitchen (zone B).

5.1. Concept 1: Lightweight wall and ceiling constructions with PCMs

The lightweight reference building is used to investigate the potential of PCMs. In the comparison, the gypsum boards used for the walls and ceilings are changed to gypsum boards with PCM. It is expected that due to different orientations (solar gains) and activities (internal heat gains) each room will have its own optimal melting temperature. Therefore, two PCM design variants are studied: design variant 1 with one optimized melting temperatures per zone and design variant 2 with two optimized melting temperatures per zone. In the simulations PCM gypsum boards are used with latent heat capacity of 330 kJ/m², specific heat capacity of 1.2 kJ/kg K, conductivity of 0.13 W/m K and a weight of 11.5 kg/m², a melting range of 2 °C is assumed. The performance indicators are calculated for a range of melting temperatures from 15 °C to 28 °C (from here on, a PCM with a melting temperature of 21 °C is referred to as PCM21).

The ESP-r program contains a PCM model which is based on the so-called *effective capacity method* [63,64]. This effective capacity method describes the material's heat capacity as a function of the material's temperature in the phase change temperature range. The model assumes that the material is fully discharged below the melting temperature and fully charged above the solidification temperature.

5.1.1. Optimized melting temperature per zone

Fig. 9 shows the results of all possible permutations of the PCM range ($15^2 = 225$) in a scatter plot. The non-dominated (Pareto) solutions are indicated with white dots, the dominated solutions are indicated with grey dots. The heavyweight reference case is indicated with a dark grey dot and the lightweight reference case is plotted as the light grey dot with a dashed lined. The area with the dominated solutions is shaded light grey. Three distinct design solutions (lowest discomfort, a trade-off solution and lowest heating energy demand) are numbered 1, 2 and 3. For each of these solutions the uncertainty range caused by the building specific parameter uncertainties is plotted (the dashed boxes). As mentioned the performance of the solutions within the uncertainty range are considered equal. Therefore, the melting temperatures

Fig. 9. Scatter plot of solutions with one melting temperature per zone. The melting temperatures per zone of three solutions are shown ($T_{m,zone}$). The dashed boxes indicate the uncertainty range of these solutions. The melting temperatures of the solutions within the uncertainty range are shown between the brackets.

of these solutions are also mentioned in the figure (between the brackets).

Solution 1 consists of PCM25 in zone A (solutions in the uncertainty range use melting temperatures from 23 to 25 °C) and PCM24 in zone B (the same melting temperatures are found in the uncertainty range). Solution 2 consists of PCM19 in zone A (18–19 °C in the uncertainty range) and PCM24 in zone B (same temperatures in the uncertainty range). Solution 3 consists of PCM19 in zone A (solutions in the uncertainty range use melting temperatures from 18 to 19 °C) and PCM18 in zone B (solutions in the uncertainty range 18–19 °C). The results show that the heating energy demand of the lowest energy solution (solution 3) is 22% lower than of the best comfort solution (solution 1). This difference can be explained by considering the temperature drop that occurs when the building is unoccupied during the heating season (a heating setpoint of 14 °C is used); PCMs with low melting temperatures (16–20 °C) slowdown this temperature drop. Therefore, less heating energy is needed to reach the higher heating setpoint in the evening and the early morning. The largest difference occurs when the PCMs melt during the day due to solar gains and internal heat gains. The number of discomfort hours of the best energy solution (solution 3) is three times higher than for the best comfort solution (solution 1). The PCMs with low melting temperatures cannot solidify during warm summer days and stay in liquid phase during the whole day. This makes these PCMs useless for preventing overheating (night ventilation to solidify the PCMs is taken into account).

In the next section, it is investigated if a combination of solution 1 and 3 improves building performance.

5.1.2. Two melting temperatures per zone

The previous design solutions showed that PCMs can be used to reduce the heating demand or reduce the discomfort hours. In this section, it is investigated if it is possible to combine both characteristics in one design solution. This is done by using walls with a double layer of gypsum boards with different melting temperatures (the boards with different melting temperatures are placed after each other). One layer with melting temperatures from 21 °C to 28 °C for thermal comfort, and the other layer with melting temperatures from 16 °C to 20 °C for heating demand reduction.

