A GENERIC QUANTIFICATION METHOD FOR THE ACTIVE DEMAND RESPONSE POTENTIAL OF STRUCTURAL STORAGE IN BUILDINGS

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ABSTRACT

Active demand response (ADR) using the thermal mass of buildings is often suggested as a key technology to enable the transition to a sustainable energy market. Nevertheless, a generic method to quantify the ADR potential of structural thermal energy storage and that enables a comparison with other buildings or even different storage technologies, is currently missing.

In this paper, the available storage capacity, efficiency of the storage process and power shifting capability are defined and demonstrated as key performance indicators for the ADR potential of structural storage.

Building energy simulations are used to quantify these indicators as function of building design parameters, showing that the ADR potential mainly depends on the heat loss coefficient and available thermal mass. Moreover, it is shown that the efficiency and the available storage capacity are not constant but depend on the dynamic boundary conditions.

INTRODUCTION

The potential of thermal energy storage – and more specific structural thermal energy storage (STES) – for active demand response is commonly evaluated in case studies, demonstrating the impact of using thermal storage to shift the peak heating and cooling demand, to increase the use of passive gains or maximize the benefits of time of use pricing [19, 8, 3, 12, 15]. Whereas these studies demonstrate the potential of STES for ADR, mostly in a specific energy market context, an in-depth analysis of the impact of the building design parameters on the demand response potential taking into account e.g. the insulation quality, the compactness or the infiltration rate is not found in literature. Moreover, a unified framework that allows for a systematic comparison of storage and demand-side management technologies in a general demand response context is not yet established.

Such a framework should specify performance indicators that quantify the techno-economic performance of storage technologies, considering both the perspective of the grid developer and the end-user. Thereby the term grid developer is used here as a general term for all stakeholders involved in developing, operating and maintaining energy distribution systems, such as transmission and distribution system operators but also government agencies. These stakeholders are in addition to economic and safety parameters, interested in (i) the total amount of energy that can be stored in the structural storage capacity, (ii) the amount of energy that is currently stored within this capacity and (iii) the additional storage losses that are introduced by activating the thermal mass [13, 9, 6]. In the case of structural storage for ADR the end-user, i.e. the building owner, is interested in (i) maintaining a comfortable indoor environment and (ii) the potential profit that could result from making the storage capacity of the building available for DSM. Thereby the latter not only refers to monetary savings but also e.g. security of supply.

In order to set up such a framework, Ibrahim et al. [10] summarize the techno-economical characteristics of storage systems to establish comparison criteria for selecting the appropriate technology. They state that in addition to operational requirements such as reliability, safety and environmental impact, the main characteristics needed to compare storage technologies are the storage capacity [kWh], energy density [kWh/kg], autonomy [s], efficiency [-], self-discharge [kWh], maximum charge and discharge power [W], ramp rate [W/s], response time [s] and cost [euro]. Similar performance criteria are used by the International Renewable Energy Agency in a technology assessment report for battery storage [7]. Although these properties are generally available for traditional storage systems, such as battery storage systems or thermal water storage tanks, no literature has been found to present quantification methods applied to the structural thermal storage capacity of buildings. Nonetheless, the first 3 characteristics, i.e. the storage capacity, energy density and autonomy, may be linked to the available thermal mass of the building, since given the allowed level of temperature variations the available thermal mass will determine how much heat can be stored for ADR. In contrast, the available power, ramp rate and response time can be linked to the heating system. The storage efficiency is expected to depend both on system characteristics and building thermal properties since the thermal losses that result from using structural thermal storage are related to the production and distribution efficiency of the system as well as the increased transmission and ventilation losses that result from the increased indoor temperature.

In an ADR context, Oldewurtel et al. [13] extended the use of these performance indicators for storage systems to demand response technologies, contrasting amongst others the power capacity, energy capacity, ramp rate and response time of both storage and DR technologies. Alternatively, Heussen et al. [9] presented the 'power node framework' that models demand response technologies as generic virtual storage units, allowing a comparison with other storage technologies. Thereby, technologies are simulated from a grid perspective whereby each supply- or sink-process is lumped into a single 'power node' making abstraction of the physical properties and internal composition of the process. The main properties describing a power node are the storage capacity C, the state of charge, the efficiency of the conversion process and the storage losses or storage efficiency. A similar, generic approach – i.e. the concept of 'Energy Hubs' – was introduced in the 'Vision of Future Energy Networks' project. The Energy Hub is defined as a unit where multiple energy carriers can be converted, conditioned and stored [6]. The model simulates the input and output energy vectors of a hub by using coupling matrices that represent the energy conversion and storage structures and their corresponding efficiencies.

