Study of Electrical Heating Setpoint Modulation Strategies for Residential Demand Response

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Abstract

In some northern regions, residential electrical heating accounts for an important share of the grid demand during peaking hours. This paper presents the use of building simulation to study the impact of multiple setpoint modulation strategies on the demand of a baseboard heated cottage during grid peak periods. The setpoint modulation is applied to selected rooms only. The impact of interzonal air transfer on the building's demand reduction potential was investigated through comparative experimental work and is found to be negligible when the outside air temperature is very low. Simulated strategies are compared over multiple indicators to assess their unitary demand reduction potential. The study emphasizes the importance of pre-programmed temperature setbacks on the heating demand reduction potential.

1   Introduction

According to StatCan (2011), 66% of households in Quebec use electric baseboards as their main heating system. During winter peak periods, space heating represents up to 80% of the total demand of the households (Le Bel & Handfield 2008). Electric space heating of dwellings is therefore a relevant load for demand response (DR) in the winter.

While many authors have treated the control of residential cooling equipment to reduce the demand during peak events (Reddy et al. 1991, Katipamula & Lu 2006, Pietila et al., 2012, among others), only a few have looked at its electric heating counterpart. Reynders et al. (2013) studied the impact of the insulation level and inherent thermal mass of a near net zero house on the ability of its photovoltaic generation system to cover the power demand of air-to-water heat pumps during grid peak periods. Ali et al. (2014) focused on an optimization procedure for the control of electrical heat storage in both the existing thermal mass of a house and in an additional heat storage device. These studies either represent the building as a single thermal zone or make use of a central heating system.

Electric baseboards are controlled by line-voltage thermostats, often operating in proportional mode, alloying temperature regulation in each room or zone individually. If dynamically programmable line-voltage thermostats were developed, sophisticated setpoint modulation strategies would become available. Such strategies, applied during so-called DR events, could help smooth the demand profile of households or reduce it during grid peak periods.

The objectives of this paper are twofold. The first part uses simulation to evaluate the impact of several setpoint modulation strategies when applied to selected rooms of a baseboard heated house. The second part exposes experimental work to assess the assumption of a negligible impact of interzonal heat transfer on the total demand reduction potential. This airflow is driven by the temperature difference between rooms and is often neglected in simulations to evaluate the demand reduction potential for a whole building because of the prevalent use of single thermal zone models (Reynders et al. 2013).

Leduc et al. (2011) also used simulation to study setpoint modulation strategies for baseboard heated houses. They, however, applied the strategies to larger groups of rooms (at least floor-

by-floor), used larger setpoint modulation magnitudes and selected a steady setpoint profile as a reference scenario. The present simulation study builds on this last study by presenting strategies based on the technical capability level of thermostats and by discussing a reference scenario incorporating setbacks.

2   Simulation Methodology

Model

The simulation was run with the non-geometric TRNSYS Type 56 multizone building model (Klein et al. 2010). A multizone model is required to represent the zonal control created by the line voltage thermostats driving the electrical baseboard in each room. It has been thoroughly validated and used to study the electrical demand of households (Guarino et al. 2013).

The architecture of the modelled house is based on the Experimental Houses for Building Energetics (EHBE) (Le Bel & Gélinas 2013). This test bench consists of two detached cottages with excavated basements, each with a 60 m² footprint, excluding the attached garage. The wall assemblies of the building were chosen to represent a light-weight wood framed house with U-values as shown on Table 1. The total fenestration area was 19 m². Vinyl framed windows with double glass and argon filled panes, (ASHRAE #A-17-23c) were modelled. Similarly to Leduc et al. (2011), the 'air capacitance' parameters of Type 56 were adjusted in each zone to match the temperature decrease rates experimentally observed after a setpoint drop. The yearly internal gains of other simulated loads and occupation are also provided in Table 1.

Table 1: Simulation parameters

U-Values[1], W/m²K (R)			
External Walls	Attic	Basement Walls	Basement Slab
0.490 (R12)	0.239 (R24)	0.877 (R6)	2.373 (R2)

Internal Gains, kWh/year			
Appliances	Occupation	Lighting	Total
3580 (water heater, small and large appliances)	1630 (4 people)	2 443 (13 W/m2)	7 653

[1] reference values computed in TRNSYS

There were a total of eight zones with baseboards in the model: *upper floor*: bedrooms 1 (C1), 2 (C2) and 3 (C3), washroom (SB); *main floor*: living room, dining room, kitchen; and *basement*. Each zone temperature was controlled by its own thermostat. Perfect regulation was assumed, which is a fair approximation of the commonly used electronic line voltage thermostats for baseboards. The garage was not heated while the basement zone was kept at 18°C in all strategies. Setpoint modulation strategies were applied to four zones out of eight: bedrooms 1 (C1) and 3 (C3), living room and kitchen. This selection of rooms was arbitrary but realistic as they constitute the most lived in spaces. They accounted for about 5/8 of the above ground floor area and for 6 kW of installed electrical heating nominal power, over a total of 13.5 kW. When all the main and top floor setpoints were kept steady at 21°C, the calculated annual heating load was 15 600 kWh for Montreal's 2009 weather. A PRISM analysis (Fels 1986) of the heating demand resulted in a heat loss coefficient (*UA*) of 142 W/°C and an equilibrium temperature of 18°C. The yearly natural infiltrations represented 2 935 kWh.