The scatter plot in Fig. 10 shows a clear shift of the Pareto front to the left compared to Fig. 9. The discomfort hours for the lowest heating solution are reduced from 382 to 168 hours for the same heating energy demand. Solution 1 consists of PCM18 for the first layer (i.e. the inside face, from here on 'layer 1', see also the

schematic in the top-right of Fig. 10) and PCM24 for the second layer ('layer 2') in zone A. Zone B consists of PCM24 for layer 1 and PCM20 for layer 2. Solution 2 consists of PCM19 for layer 1 and PCM25 for layer 2 in zone A, and PCM18 for layer 1 and PCM24 for layer 2 in zone B. In the figure, four clusters of solutions are indicated with colors (black, dark grey, grey, light grey); the clusters refer to the order of the PCM layers (low = PCM for energy demand reduction, high = PCM for thermal discomfort reduction; see legend). It shows that the double layer with the higher melting temperatures on layer 1 (the inside face) and the lower melting temperatures on layer 2 (the black dots), reduce the discomfort hours; however, it does not reduce the heating energy demand (compare to the dark grey dots). This is caused by the low conductivity of the gypsum boards; layer 2 is thermally insulated by layer 1 and is thus not used, i.e., during most heating days it does not reach the melting temperature during the day.

The lowest energy demand solutions (dark grey dots) use layer 1 to store heat during cold days for reducing the energy demand and use layer 2 during warm days for reducing discomfort hours. The results show that the high melting temperatures in layer 2 are used, but less effectively than using them in layer 1 (compare to the black dots). Comparing the performance to the single layer with low melting temperatures (Fig. 10), the results show that the same heating energy demand can be achieved, but with lower discomfort hours. Thus, this layer combination is shown to be beneficial. The solutions with the lowest discomfort hours (the white dots), use high melting temperatures in layer 2 for zone A. Although these PCMs are not used efficiently, it is still enough to reduce the discomfort hours in the zone.

The results show that the low melting temperature should be used in layer 1 and that the high melting temperature can be used on layer 1 and 2, however, the latter is less effective in layer 2. The results show that the double layer approach slightly improves the performance of the best comfort solutions compared to the design with one melting temperature per zone; however, the improvement of the best energy demand solutions is much stronger (indicated by the horizontal shift of the Pareto front to the left).

5.2. Concept 2: High thermal storage wall with variable emissivity and absorptivity coating

Thermotropic coatings are coatings with changing material properties depending on temperature. In this case study a coating is studied that increases its long-wave emissivity (infrared

Fig. 10. Scatter plot of solutions with two melting temperatures per zone using a double layer of gypsum boards. The melting temperatures of two solutions are shown ($T_{m,zone}$). The dashed boxes indicate the uncertainty range of these solutions. The melting temperatures of the solutions within the uncertainty range are shown between the brackets. The colors indicate the melting temperatures of each layer for zone A and B: 'high-low' means high melting temperatures (21–28 °C) on layer 1 (the surface in contact with the room; see schematic on the top-right) and low melting temperatures (16–20 °C) on layer 2.

radiation with wavelengths of 8 to 15 μm) with increasing temperature. It is assumed that the coating is able to switch between a low and a high emissivity value at a specified temperature. The objective is to investigate which switching temperature is optimal. The potential is investigated using the lightweight case study building. It is expected that the coating requires a large surface to be effective, therefore the coating is applied to the walls. The storage capacity of the walls is increased by replacing the gypsum board constructions with heavyweight wall constructions (concrete; water walls can also be used). By using the heavyweight walls, this case study cannot be qualified as lightweight anymore. However this case study is useful for the purpose of this investigation. If the adaptation potential is small for this case with high storage capacity and a large surface, then it is certainly not useful for variants with less storage capacity and smaller surfaces. A controller has been developed in ESP-r which is able to control the long-wave emissivity (from here on emissivity) of all surfaces in the model. The controller changes the emissivity coefficients of a surface when the surface temperature reaches a set point temperature. Two coefficient values are

possible, low emissivity = 0.2 and high emissivity = 0.9. More details about this controller can be found in [50]. The model's uncertainty due to the building specific parameters is assessed with a MCA analysis: thermal discomfort shows a standard deviation of 6% and heating energy demand of 4%.