Both frameworks have shown a strong potential to simulate and assess the operational flexibility in power systems [1, 2, 11, 18]. Their main strength thereby lays in the generic description of demand response and storage technologies, allowing for a combined evaluation of a large mix of technologies. In the context of structural storage the challenge however still lays in a detailed and accurate specification and quantification of the required flexibility characteristics.

The goal of this paper is therefore in a first step to establish a generic set of key performance indicators that allows the evaluation of the ADR potential of a building. These performance indicators should not only allow a comparison between different buildings, but also facilitate a comparison with other ADR technologies.

In a second step, a parametric study is carried out to quantify the impact of building design parameters on the potential of structural thermal mass for active demand response. Thereby it should be noted that although it is evident that the efficiency of the thermal systems, such as heat pumps or combined heat and power units, used to activate the structural storage capacity is a key parameter in the suitability of thermal storage for ADR, the focus of this work is on the design of the building structure and its relation with the emission system. For the latter, radiators and floor heating are compared as they are common practice in Belgian residential buildings and represent two fundamentally different approaches of activating the thermal mass.

DEFINITIONS AND QUANTIFICATION

In this section the key performance indicators for active demand response are defined and quantification methods for the ADR potential of structural thermal storage are presented. In this work specifically the available storage capacity, the storage efficiency and the power shifting capability are presented.

The definitions and quantification methods for the available storage capacity and the storage efficiency are based on a simulation of an ADR event and a comparison of the resulting heating power to a reference case with the building in normal operation. As such, the ADR event is defined as a temporary deviation from normal operation, in this case an increase of the set-point temperature for heating and is used to activate the thermal mass as schematically shown in Fig. 1. Assuming that a reference (optimal) control would maintain a minimum temperature allowed by thermal comfort in order to minimize the energy use. An ADR event will thus for heating systems always result in a temporary increase of the indoor temperature compared to this reference. Note that the definitions given below are readily extended to cooling application. Moreover, since this study focusses on the performance of the building rather than the thermal system, the heating power in this paper corresponds to the net heating power emitted by the emission system to the building and not the produced power of the heating system. In other words, potential system losses are not taken into account, even though the same methods can be applied to include thermal systems as well.

Available structural storage capacity

The heat that can be stored within a dwelling and the efficiency of this storage process not only depend upon the thermal properties of the building fabric, but also on the properties of the heating and ventilation systems. Moreover for structural thermal mass these performance indicators are, in contrast to f.i. batteries, not constant but vary with the climatic boundary condition and occupant behaviour.

Definition The available structural storage capacity for active demand response (C_{ADR} [kWh]) is defined as the amount of heat that can be added to the structural mass of a dwelling, in the time-frame of an ADR event, without jeopardizing thermal comfort.

Quantification To quantify the available storage capacity, an ADR event is simulated starting from a building with an indoor temperature equal to the minimum comfort temperature (Fig. 1). During the ADR event the temperature set point for the heating systems in increased by dT_{comf} $[^{\circ}C]$ for the duration l_{ADR} $[s]$.