Results are discussed for January 16th, 2009 only, a historical grid peak day, with outside air temperatures (OAT) averaging -23°C. Figure 1 shows the OAT and total horizontal solar ra-

diation on that day and the previous one. Two grid peak demand periods were defined as follows: one in the morning between 6:00 and 9:00 and another in the late afternoon/early evening from 16:00 to 20:00. Grid peaks are more frequent in the middle hours of these periods. A simulation timestep of five minutes was used.
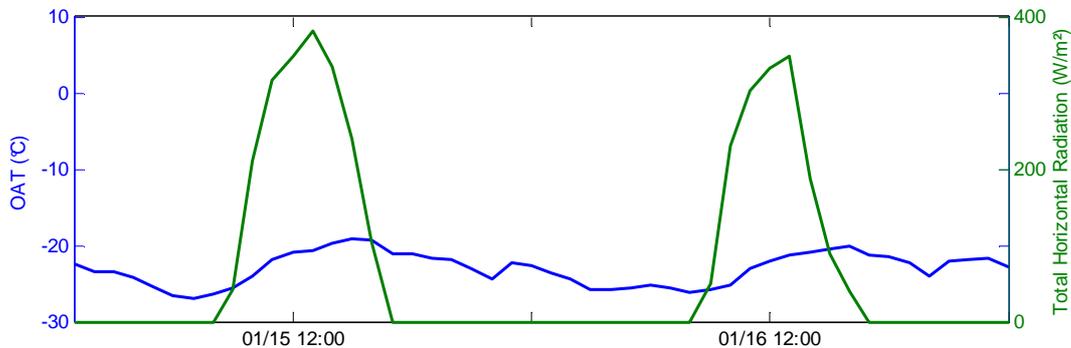
Figure 1: Weather

Setpoint Modulation Strategies

The following sections describe the setpoint modulation strategies that were applied to the model under the weather conditions of the chosen grid peaking day. A reference scenario was used to compare the effect of the strategies enabled by three levels of thermostat processing capabilities: basic, smart and advanced.

The suitable magnitude for setpoint modulations for DR events is dependant upon numerous factors. The magnitude of setbacks normally initiated by occupants provides a good insight as to what would be acceptable to occupants. Private data indicates that the average declared setback magnitude is 3°C. These setbacks are set by the occupant and likely correspond to changes in occupation level or types of activity within the household. They presumably are the maximal possible decrement that could be applied and still be considered acceptable by the occupants. For the purpose of this study, the strategies were limited to a two-degree decrement beneath the comfort temperature (21°C) and a one-degree increment over the comfort temperature. Within such limits, discomfort was assumed to be limited.

Some communicating thermostat protocols provide two optional random delays, one before the application of a command (setpoint modification) and another before the return to normal conditions. Both delay values could be up to an hour and are evaluated at the thermostat level for each command. These delays help to desynchronize the power demand fluctuation from one load to another. To emulate these delays in the simulation, they were replaced by a 15-minute delay between the applications of a strategy to each of the four controlled thermostats. The strategy was applied to the kitchen zone 5 minutes before the event start time, to the living room 10 minutes after the start time, to the first bedroom 25 minutes after the start time and to the third bedroom 40 minutes after the start time. This allowed the reproducible overlapping of demand changes from one strategy to another.

Reference Scenario

In past studies, a large fraction of Canadian households declared operating either manual or programmed temperature setbacks (Manning et al. 2007). In the reference scenario (R), setbacks to 18°C were operated from 9:00 to 16:00 and from 22:00 to 6:00, as shown on Figure 2. Three of those four time boundaries also correspond to the boundaries of the grid peak periods. Significant power is drawn to bring the temperature back to comfort levels at the end of the setback periods. Since those moments generally correspond to grid peak periods, dwell-

ings with two setbacks per day impose the highest stress on the grid and produce the most challenging demand profile. This is why a setpoint schedule with two setbacks was chosen for the reference scenario.

Realistic behaviour concerning setpoint adjustments is notoriously less regular than this type of fixed schedule (Urban & Gomez 2013). It is however difficult to obtain realistic user-behaviour profiles, especially during extreme weather conditions causing the launch of DR events. While fixed schedules allowed comparing strategies, the resulting reduction potential values should only be considered as a first approximation.

Basic

For the first technological level, named "basic", the setpoint modulation strategy is assumed limited to a single command without any adjustment in regard to the normally applied setback profile. The first proposed strategy (B1) maintained the comfort temperature, while the second (B2) reduced it by 2°C. In the field, these two strategies could alternatively be created by manually switching thermostats to manual mode (hold). Figure 2 shows all the proposed setpoint modulation strategies.
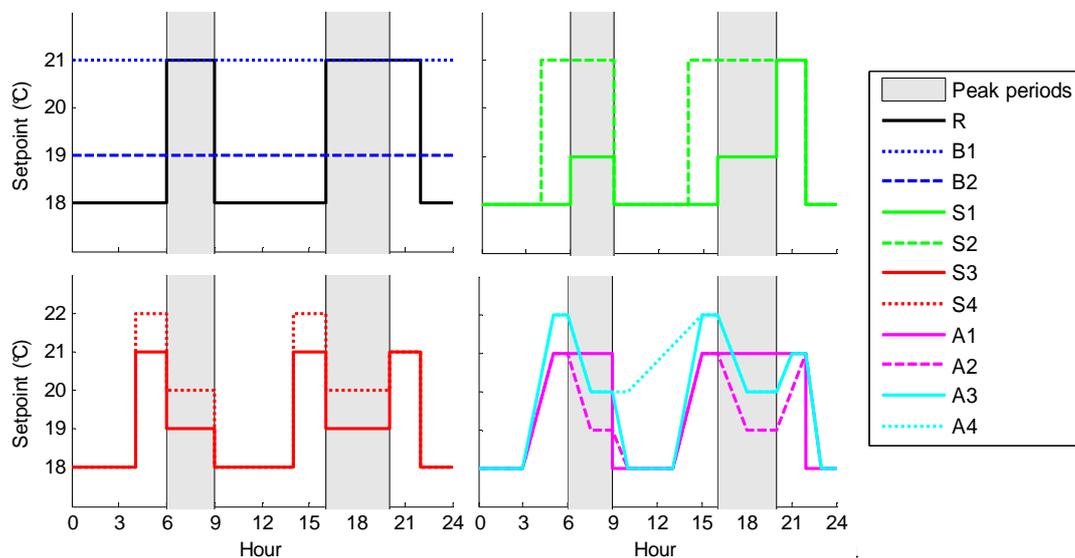
Figure 2: Simulated setpoint modulation strategies

Smart

At the "smart" technological level, intelligence was added to allow for two additional features:

- Strategies could be adjusted according to programmed setbacks in order to not produce setpoints lower than setback levels and to not allow a setpoint rise in the middle of peak periods.
- Multiple setpoint commands could be put together to create more complex strategies such as preheating.

