Arteconi, A., Costola, D., Hoes, P. & Hensen, J.L.M. 2014. "Analysis of control strategies for thermally activated building systems under demand side management mechanisms", Energy and Buildings, Vol. 80, Sept., pp. 384–393. DOI: 10.1016/j.enbuild.2014.05.053

Analysis of control strategies for thermally activated building systems under demand side management mechanisms

A. Arteconi[*][a], D. Costola[b], P. Hoes[b], J.L.M. Hensen[b]

[a]Università degli Studi eCampus, via Isimbardi 10, Novedrate (CO), 22060, Italy

[b]Building Physics and Services, Eindhoven University of Technology,

P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Abstract

Thermally activated buildings systems (TABS) are systems that integrate heating/cooling devices in the building structure, so that the building elements act as thermal storage and have an active role in the energy supply and demand management. Although TABS are well known systems, there are still open questions in their realization, mainly concerning appropriate control strategies which are influenced by the large thermal inertia. The purpose of this paper is to analyze the influence of demand side management control strategies on the performance of a thermally activated building system applied in a commercial building. The goal is to estimate the potential of TABS for load shifting requested by the electricity grid. The analysis is performed by means of a sample case: first the existing TABS control strategy and then the possible implementation of DSM mechanisms are analyzed. In particular three different demand side management mechanisms are evaluated: (i) a peak shaving strategy, (ii) a random request of switching on/off the system and (iii) a night load shifting strategy. The simulation results show high potential of TABS within the DSM framework, since TABS allow load control while scarcely affect thermal comfort.

Key words: TABS; DSM; control strategy; load shifting.

---

[*] Corresponding author: Tel.(+39) 071 2204432, Fax (+39) 071 2204770, email: alessia.arteconi@uniecampus.it

1. Introduction

Thermally activated buildings systems (TABS) are systems that integrate heating/cooling devices in the building structure, so that the building elements act as thermal storage and have an active role in the energy supply and demand management. They are typically realized by means of pipes embedded in concrete slabs (floors, ceilings, walls) with water as heat transfer medium. Main advantages of these systems are: they allow for demand peak shaving and consequently for reduction of heating/cooling capacity; energy demand and supply can be shifted thanks to mass thermal buffer; the large thermo-active surfaces allow small temperature differences between room and structure and low temperature heating and high temperature cooling sources [1].

Although TABS are well known systems and recognized as energy efficient and economically viable, there are still open questions in their realization, mainly concerning the control strategy. The control strategy is influenced by the large thermal inertia of TABS, it has to comply with different comfort requirements in different rooms within the same hydraulic circuit and it has to be designed for year-round operation and to avoid frequent switching between heating and cooling mode [2]. TABS have a self-controlling effect, meaning that they could be supplied with constant water temperature (e.g. 22°C all the year-round) and be able to achieve thermal comfort, providing both heating and cooling, when there is a small temperature difference between the water temperature and the room air temperature. This strategy is not effective for high heat gains and large temperature fluctuations [3]. Gwerder et al. [2] listed typical features of TABS control solutions: (i) they use water flow temperature compensated on the basis of the outside temperature (the temperature set point of the water flow is shifted with varying outside temperature according to the heating curve); (ii) they do not employ feedback signals from the TABS zones; (iii) heating or cooling mode depends on the season and/or on the outside temperature.

Generally these systems are operated continuously with a constant flow rate, but also intermittent operation has been evaluated. Gwerder et al. [4] showed that with a pulse width modulation control (PWM), which operates the TABS zone pump in an intermittent way, energy savings are obtained and operation periods of the plant can be shifted to times with high energy generation efficiency. Due to the large thermal inertia of TABS, instant correction of the room temperature cannot be achieved, however day-to-day room temperature compensation is promising [4]. Furthermore, Sourbron et al. [5] demonstrated that room temperature feedback control strategies can be inadequate for TABS because they cause frequent switching between heating and cooling with a dramatic impact on the energy performance. De Wit and Wisse [3] stated that the operating mode can be controlled by the room air temperature if a dead band is applied between the air temperature set point for the heating mode and the air temperature set point for the cooling mode, so that the system is more stable. It is possible to control different rooms with different comfort requirements by dividing the building into several zones with similar features and control each zone separately. Not only the division in zones, but also the hydraulic circuit topology has a paramount importance on the operating conditions and energy demand of TABS [1, 3].