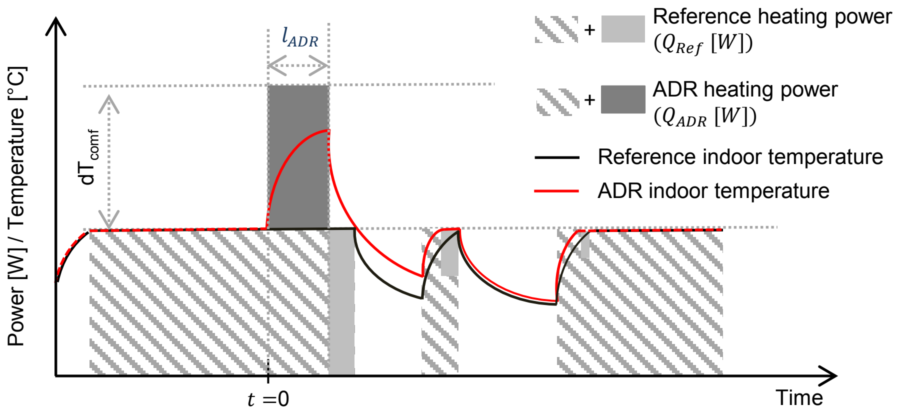

Figure 1: Scheme of the simulation experiment used to quantify the available storage capacity and the storage efficiency

The available storage capacity is then given by the integral, represented by the dark grey area in Figure 1, of the difference between the heating power during this ADR event ($Q_{ADR}\,[W]$) and the heating power in normal operation ($Q_{Ref}\,[W]$), i.e. the temperature set point equal to the minimum comfort temperature:

$$C_{ADR} = \int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref})dt \tag{1}$$

It represents the maximum amount of heat that can be stored in the structural storage capacity of the building in l_{ADR} without exceeding the maximum comfort temperature, given the boundary conditions for climate, occupant behaviour and heating system. Due to the latter, it is evident that the available storage capacity – as well as the storage efficiency defined below – are not constant, but vary in time depending on the boundary conditions.

Storage Efficiency

As shown in [17, 4], the activation of the storage capacity results in an increased temperature within the building and thus the transmission and ventilation losses increase. As a consequence, only a part of the heat that is stored during an ADR event can be used effectively to maintain thermal comfort and reduce the heating power in the period following the ADR event.

Definition The storage efficiency (η_{ADR} [-]) is defined as the fraction of the heat that is stored during the ADR event that can be used subsequently to reduce the heating power needed to maintain thermal comfort.

Quantification The efficiency is calculated using the same simulations that are used to quantify the storage capacity. Given these simulations, the efficiency is calculated as:

$$\eta_{ADR} = 1 - \frac{\int_0^{\infty} (Q_{ADR} - Q_{Ref})\, dt}{\int_0^{l_{ADR}} (Q_{ADR} - Q_{Ref})\, dt} \tag{2}$$

The integral in the denominator is equal to the heat stored in the storage event or the available storage capacity (C_{ADR}), shown as the dark grey area in Figure 1. A part of this heat can be used after the ADR event to reduce the heating power needed to guarantee thermal comfort as indicated by the light grey area in Figure 1. The storage losses induced by activating the thermal mass – i.e. the numerator in equation 2 – thus correspond the fraction of the heat stored during the ADR event that is not recovered after a long period.

Power shifting capability

Whereas C_{ADR} and η_{ADR} can be considered as characteristic properties of the building, the power shifting capability is a measure for the instantaneous flexibility that can be delivered by using the structural storage capacity. In contrast to the state of charge – which is single value often used in electric storage systems – and represents the energy content of a storage medium, the power shifting capability describes the relation between the shift in power that can be obtained and the duration this shift can be maintained.

Definition The power shifting capability is the relation between the change in heating power (Q_δ) and the duration (t_δ) that this shift can maintained before the normal operation of the system, i.e. thermal comfort, is jeopardized.

Quantification method Starting from the building in a current state, the thermal response of the building to a change in the heating power is modelled. The duration this shift can be maintained is then calculation as the duration until the thermal comfort boundaries, either T_{max} or T_{min}, are reached. The power shifting capability is then expressed as the duration as function of this power shift. The power shift (Q_δ $[W]$) is defined as the difference between the heating power during the ADR event (Q_{ADR} $[W]$) and the reference heating power (Q_{Ref} $[W]$) during normal operation.

$$Q_\delta = Q_{ADR} - Q_{Ref} \tag{3}$$

A distinction is made between the upward and downward shifting capability, representing respectively an increase or a decrease of the heating power compared to the current state.

SETUP PARAMETER STUDY

In this work an extensive parameter study is carried out to quantify the impact of the main building design parameters on the available storage capacity and storage efficiency. The parameter study aims at providing guidelines for the different stakeholders. On the one hand the results may be used by grid operators to identify the most efficient portfolio of buildings that can be used to provide operational flexibility. On the other hand, the results can be used by building designers to find the optimal design of dwellings from an ADR perspective.