The S1 strategy simply limited the setpoint to 19°C. For S2, a two-hour preheating period at the comfort temperature was initiated before peak periods. For S3 and S4, the preheating period was followed by a 2° temperature decrement. In S3, the preheating occurred at the comfort temperature (21°C), while it occurred at 22°C in S4. The latter allowed for a higher setpoint during peak periods for a same decrement level (-2°C).

Advanced

At the "advanced" technological level, most instantaneous setpoint variations were replaced by ramps. This reduced peak demand and allowed to set the time of occurrence of the minimum demand within the peak period. The minimum demand occurred at the end of the setpoint ramp down. For strategy A1, preheating was initiated by progressively increasing the setpoint over 2 hours and keeping it steady at the comfort level for an hour before peak periods. A2 was based on A1 with the addition of a setpoint ramp down over each first half of the peak periods. The 2°C temperature decrement was then held until the end of the peak periods, where ramps were used to return to the default setpoint. In A3, preheating was operated at 22°C to allow a higher temperature during peak periods for an equal decrement value. Case A4 was added to reduce the demand needed to preheat the evening peak period.

Demand Reduction Indicators

After the simulations, demand reduction indicators were computed to quantitatively compare the resulting demand profiles over peak periods with the reference scenario. The possible demand rebound at the end of the setpoint modulation strategies could also create new peaks. The demand impact over the few hours following the peak period was thus of interest.

Results were first averaged over 15-min. intervals, the timebase used for demand metering. Every indicator was expressed in terms of the daily demand profile vector components:

$$\vec{Q}^s = \left[q_{0.25}^s, q_{0.5}^s, q_{0.75}^s, \cdots q_{24}^s \right], \tag{1}$$

where the indices are timestamps ranging from 0.25 to 24 by steps of 0.25. The s superscript is the name of the strategy.

$$\Delta q_t = \left[q_t^{ref} - q_t^s \right] \tag{2}$$

is the demand change at time t caused by strategy s in relation to the reference scenario.

- **Average demand reduction over a peak period** (kW)

$$\overline{\Delta q}_{AM} = mean\left[\Delta q_{6.25}, \dots \Delta q_9 \right], \ \overline{\Delta q}_{PM} = mean\left[\Delta q_{16.25}, \dots \Delta q_{20} \right] \tag{3}$$

- **Average demand reduction over critical hour(s) of a peak period** (kW)

$$\overline{\Delta q}_8 = mean\left[\Delta q_{7.25}, \Delta q_{7.5}, \Delta q_{7.75}, \Delta q_8 \right]$$
$$\overline{\Delta q}_{18} = mean\left[\Delta q_{17.25}, \Delta q_{17.5}, \Delta q_{17.75}, \Delta q_{18} \right] \tag{4}$$
$$\overline{\Delta q}_{19} = mean\left[\Delta q_{18.25}, \Delta q_{18.5}, \Delta q_{18.75}, \Delta q_{19} \right]$$

- **Maximal rebound demand change** (kW), computed over the two hours following the end of a peak period

$$rebound_{AM} = \max\left[q_{9.25}^s, \dots q_{11}^s \right] - \max\left[q_{9.25}^{ref}, \dots q_{11}^{ref} \right]$$
$$rebound_{PM} = \max\left[q_{20.25}^s, \dots q_{22}^s \right] - \max\left[q_{20.25}^{ref}, \dots q_{22}^{ref} \right] \tag{5}$$

- **Daily Energy Use Variation** (%)

$$DEUV = 100 \cdot \int \overrightarrow{Q_{strat}} \, dt \bigg/ \int \overrightarrow{Q_{ref}} \, dt \tag{6}$$

Morning (AM) and evening (PM) periods were treated separately except for the daily energy use. Each indicator reflects the impact of a setpoint modulation strategy in comparison to the reference scenario.

3 Experimental Methodology

The use of a multizone building model and partial setpoint controls required clarifying the effect of interzonal airflows on the overall building demand reduction potential. Persson et al. (2005) included a simple correlation based on the theory of Barakat (2007) to account for heat transfer between zones caused by air circulation through openings and doors. Their model was used to evaluate the demand reduction when using a pellet stove in a centralized position within the house. Since airflow profiles will vary according to the zone air temperatures and stratification patterns induced by the type of heating equipment used, further investigation is needed.

An experiment was set up in order to validate the stated assumption of the negligible impact of heat transfer from airflows between zones with different temperature setpoints on the estimation of the household's demand reduction potential during peak periods, which is when the OAT is very low. LTE's EHBE test bench as described in Le Bel & Gélinas (2013) was used. Data points included temperatures at the center of the zones, energy consumption (per baseboard, all other uses individually), relative humidity, air velocity, thermal flows; they were recorded at 15-min. intervals.