In order to determine the water supply temperature the UBB (Unknown-But-Bounded) approach has been proposed by Gwerder et al. [2]. It takes into account the dynamic behaviour of the system and the influence of internal and external gains on the heating and cooling loads. Such gains have an important role for the achievement of the required indoor thermal comfort, as demonstrated by Saelens et al. [6], who analyzed the energy and comfort performance of TABS under different occupant behaviour. Kolarik et al. [7] showed that the application of the TABS decreases the primary energy use in comparison with traditional systems without a significant decrement of occupants' performance. Moreover another recent topic of research about TABS concerns the positive role of model predictive control to increase their energy efficiency [8, 9].

The purpose of this paper is to examine in depth TABS control strategies and their potential for load shifting on demand. In particular the aim is to analyze, by means of a sample case, the influence of demand side management (DSM) mechanisms on the performance of a thermally activated commercial building.

All strategies intended to influence the customer's use of energy are considered demand-side management and can be used to reduce customer demand at peak times, reduce energy consumption seasonally or yearly, change the timing of end-use consumption from high-cost periods to low-cost periods and increase consumption during off-peak periods [10]. DSM programs can have a benefit both for customers and utility. From the customer point of view, they can allow cost benefits for lower electricity bills and this is strongly influenced by a price responsive demand which is deemed fundamental for the demand-side management concept [11]. From the utility perspective proper DSM mechanisms help to make more efficient use of the existing generating capacity and can reduce the need for new capacity. TABS with their high thermal mass behave like a thermal storage so they have an undeniable potential to shift loads on the basis of external requests [12]. This paper aims at analyzing their behaviour and assessing their potential as DSM instruments.

2. Methods

The analysis is performed by means of a sample case, represented and simulated with a dynamic simulation tool (TRNSYS [13]). The study of this commercial building was part of the activities of the GEOTABS project [14]. In this paper first the performance of a conventional TABS control strategy is investigated, then the possible implementation of DSM mechanisms are analyzed by means of sensitivity analysis and multi-objective optimization. As far as the conventional control strategy is concerned, the influence of the supply water temperature on the building performance is evaluated, in order to understand the robustness of the system as it is. Secondly, the TABS behaviour under three different demand side management mechanisms is assessed: (i) a peak shaving strategy (DSM1), (ii) a random request of switching on/off the system (DSM2) and (iii) a night load shifting strategy (DSM3).

2.1 The sample case

The reference building is named Hollandsch Huys, it is located in Belgium. The building total floor area is 4500 m^2 which are currently partially occupied. The building is well insulated (external walls U-value 0.21W/m^2.K) and triple glazing is adopted (U-value of 0.65 W/m^2.K and g-value of 0.5). The building has 4 floors with different schemes of TABS integration with additional HVAC systems. The concrete slabs of Hollandsch Huys, which act as TABS, are built around voids (Figure 1) of 0.24 m height and average 0.20 m side, with distance between the centres of adjacent air boxes of 0.30 m. Pipes have outer diameter of 0.02 m, and are spaced horizontally in two layers, following the layout of voids, i.e. 0.30 m between pipes. A dynamic slat shading system is provided, it is lowered when the total irradiation on the façade exceeds 250 W/m^2, while it is raised again when the irradiation falls below 150 W/m^2. The slat inclination angle depends on the solar altitude. The heating, ventilation and air condition (HVAC) system comprises an air handling unit (AHU) and the production unit (a ground coupled heat pump). The AHU is dedicated to maintain the indoor air quality based on CO_2 level. Heating and cooling of fresh air is done using water provided by the production unit, and a backup boiler is available in case the heat pump heating capacity is not enough. The heat pump has a nominal cooling/heating capacity of 142 kW and 181 kW respectively. The heat pump is connected to the building and to the ground by a number of heat exchangers, storages and pumps. The geothermal system comprises 2 linear bore fields of 14 and 8 U-tube ground heat exchangers (GHX) with a 75 m depth and 5 m spacing in between. The pipes are made of PE 100 and have an external pipe diameter of 0.032 m and a shell thickness of 0.003 m.