A description of the simulation models and the evaluated parameters is presented in this section. Note that the evaluation of building parameters is not limited to new buildings, since the main potential of structural storage is expected from the thermal mass that is already available in existing buildings.

Three types of design parameters are analysed in this work: (i) geometric properties of the building, (ii) thermal properties of the components and (iii) type and specifications of the heat emission and ventilation system. Table 1 gives an overview of the properties and the range of values that are analysed.

Model description and parameter definition

The parameter study is carried out on a single-zone building, simulated using the IDEAS library in Modelica. Although, the concepts and methodologies presented in this study can also be used for multi-zone buildings, a single-zone model was chosen to simplify the interpretability of the results. Moreover, in order to improve the interpretability, the boundary conditions are simplified to a constant outdoor temperature and solar and internal gains are not included. All dynamic excitation of the thermal mass is thus induced by the heating system as the goal is to analyse how structural thermal energy storage can be actively used for ADR. Note that, the constant outdoor temperature ($T_e\ [°C]$) is also included as a parameter in the parameter study in order to estimate the potential for ADR during different outdoor conditions.

As an example, a semi-detached building is implemented comparing both radiator and floor heating systems as described in [16]. The former is modelled assuming 70 % of the heat is emitted by convection and 30 % by radiation. For the latter, the thermal power is induced uniformly to the bottom of the screed layer of the insulated ground floor. The floor is modelled in contact with the ground. The roof is a flat roof adjacent to the outdoor environment. A single window, oriented South, is placed in the wall opposite to the common wall.

The geometric properties are calculated by a parametric building design using only the ground floor area, the ceiling height, the compactness, window to wall ratio and internal wall ratio as input parameters (Table 1). The thermal properties of the dwelling are based on typical construction methods found in Belgium. The parameters that are varied in the presented parameter study are listed in Table 1. The ventilation system and the infiltration losses are combined and implemented as a constant air flow. Thereby the ventilation and infiltration rates are fixed and the efficiency of the heat recovery is assumed constant. Both air flows are combined in the analysis using the effective air change rate as parameter. The exterior walls are modelled as cavity walls - a common construction method in Belgium. Both the insulation thickness ($d_{insul,ext}$) as the thickness of the inner leaf ($d_{innerleaf,ext}$) are varied in thickness. The former is varied to evaluate influence the overall heat loss coefficient, the latter to analyse the impact of the available thermal mass. Thereby the thickness of the inner leaf of 0-2 cm are equivalent to a building with interior insulation, as can be found in renovation projects. In that case, the contribution of the exterior walls to the available storage capacity is expected to be marginal.

Table 1: Overview of the parameters for the parameter study

Parameter	range of values
$A_{floor}\ [m^2]$	75, 100, 125, 150, 200, 250
height $[m^2]$	2.75, 3, 3.5, 4
compactness $[m]$	0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5
window to wall ratio $[-]$	0, 0.25, 0.5, 0.75
internal wall ratio $[-]$	0.5, 0.75, 1, 1.25, 1.5, 1.75, 2.0
air change rate $[ACH]$	0, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8
$d_{insul,roof}\ [cm]$	0, 2, 5, 8, 12, 15, 20, 25
$d_{insul,walls}\ [cm]$	0, 2, 5, 8, 12, 15, 20, 25
$d_{brick,walls}\ [cm]$	0, 2, 5, 8, 12, 20
$d_{wall,inner}\ [cm]$	5, 10, 15, 20, 25, 30
system sizing factor $[-]$	0.8, 0.9, 1, 1.1, 1.25, 1.5, 2
$l_{ADR}\ [min]$	15, 30, 45, 60, 120, 180, 240, 480
$dT_{comf}\ [°C]$	1, 2, 3, 4
$T_e\ [°C]$	-10, -5, 0, 5, 10

Additionally, the available thermal mass is varied by modifying the internal wall ratio – defined as the ratio of the inner wall surface area to the outer wall area – and the thickness of the internal walls ($d_{walls,int}$). The interior walls consist of brick walls whereby the 20 and 30 cm thickness have been included as extreme cases.