A testing methodology was developed. Both houses in the test bench were used in the test. The setpoint temperature in the basement of each house was maintained at 17°C and the main floor at 18°C in order to limit the heat transfer from the lower floor to the second floor. The second floor of each house was isolated from the rest of the house using a plastic film at the top of the staircase as illustrated by Figure 3.
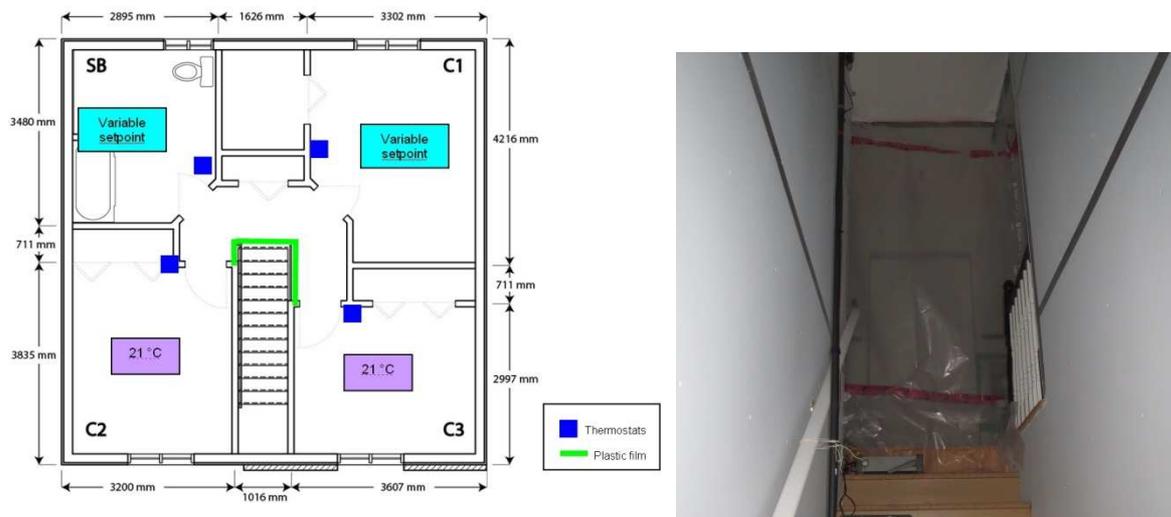
Figure 3: Test configuration on the second floor of H2 in the EHBE

Setpoint adjustments were made in two zones of the second floor of each house. Zones C2 and C3 temperature setpoints were kept constant at 21°C; zones SB and C1 were variable in time as illustrated in Figure 4. The doors of the second floor zones were closed in house #1 (H1) and open in house #2 (H2); the doors in the basement, the garage and on the main floor remained closed in both houses. Mechanical ventilation was turned off and air supply outlets were blocked using a sealed plastic film.

Tests were conducted over a five-day period in February 2013 (with peak periods occurring on three days); the weather conditions are illustrated in Figure 4. Solar radiation through the windows was blocked using reflective foil to limit the solar gains but zones C1 and SB still received some solar gains in the morning. Apart from the first day of the test, the OAT averaged -20°C and the maximum total horizontal solar radiation was 500 W/m^2, which is high for that time of year.
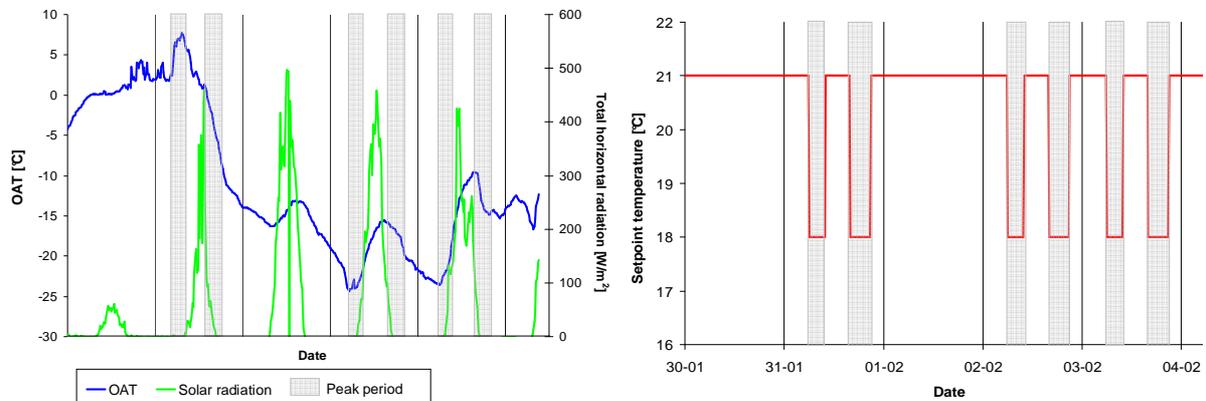
**Figure 4: Weather during testing days and setpoint adjustments in SB and C1**

4   Experimental Results and Discussion

Impact on Individual Zones

The test results for both the zonal demand and temperature profiles are shown in Figure 5; they are presented for adjacent zones (source-sink couple) C1-C3. The results for C2-SB were similar.

We noticed that the setpoint reduction in C1 of H2 (C1-H2) was partially compensated by the adjacent zone with a constant setpoint (C3-H2). During the peak period, the lower setpoint was not reached when the doors were left open (H2) whereas it was quickly reached (less than two hours) when the doors were closed (H1). Therefore, C1-H1 resumed its heating demand in the zones with setbacks before the end of the peak period, hence the greater average demand. C3-H2 transferred warm air to C1-H2 during the peak period and its average heating demand increased compared to that of C3-H1. The ambient temperature of C3-H2 also decreased during the peak period, which could be explained by what could be qualified as a configuration effect. It is thought that the temperature reading of the thermostat's sensor was no longer representative of the temperature at the center of the zone due to the warm airflow from the source zone to the sink zone.

A slightly higher average demand for the second floor of H2 could then be anticipated, corresponding to the energy supplied by C2 and C3 during the peak period. As will be discussed in the next section, this was true until the lower setpoint was reached; then the difference was negligible (H1-H2).