For reference purposes Fig. 11 shows the building performance for two (fixed) coatings with low (0.20) and high (0.90) emissivity. The figure shows that changing the emissivity from the high to the low value reduces the heating energy demand from 1639 kWh to 1562 kWh; a difference of 5%. This difference is caused by the high long-wave reflectivity of the storage walls compared to the reflectivity of the lightweight floor and ceiling. This causes the floor and ceiling to absorb more long-wave radiation. Due to the low storage capacity of the floor and ceiling, their surface temperatures rise and due to convective heat transfer the air temperature also rises. During warm periods, the storage walls are not able to cool down easily due their low emissivity. This causes overheating and discomfort hours: 207 wPPDh for low emissivity compared to 137 wPPDh for high emissivity. Fig. 11 also shows the

Fig. 11. Performance of case study with variable emissivity coatings on the inside surfaces. The switching temperatures of two solutions are shown ($T_{s,zone}$). The dashed boxes indicate the uncertainty range of solutions 1 and 2. The switching temperatures of the solutions within the uncertainty range are shown between the brackets.

Fig. 12. Schematic representation of the wall with dynamic thermal insulation in decoupled state (top) and coupled state (bottom).

results of the adaptable emissivity coating for switching temperatures from 16 °C to 28 °C (per room). The switching temperature of solution 1 is 17 °C in both zones. The switching temperature of solution 2 is 20 °C in both zones. The difference between both solutions is small; the heating energy demands overlap, but there is a difference in thermal discomfort. In general low switching temperatures show the lowest discomfort, while higher switching temperatures show higher discomfort. This was expected, since the coating performs as a fixed low-e coating, when the switching temperature is chosen too high (the surface temperature never reaches the switching temperature).

The variable emissivity coating shows potential to improve the building performance; however, its influence is small and depends on the availability of large surfaces of the storage medium. Nevertheless, it is a relatively low tech solution which can be used to enhance the performance of other storage methods (creating hybrid solutions).

5.3. Concept 3: High thermal storage wall with dynamic insulation or movable insulation

This concept consists of a storage wall (concrete, the same concept can also be used for a water wall) with on the inside of the room an interface construction of dynamic thermal insulation and a coated metal sheet (Fig. 12). The dynamic insulation layer is able to switch between states of low and high conductivity, thus

thermally coupling or decoupling the storage wall from the room. The dynamic insulation layer is applied on the inside face of the west and east walls and of the partition walls between the rooms. The dynamic insulation can be one of the adaptation mechanisms based on conduction discussed in Section 3.2.2, e.g. thermodiodes, smart insulation or switchable insulation.

The model used for this concept does not simplify the switching from low to high thermal capacity as in the simplified approach discussed in Section 2, but the model takes discharging effects and history effects into account. A model based controller is used to operate the dynamic insulation. More details about this model and the controller can be found in [47]. Due to space constraints in this paper only the final results of this concept are shown here.

Fig. 13 shows the results of this concept for different controller settings and for two reference control sequences (thermal insulation turned on or turned off) during the whole year; the dots represent different optimized controller strategies. The results show that the storage walls with dynamic insulation are able to reduce the heating energy demand compared to the heavyweight reference case by 28%, while the discomfort hours are increased by 13 wPPDh. Note that the discomfort hours are distributed differently over the year; the heavyweight reference case shows discomfort mainly during the winter period, while this HATS concept shows discomfort during the summer period. The latter is caused by high surface temperatures of the adaptable wall construction (metal sheets), which can be reduced with additional ventilation during the summer months. Compared to the lightweight reference case, the heating energy demand is reduced with 26% and the weighted discomfort hours are reduced by 241 wPPDh; the heating energy demand reduction compared to the reference case is caused by the lower effective thermal capacity of the zones when the wall is decoupled (only the thermal capacity of the metal sheets is available when decoupled).

5.4. Performance comparison

Fig. 14 gives an overview of the performance of concepts 1, 2 and 3 (all simulated for a full year) for the 'evening' occupant scenario with internal gains of 4 W/m² and a ventilation rate of 1.2 ACH during occupied hours (as defined in Section 4). The figure shows the Pareto fronts of the optimized HATS concepts 1 and 2 and of the optimized HATS control strategy for concept 3. The

Fig. 13. Performance of case study with high thermal storage wall and dynamic thermal insulation. The dots indicate different settings for the controller that operates the dynamic insulation. Two reference control sequences are also shown (thermal insulation turned on or off during the whole year). The dashed box indicates the uncertainty range of solution 1.

Fig. 14. Pareto front of optimized HATS concepts (1 and 2) and of optimized HATS control strategy (concept 3) compared to the reference cases.