Finally the parameters for the rule-based ADR control strategy are shown in Table 1. Whereas state-of-the-art studies suggest the use of optimal control or model predictive control (MPC) strategies [14, 5], a simple thermostatic control that increases the set-point temperature with an amplitude dT_{comf} during an ADR event with duration l_{ADR} is implemented following methodology presented in Figure 1. The simplicity of this rule-based control strategy together with the simplification of the boundary conditions are chosen to increase the interpretability of the result. This choice is additionally supported by the fact that the rule based control allows to analyse the impact of control settings. More specific, the duration of the ADR event and the allowed comfort range are evaluated in this work.

Methodology parameter study

Using the parameter distributions of Table 1, a random sample containing 2500 data points is generated. The required number of samples was validated by comparing the sampled distribution of the building parameters. For each of these datasets the heating experiments of Figure 1 are simulated and the storage capacity and efficiency are quantified using Eq. 1 and 2.

A multivariate regression analysis is then carried out to identify the building properties that play a dominant role in the storage efficiency are identified. Thereby the building parameters are first standardized to allow a comparison of their relative importance by comparing the absolute values of the regression coefficients.

This multivariate linear regression is first carried out for each duration of the ADR event (l_{ADR}), allowed temperature variation for ADR (dT_{comf}) and outdoor temperature (T_e). Thereby, a backward selection process is carried out to find optimal set of building parameters that is able to predict the efficiency. The regression model is given by Eq. 4 with x_i the value of building property i and θ_i estimated regression coefficient.

$$\hat{\eta}_{ADR} = \sum \theta_i x_i \tag{4}$$

In a second step, the obtained set of regression models are compared in order to find a single set of building parameters that gives a reliable prediction of the efficiency for all durations, outdoor temperatures and comfort ranges. Building properties with only a small contribution to the model for all durations, i.e. the standardised regression coefficients is of a lower order of magnitude, are excluded from the general model. However, properties that are insignificant for short durations but show high standardised regression coefficients for long durations, and vice versa, are maintained. Once this minimum set of building parameters is obtained the multivariate regression is repeated, using the non-standardized inputs.

In the third and final step, for each of the regression coefficients the relation between the duration of the ADR event, the outdoor temperature and the estimated regression coefficients θ_i is fitted:

$$\hat{\theta}_i = \alpha_0 + \alpha_1 l_{ADR} + \alpha_2 l_{ADR}^2 + \alpha_3 l_{ADR}^3 + \alpha_4 T_e + \alpha_5 l_{ADR} T_e \tag{5}$$

In Eq. 5 the regression coefficients α_i are obtained by least squares estimation, removing insignificant parameters using a backward selection procedure. As such, a non-linear multivariate regression model is obtained that can be used to predict the storage efficiency as function of the duration of the ADR event, the outdoor temperature and minimum set of building parameters.

Results

Qualitative comparison of available storage capacity and storage efficiency

Figure 2 gives an overview of the available storage capacity and storage efficiencies obtained for both radiator and floor heating cases as function of the duration of the ARD event.

The boxplots demonstrate a wide spread on the storage capacity obtained for both the radiator and the floor heating system. Obtained values vary from near zero up to 800 kWh when the ADR event lasts 12 h. The extreme low values occur when the simulated outdoor temperature is equal to the design outdoor temperature of $-10°$C that is used for the sizing of the heating system. Consequently, the heating system already operates close to its maximum power and thus limited additional flexibility is available for activating the storage capacity.

When the duration of the ADR event increases, the rate of increase of the available storage capacity is reduced. This is explained by the fact that during the first minutes the heating system is able to increase its heating power from the level needed to maintain the constant minimum indoor temperature to the nominal power of the system. Note that as such a linear increase of the storage capacity in function of the duration of the ADR events is obtained until the maximum comfort temperature is reached. Afterwards the heating power needs to be reduced to avoid overheating. A slight deviation in the storage capacity for both systems is observed. Due to its high time constant, the floor heating system is able to operate at maximum heating power longer than the radiator system. The latter has an immediate impact on the indoor temperature and will reach the maximum comfort temperature after shorter periods, limiting the amount of heat that can be stored. Note that a constant value is not obtained since even after reaching the upper comfort boundary the thermal mass is able to absorb heat. The maximum heating power can however not be maintained and needs to be reduced at that time to avoid overheating, resulting in a reducing rate of increase of the available capacity. The median capacities available for storage over a 2 h period differ from 13 kWh to 18 kWh for respectively the radiator and floor heating systems. Taking into account the large number of buildings this distributed