C1

C3
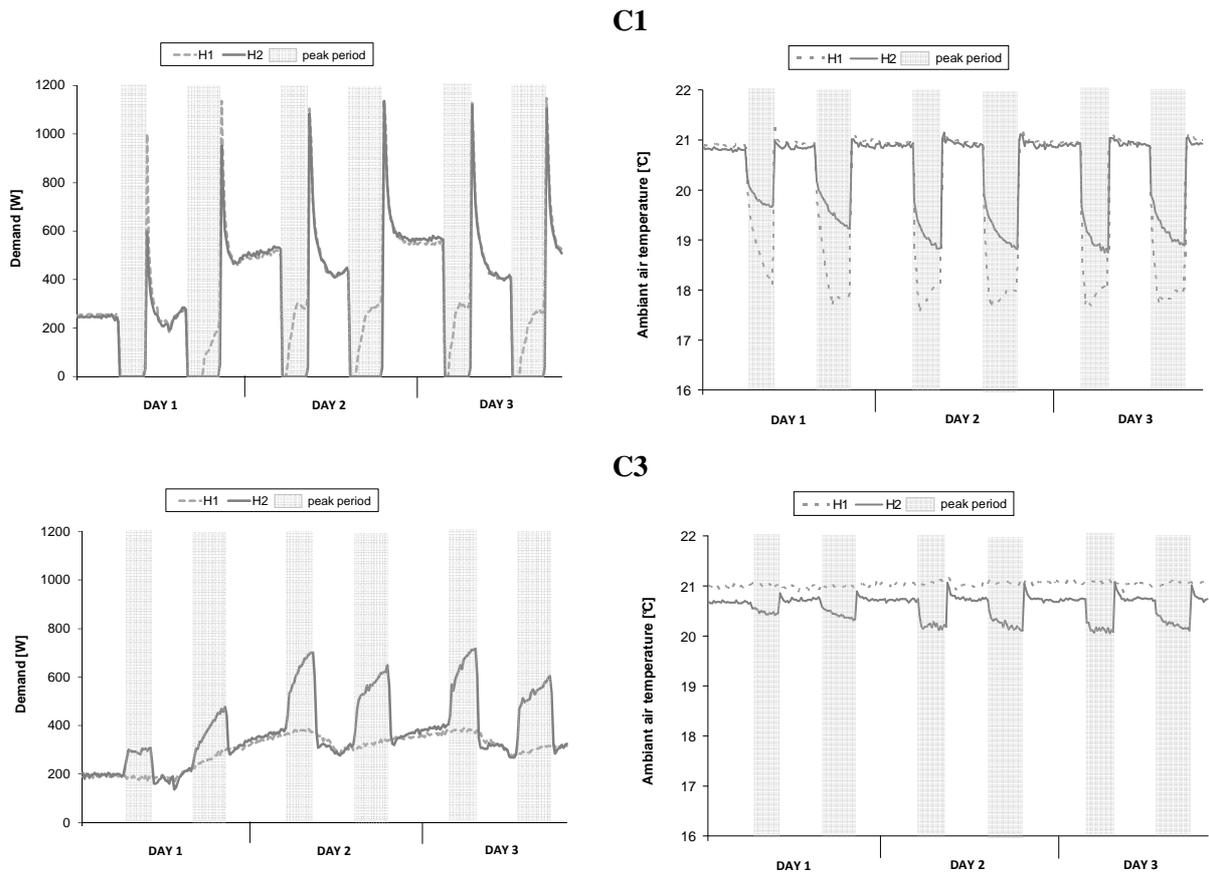
Figure 5: Demand – C1-H1/H2 and C3-H1/H2 ($q_{2ndfloor,H1}$ and $q_{2ndfloor,H2}$)

*Impact on Second Floor (Aggregated Impact)*

The results were aggregated for both of the entire second floors (Figure 6), i.e. the sum of all the demand profiles on this floor ($q_{2ndfloor,Hx}$). One can see that the absolute instantaneous difference between $q_{2ndfloor,H1}$ and $q_{2ndfloor,H2}$ ($\Delta q_{2ndfloor,H1-H2}$) during peak periods did not exceed 296 W. The difference was greatest right after the peak periods, as will be discussed later.
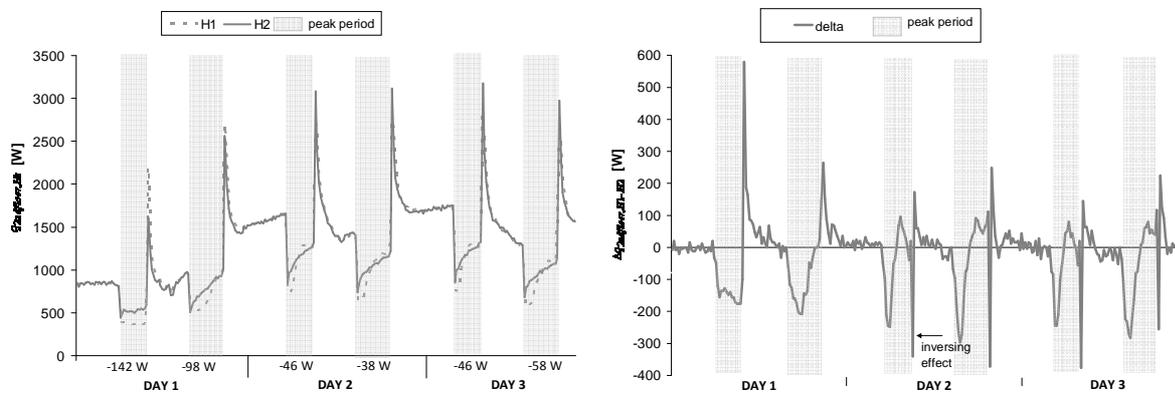
Figure 6: Demand profiles,
second floor H1/H2 ($q_{2ndfloor,H1}$ and $q_{2ndfloor,H2}$) and $\Delta q_{2ndfloor,H1-H2}$

Figure 6 also presents the values of the indicators described previously regarding the difference occurring between the areas with open and closed doors (H2-H1), $\Delta q_{2ndfloor,H1-H2}$. Measurement errors totalled an estimated maximum value of 12 W and the systematic error between H1 and H2 was estimated at 30 W. The global error of $\Delta q_{2ndfloor,H1-H2}$ was estimated at 32 W. The average power differences $\overline{\Delta q}_{2ndfloor,H1-H2,\Delta t} < 32$ W (where Δt is a selected time interval) were judged non-significant because they fell within the global error margin.