Fig. 15. Trade-off solutions of the HATS concepts (dots with bold border) with their reference values (dots with dashed border); the reference values of concept 3 are labeled.

performance of the concepts is compared to the performance of the heavyweight and lightweight reference cases; the reference cases are two identical buildings (including the control strategies for heating and ventilation) except for their thermal mass. The figure shows that concept 3 (the storage walls with dynamic insulation) is Pareto dominant over the other concepts regarding the investigated performance indicators.

The *adaptation potential* of each concept cannot easily be seen from Fig. 14, since the building designs of concepts 2 and 3 are not identical to the reference cases (different wall constructions). Therefore, Fig. 15 shows the performance of each concept compared to two reference values per concept; the reference values of concept 2 are the performance values of coatings with fixed emissivity values, and the reference values of concept 3 are the performance values with the storage walls coupled (thermal insulation turned *off*) and decoupled (thermal insulation turned *on*) throughout the year. The vectors in the figure point from the reference values to the optimized solutions and thus indicate the adaptation potential of the concept. For clarity the figure only presents the trade-off solutions per concept. Concept 3 shows the largest relative improvement between the reference values and the optimized solution. Concept 2 shows the smallest relative improvement.

From Figs. 13 and 14 it can be concluded that concepts 1 and 3 are promising concepts, while concept 2 shows less potential. However, concept 2 can be used to enhance the performance of the other concepts in hybrid solutions.

6. Conclusions

The first part of this paper explains the general concept of HATS and gives an overview of possible adaptation mechanisms and promising HATS concepts. In the second part the performance of the following concepts are investigated using computational building performance simulation:

- Concept 1: Lightweight wall and ceiling constructions with PCMs.
- Concept 2: High thermal storage wall with variable emissivity and absorptivity coating.
- Concept 3: High thermal storage wall with dynamic insulation or movable insulation.

The research shows that all concepts are able to reduce the heating energy demand (with 24%, 5% and 26% for concepts 1,

2 and 3, respectively) compared to the *lightweight reference case*, while improving thermal comfort. Moreover it shows that the concepts are able to reduce the heating energy demand (with 26%, 8%, 28%) compared to the *heavyweight reference case*, while showing almost the same level of thermal comfort. From these results it can be concluded that concepts 1 and 3 are the most promising concepts, while concept 2 shows less potential. However, concept 2 can be used to enhance the performance of the other concepts in hybrid solutions. The results show that the potential energy demand reduction depends on the chosen HATS concept, however it also depends on the building scenario (occupant scenario and climate) and building design:

- The potential strongly depends on the occupancy pattern. In general, buildings which are used intermittently or during short periods benefit from adaptable thermal energy storage. Examples of such buildings are residential houses with people working during the day or hotel rooms. However, buildings which are used during long and constant periods benefit less from adaptable thermal energy storage.
- The potential depends on the possibility to charge and discharge the storage material during the day. Therefore, these concepts are more effective in climates with moderate or large temperature differences during the day (e.g. the investigated Dutch climate or other similar climates, Köppen climate C_b), than in climates with small temperature differences (e.g. tropical climates).

In general the research shows that the HATS approach is able to reduce the heating energy demand and increase thermal comfort in lightweight Dutch residential buildings, which supports the hypothesis mentioned in the Introduction.

The application potential of HATS concepts in lightweight buildings depends on the design problem at hand. Basically, two types of HATS concepts are investigated in this research: lightweight concepts and heavyweight concepts. These types are not suitable for each design problem:

- Lightweight concepts are based on latent thermal energy storage (PCM) or building elements embedded with pipes and transport fluids (water, PCS). These concepts are especially suitable when the building weight is a design constraint. For example in top-up extensions for renovation projects where the existing building foundations are a constraint or for temporary or floating buildings.
- Heavyweight concepts are based on building elements with a high (sensible) storage capacity, e.g. water walls or concrete floors. These concepts are only suitable when the additional weight of the storage medium can be accommodated by the building design, i.e. by using heavier foundations.

The combination of HATS concepts with climate adaptive building shells (CABS) will be investigated in future research. CABS are facades that are able to adapt to their environment [65]. Combining HATS and CABS might improve building performance significantly. Furthermore, the possibilities of using active HATS concepts in demand side management (DSM) strategies will be investigated. DSM strategies are used to change the shape of the load on the electricity grid in order to optimize the whole electricity system. This becomes important in order to avoid grid instability when more non-dispatchable energy sources (wind, solar) are used to generate electricity and supply electricity to the grid [66].

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