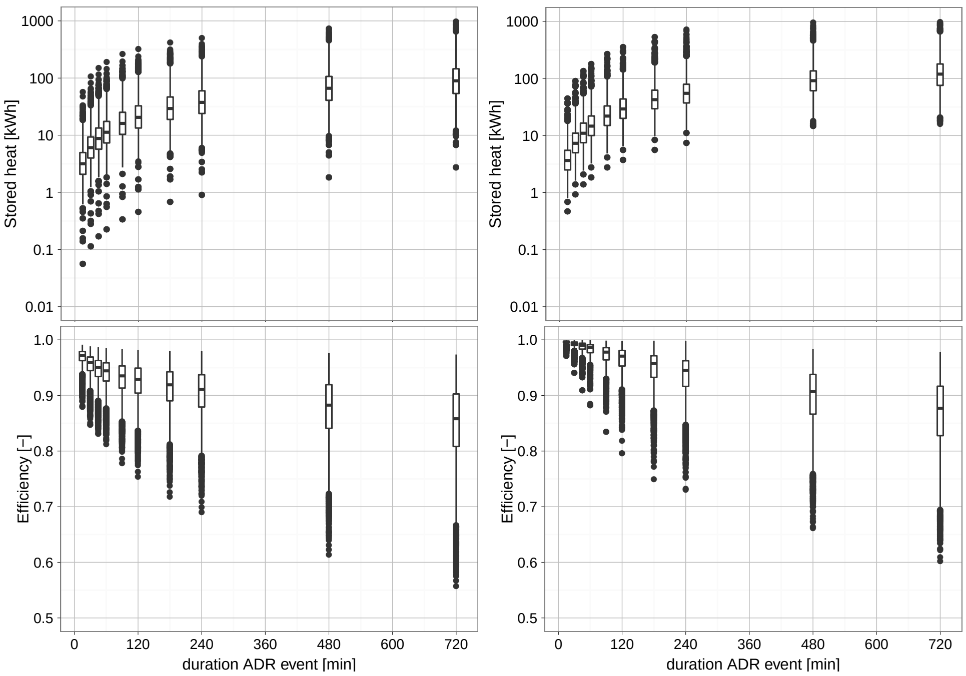

Figure 2: The storage capacity (top) and storage efficiency (bottom) obtained for the radiator (left) and floor heating (right) system. The boxplots show 10th, 25th, 50th, 75th and 90th percentiles. The dots are outliers.

storage may play an important role in active demand response programs, as demonstrated in [15, 16].

A similar spread is also found for the storage efficiency shown on the bottom graphs of Figure 2. Depending on the properties of the building, the heating system and the duration of the ADR setting storage efficiencies between 100 % and 55 % are found. Thereby it is found that on the one hand the efficiency decreases with increasing duration of the ADR event. When ADR events are limited to a charging time of 3 h, a median value for the efficiency of 93 % and 96 % is obtained for buildings with respectively the radiator and floor heating systems. On the other hand, higher storage efficiencies are in general obtained for the floor heating cases. The floor heating system directly activates the thermal mass of the floor, which is characterized by a high thermal capacity and relatively small losses to the ground. Consequently, the heat stored within the floor is released at a low rate, resulting in a less sharp increase of the zone temperature and therefore less thermal losses. In contrast, the radiator system is characterized by a high convective heat emission (70 %). Increasing the heating power during an ADR event therefore immediately activates the less capacitive indoor air, resulting in higher indoor temperatures and corresponding ventilation and transmission losses.