The average power differences during the peak periods ($\overline{\Delta q}_{2ndfloor,H1-H2,AM/PM}$) ranged from low (140 W) to non-significant. The maximum difference occurred when the OAT was higher. In fact, $\overline{\Delta q}_{2ndfloor,H1-H2,AM/PM}$ is inversely proportional to the heat losses, as shown in Figure 7. This figure also shows that $\overline{\Delta q}_{2ndfloor,H1-H2,AM/PM}$ for OATs lower than -15°C was close to the global error. Since the heat losses were proportional to UAΔT where $\Delta T = $ (OAT-T_{int}), one can also conclude that there will be a higher difference for buildings with lower UA for a given ΔT. The period of the afternoon of 2013-02-03 behaved slightly differently by showing small differences even if the OAT was -13°C, a value comparable to the value of the afternoon of 2013-01-31. This can be explained by two phenomena reducing the stored energy in the building mass: 1) the OAT on the morning of 2013-02-03 was much lower than that of the morning of 2013-01-31, 2) this was the fourth consecutive period of the setback strategies.
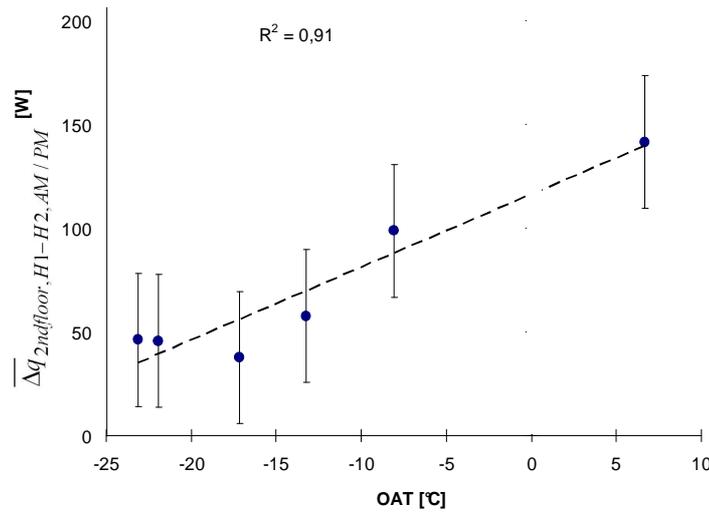
Figure 7: Difference in demand, $\overline{\Delta q}_{2ndfloor,H1-H2,AM/PM}$, versus average OAT

The rebound effect was a function of the OAT, therefore of the heat losses during the peak period in C1 and SB. When the setback temperature was reached, hence with cold OAT, the rebound indicator was negative (H2 > H1) but the opposite was true when the OAT was mild. This inverse effect (shown in Figure 6) was limited in time; after 30 minutes, $q_{2ndfloor,H1}$ was higher than $q_{2ndfloor,H2}$. This is explained by the fact that adjacent zones C2 and C3 in H2 had lower ambient temperatures at the end of the peak period compared to H1; therefore $q_{CC2,H2}$ and $q_{CC3,H2}$ were higher than $q_{CC2,H1}$ and $q_{CC3,H1}$ until their setpoints were reached in H2. After 30 minutes, there was still a difference between $q_{2ndfloor,H1}$ and $q_{2ndfloor,H2}$ because C2 and C3 in H1 had reached lower ambient temperatures during the peak period than C2 and C3 in H2.

The instantaneous maximal difference between H1 and H2 ($\Delta q_{2ndfloor,H1-H2}$) was in the order of magnitude of 10-12% of the estimated average demand without DR strategies, when $q_{2ndfloor,H1} < q_{2ndfloor,H2}$.

These tests demonstrated that heat transfer from airflows is significant between adjacent zones with different temperature setpoints; hence, the temperature and demand profiles of individual zones will greatly differ if doors are open or closed during a DR event. But when an entire floor's average heating demand is calculated with a low OAT, as is the case during grid peaking periods, the differences on the overall heating demand reduction potential become negligible, the thermal demand remaining the same but the heat source location differing. A more significant difference is observed for the rebound effect, at about 10-12% of the estimated demand if no setback strategies are applied. Hence, for the purpose of estimating the average demand reduction ($\overline{\Delta q}_{2ndfloor,H1-H2,\Delta t}$) of setpoint modulation strategies, the use of a model that does not include heat transfer from airflows between zones is acceptable in the case of partial setpoint control. However, a model including such interzonal heat transfer would be needed for a study on comfort levels since temperature profiles will differ from one zone to another. An empirical model such as the one used by Persson et al. (2005) or a more detailed model such as TRNFlow (Transsolar, 2009) could be used.

5   Simulation Results and Discussion

Figures 8, 9 and 10 depict the simulated demand profile for each of the setpoint modulation strategies. Table 3 provides the same results, in terms of reduction indicators.

*Reference Scenario and Basic Strategies*

Figure 8 shows how the reference scenario had sharp demand increases when setpoints were switched back to comfort levels. These rises, of more than 4 kW, were less than the nominal heating power of the modulated zones because their baseboards were already operating to maintain the lower setpoint temperature. It should be noted that no time offsets were simulated between setpoint applications in the reference scenario as it is unlikely that time offsets would be programmed by typical users. Oscillations of 450 W on the demand were caused by the simulated refrigerator and freezer consumption. The heating demand for that day was 143 kWh.

Basic strategies B1 and B2 imposed a steady temperature profile and therefore resulted in much less fluctuating demand profiles, except when switching the setpoint to a constant value, simulated in this case at midnight. They resulted in an average reduction during the morning ($\overline{\Delta q}_{AM}$) and evening ($\overline{\Delta q}_{PM}$) peak periods of respectively 1.3 to 1.9 kW, the highest value being obtained in the morning for the lowest temperature setpoint. Such steady strategies do however create an increased demand in the hours following the morning peak period ($rebound_{AM}$) because of the drop in the reference scenario demand. In comparison to the reference scenario, the daily energy consumption (*DEUV*) increased by 5% when the comfort temperature was held steady and decreased by 2% when 19°C was maintained .

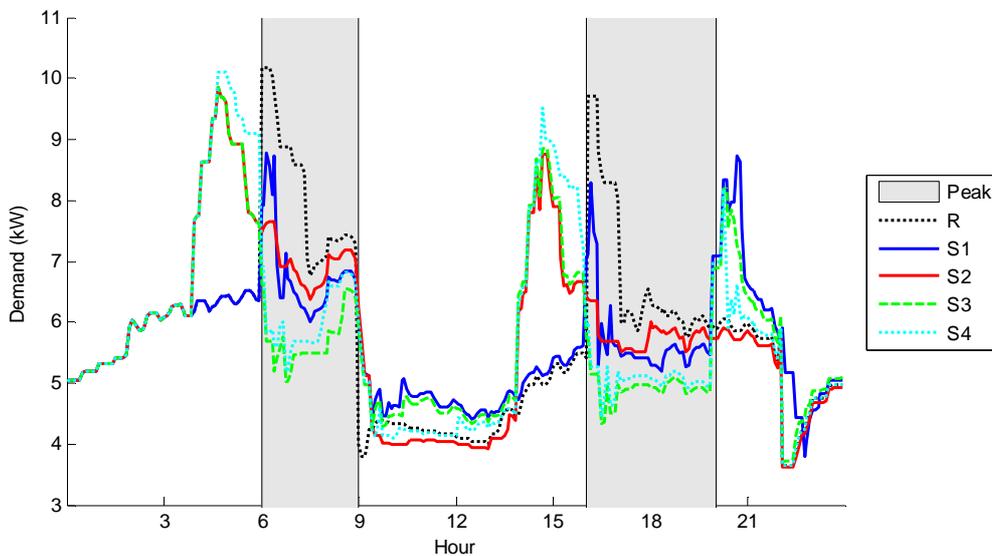*Smart Strategies*

In the first "smart" strategy (S1), the setpoint level was limited to 19°C during peak periods. During these periods, the result, as shown on figure 9, was a reduced demand with a similar shape as in the reference scenario but of a lower magnitude. The average demand reduction during the morning peak period ($\overline{\Delta q}_{AM}$) was 1.0 kW and 1.3 kW in the afternoon period

($\overline{\Delta q_{PM}}$). An important rebound ($rebound_{PM}$) was created after the evening event to bring the temperature back to comfort level. A lesser demand increase was also created right after the morning period ($rebound_{AM}$) as setpoints were progressively applied to each zone while they were applied synchronously in the reference scenario.
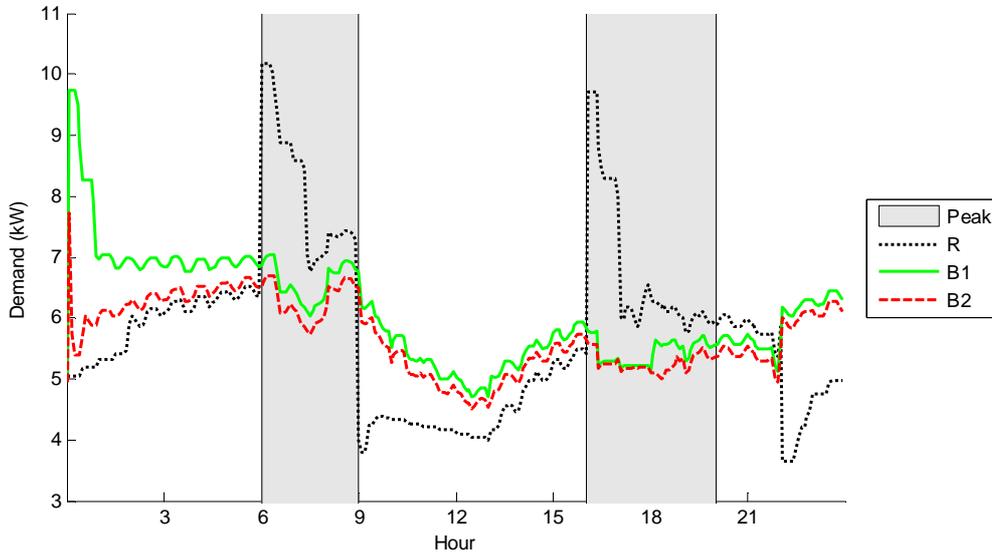
Figure 8: Resulting demand profile for the "basic" technological level
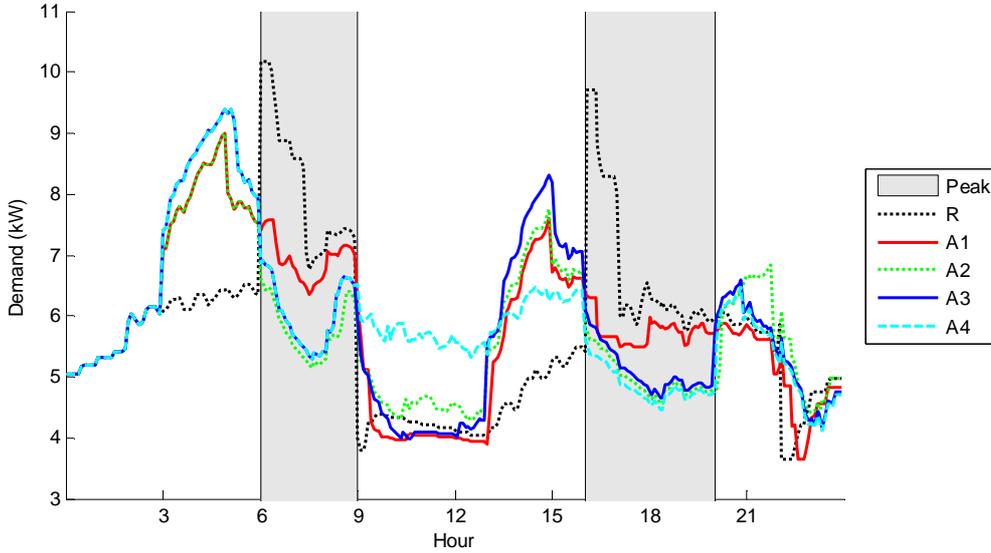

Figure 9: Resulting demand profile for the "smart" technological level

All the other smart strategies had preheating periods that shifted the maximal demand to before the grid peak periods. S2 allowed to sustain the comfort temperature during the peak periods and resulted in an average reduction ($\overline{\Delta q_{AM/PM}}$) comparable to S1 with a lesser rebound in the evening ($rebound_{PM}$). S3 and S4 produced an additional reduction by decrementing the setpoint by 2°C at the beginning of each peak period. S4 preheated at 22°C rather than 21°C, resulting in a higher temperature during the peak period while providing a comparable de-

mand reduction ($\overline{\Delta q}_{AM/PM}$). S4 also had a lower $rebound_{PM}$ as the needed power to reach comfort level was lower. The demand level of S4 at the start of the preheating periods was comparable to the maximal demand level of the reference scenario. However, as they occurred about 1.5 hour before the beginning of the peak periods, they were less detrimental.