Multivariate regression for storage efficiency

Although the average storage efficiency is found to be high, the spread on the results indicates the sensitivity of the storage efficiency to the building design parameters and the duration of the ADR event. In this paragraph, the correlation of the storage efficiency to the building and system design parameters as well as the duration of the ADR event and the outdoor temperature are quantified by a multivariate regression analysis, as explained above. Figure 3 shows the standardized regression coefficients for identification on the datasets for each duration, indicating the clear dependence of the relative importance of the regression coefficients on the duration of the ADR event. Analysing the standardized regression coefficients shows that for both heating systems the HLC and $HLCperCTOT$ parameters are the most important regression coefficients. The latter is defined as the fraction of the heat loss coefficient of the building divided by the total thermal mass of the building fabric. Thereby it is interesting to see that for short ADR events - less than 60 min. - the HLC is the dominant coefficient, while for longer periods its contribution to the model reduces and the $HLCperCTOT$ becomes dominant. This can be explained by the fact that the storage efficiency is influenced by the dimensionless relation between the thermal insulation quality of the dwelling and its storage capacity. While the HLC is influenced by both the insulation quality itself and by the size of the building, the impact of the latter is eliminated by using $HLCperCTOT$. For short term events the thermal mass of the structure is found of less importance resulting in the lower contribution of $HLCperCTOT$ compared to HLC in the model.

Shown by the positive regression coefficient, the thermal capacity of the indoor air has a positive impact

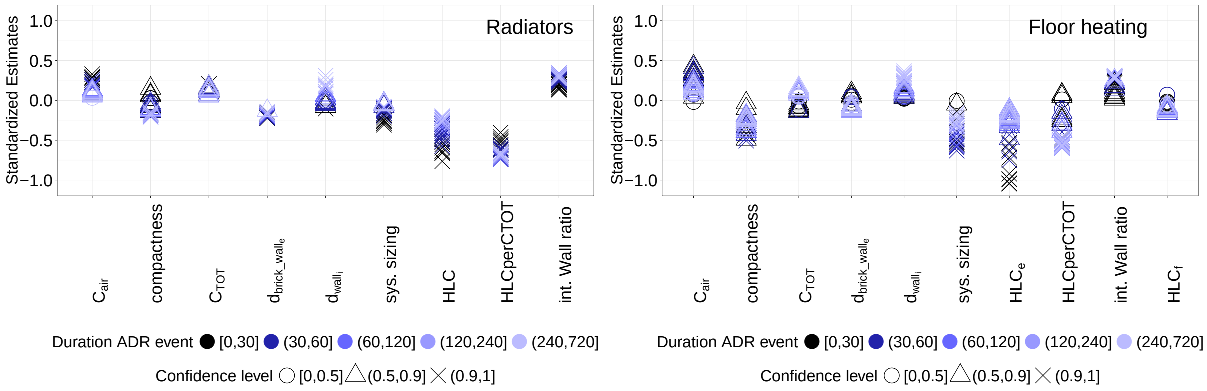

Figure 3: Standardized regression coefficients for the radiator (left) and floor heating system (right) estimated for different durations of the ADR events. The colour-scale indicates l_{ADR}, the size of the points indicates the confidence level of the estimated value.

on the storage efficiency. For dwellings with radiator heating, the contribution is however only important for short ADR events. This positive correlation is also found for the floor heating case. However, the uncertainty on the regression coefficients for C_{air} is high and also the link with the ADR duration is less pronounced.

In case of longer ADR events, both the inner wall ratio and the thickness of the inner walls have an significant positive contribution to the storage efficiency. The availability of thermal mass at the inside of the outer walls, evaluated by the thickness of the inner brick, shows to be insignificant and even a negative correlation is found. The total structural storage capacity has, at least for long ADR events, a significant positive contribution to the model. Nevertheless, on short term in case of floor heating the standard deviation for this coefficient is high, demonstrated by the low reliability.

Finally, Figure 3 shows that over-sizing of the heating system has a significant negative correlation with the efficiency of structural storage for floor heating for ADR periods between 30 min and 240 min, while for radiator heating the effect is only shown for short periods. This is a consequence of the faster rise of the indoor temperature and the corresponding thermal losses, as a result of the higher additional power that is available for charging the thermal capacity of the dwelling. Once the maximum comfort temperature is reached the power of the system is reduced to maintain this temperature and the effect of over-sizing is eliminated. Given the slow thermal response of floor heating systems, it takes longer before this maximum temperature is reached and thus the effect of over-sizing lasts longer.

Power shifting capability

Figure 4 shows the relative power shifting capability for buildings initialized at an indoor temperature between $20°C$ and $22°C$. There relative capacity is thereby obtained by dividing Q_δ by the nominal power of the system. Since the heating system operates on approximately 25 % of its power capacity for the outdoor temperature of $0°C$, the relative upward power shifting capability is limited to about 75% for all initial temperatures. Nevertheless, the period for which this shift can be maintained increases significantly for lower starting temperatures and higher comfort ranges. For a comfort range of $2°C$ an increase of the heating power to the nominal power can be maintained for 3 h when started from the minimum comfort $20°C$. Starting from a steady state condition with an indoor temperature of $21.5°C$ the maximum comfort temperature $(22°C)$ is already reached after 30 minutes. For a comfort range of $4°C$ and starting from an indoor temperature of $20°C$ the maximum heating power in this case can be maintained for almost 18 h.

A similar cooling down period is shown starting from an indoor temperature of $21°C$. Evidently, the possible duration of a negative power shift is found to be zero when starting from the minimum comfort temperature of $20°C$. Note that for the negative flexibility no difference between the comfort ranges is found, as in both cases the same minimum comfort temperature is used.

Finally, it should be emphasized that the demonstrated power shifting capabilities are calculated for stationary boundary conditions. As such, smooth curves are obtained and the duration goes to infinity for a power shift equal to zero. For dynamic boundary conditions, the required heating power to maintain a constant temperature will not be constant nor equal to the current state. The shape of the power shifting capability functions will therefore depend on these boundary conditions.

CONCLUSIONS

A generic simulation based methodology to quantify the potential of a building for active demand response using the structural thermal energy storage capacity

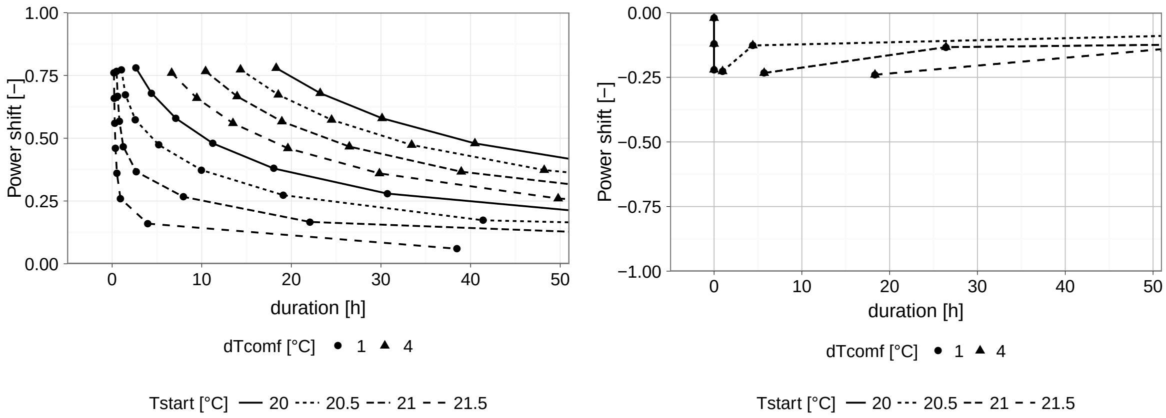

Figure 4: Comparison of upward (left) and downward (right) relative power shifting capability for a constant outdoor temperature of 0°C and varying initial indoor temperatures ($Tstart$)

has been developed. Thereby, the available storage capacity for ADR, the storage efficiency and the power shifting capability are defined as a set of key performance indicators which are able to represent different aspects of the flexibility. The available storage capacity and efficiency are shown to be closely linked to the thermal properties of the dwelling – especially the heat loss coefficient and available thermal mass – and can be interpreted as characteristics of the building. Nonetheless, they are found to strongly depend on the boundary conditions and are therefore not constants but vary in time.

The power shifting capability is defined a measure for the instantaneous flexibility of the dwelling. In contrast to measures found in literature, such as the state of charge or the ramping rate, a time dimension is added to the definition. As such, it not only gives information about the shift in power that can be delivered but also on how long this shift can be maintained.

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