Advanced Strategies

In these strategies, sharp changes in setpoints were replaced with ramps resulting in more progressive changes in demand and a lower maximal demand. Strategy A1 compared to S2 in all indicators but with a less stringent preheating period. By adding a ramp down during peak periods, strategies A2, A3 and A4 allowed to shift the minimum demand to the middle of the peak periods, assumed as the most critical hours. It translates, in Table 3, to a higher reduction over the mid peak hours ($\overline{\Delta q}_8$, $\overline{\Delta q}_{18}$ and $\overline{\Delta q}_{19}$) for a comparable average reduction ($\overline{\Delta q}_{AM/PM}$). A3 offered somewhat reduced indicators compared to A2 but at higher temperatures during peak periods. A4 removed most of the midday preheating demand by spreading it over a longer period. This also slightly increased the reduction indicators ($\overline{\Delta q}_{18}$, $\overline{\Delta q}_{19}$, $\overline{\Delta q}_{PM}$) for the second peak period.

Figure 10: Resulting demand profile for the "advanced" technological level

Table 3: Reduction indicators (in kW, except DEUV, in %) for each strategy

		R	B1	B2	S1	S2	S3	S4	A1	A2	A3	A4
AM	$\overline{\Delta q}_8$	0.0	1.4	1.7	1.4	1.0	2.1	1.9	1.0	2.3	2.2	2.2
	$\overline{\Delta q}_{AM}$	0.0	1.6	1.9	1.3	1.2	2.4	2.1	1.2	2.4	2.1	2.1
	$rebound_{AM}$	0.0	2.0	1.7	1.2	1.3	1.0	1.1	1.3	1.0	1.1	1.8
PM	$\overline{\Delta q}_{18}$	0.0	1.1	1.1	0.8	0.7	1.3	1.2	0.8	1.4	1.2	1.5
	$\overline{\Delta q}_{19}$	0.0	0.7	1.0	0.8	0.3	1.2	1.1	0.3	1.4	1.4	1.5
	$\overline{\Delta q}_{PM}$	0.0	1.3	1.5	1.0	1.0	1.8	1.6	1.0	1.8	1.6	1.9
	$rebound_{PM}$	0.0	-0.3	-0.5	2.2	-0.2	1.9	0.9	-0.2	0.7	0.4	0.2
-	DEUV	0	5	-2	-1	1	-1	-1	-1	0	1	2

Simulation Results Discussion

Of all the strategies applying a comfort setpoint during the entire peak periods (B1, S2 and A1), the steady setpoint strategy (B1) was the one resulting in the highest reduction. However, it was the strategy that differed the most from the user's preferred settings (R) and that created the greatest, though modest, increase in energy consumption. It is interesting to note that all the other strategies had a negligible impact on energy consumption ($|DEUV| \leq 2$ %). Of all the strategies with a decrease in temperature to 19°C during peak periods (B2, S1, S3 and A2), A2 seems the most advantageous. S3 slightly outperformed in the case of some indicators but the average temperature over the peak periods was lower.

Many factors need to be considered when selecting a setpoint modulation strategy for DR. If one does not want to tamper with the setpoint during peak periods, strategy B1 offers the best reduction if one can tolerate a higher temperature during the night. This strategy can be implemented with the basic technology level. On the other hand, the only way to obtain maximal reduction is to use strategies combining a preheating period and a decrease in setpoint temperature during peak periods, such as strategies S3, S4, A2, A3 and A4. These allowed to reduce the average demand by more than 2 kW over the morning peak period and by 1.5 kW in the afternoon peak period, always for the specific simulated building and weather conditions. Other factors, such as a higher setpoint during peak periods, lesser maximal off-peak demand or positioning the minimal power draw during a peak period can all lead to considering ramps and higher preheating temperatures.

All the results presented are relative to a reference scenario consisting of two 3°C daily setbacks. While this is one of the most disruptive from a demand point of view, a dissimilar reference scenario would have produced different results. Strategies other than the ones involving steady temperatures have to be adapted in regard to the time of occurrence and drop level of the reference setbacks. Some processing is therefore needed to replace the scheduled setpoint profile by one which would satisfy both the demand reduction effort and the building occupants. A higher level of intelligence allows a finer control of the demand profile or results in a better comfort level for a comparable demand reduction. More sophisticated control strategies could even take advantage of weather forecasts and zonal thermal models to better solve the multi-objectives problem of maintaining comfort while taking action in DR events.

6   Conclusions

This study aimed at evaluating the impact of several setpoint modulation strategies when applied to selected rooms of a baseboard heated house. Results show that the demand reduction potential, for a specific building and given weather conditions, will depend on both the technology available to materialize the setpoint modulation strategies and the acceptable disruption from the normal comfort level. While these are limits inherent to DR strategies based only on control modifications, significant load reduction can be achieved without any added heat storage equipment or building construction modifications.

It was also demonstrated that, though the heat transfer from airflows that come along with the partial control of the building are significant, the overall effect on the demand reduction potential is negligible when outside temperatures are very cold.

Future work in this field will include experimental validation of the strategies identified as the most interesting. The inclusion of a correlation to account for heat transfer from interzonal air flows should be included in the building model if an analysis of zonal comfort is sought, given the non-uniform setpoints from zone to zone.

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