The production plant can work in heating mode, active cooling mode or passive cooling mode. In the latter the cold is extracted from the ground through direct heat exchange between the brine and the cold storage tank and the heat pump is switched off. The operative mode is chosen by a control algorithm on the basis of the last 3 days average outdoor temperature: the switch between heating and cooling mode is set at 14°C with a hysteresis of ±1°C. For active cooling to be allowed, the outside air temperature must be higher than 26°C. The TABS supply water temperature set points (Figure 2) depends on the running average outdoor temperature of the six previous hours. Each floor of the building is divided into four control zones. Each of these zones is controlled with a binary two-way valve, that will open for approximately 10 minutes every hour of the day. When, at the end of this period, the temperature difference between the supply and return temperature for that zone is higher than 2°C, the valve is kept open for the rest of the hour, and so on.

The variable air volume (VAV) boxes of the AHU are on/off controlled based on time schedules (on 8:00 – 18:00 hours). The supply air set temperature equals 22°C when the outside air temperature is below 19°C and 20°C when the outside air temperature is above 20°C and is linearly interpolated in between.

A detailed description of the building and its HVAC system is provided elsewhere and is available on the website of the GEOTABS project [15, 16].

2.2 The simulation model

A simulation model for the case study building was realized. The transient simulation of the system was performed by means of TRNSYS [13]. It is a well known simulation environment for dynamic evaluations and it is composed of different models (Types) that represent buildings and plant equipments, including control strategies, occupant behaviour, alternative energy systems (wind, solar, photovoltaic, hydrogen systems), etc.

In Figure 3 a conceptual schematic of the TRNSYS model is shown. A simplified approach was chosen in order to reduce the computation time and only the first floor of the building, divided in 12 zones (Figure 4), was represented. The subdivision in zones was introduced because it is useful for evaluating the influence on thermal comfort of room size and orientation. Considering the purpose of the simulation, aiming at highlighting the TABS behaviour, the HVAC system was not modelled and it was assumed that the supplied water temperature is always as requested by the design curve of Figure 2. The AHU is also modelled in a simplified way using a fixed air change rate. The TABS was simulated by means of the active layer in TRNSYS Type 56. Equivalent properties to represent the real double layer piping by means of the 1D heat transfer model of the simulation tool were assessed (report available on the GEOTABS project website [17]). The main thermophysical properties of the first floor envelope and the technical specifications of the TABS and AHU supply systems are provided in Table 1 and Table 2 respectively. The internal loads considered are composed of occupants, computers and artificial lightings. The occupation rate of the building is assumed equal to 20 m^2 per person with an occupation factor varying during the day (8-9h: 50%; 9-12h: 75%; 12-13h: 40%; 13-17h: 75%; 17-18h: 50%) from Monday to Friday 8:00-18:00. The load of a computer is 140W and the number of computers is the same as occupants. The total heat gain of artificial lighting is 10W/m^2 which includes 40% convective part. Infiltration of peripheral zone is modelled as a constant air flow of 0.5 ACH (air changes per hour). Brussels weather available in TRNSYS is the weather file used in the model. The simulation time step is 2 minutes. It was verified by comparison with results from GEOTABS project [16] that such a simplified model maintains its predictive capabilities.

On the basis of the energy demand for the first floor, the global energy demand for the whole building was extrapolated considering the ratio between the air and water flow rates of the HVAC system for the first floor and for the total building (see Table 2). As performance parameters, the building energy demand (E_{build}), the electricity consumption (E_{el}), the primary energy (E_{pr}) and the overheating and underheating hours were calculated as it follows:

$$E_{build} = E_{TABS} + E_{AHU} \tag{1}$$

$$E_{el} = E_{HP} + E_{fan} + E_{Pumps} \tag{2}$$

$$E_{pr} = \frac{E_{el}}{\eta} + \frac{E_{boiler}}{\varepsilon} \tag{3}$$

The building energy demand (E_{build}) takes into account the energy exchanged by the supply water of the TABS and by the air of the AHU with the building itself. The electricity consumption (E_{el}), instead, is composed of:

- the electricity for the heat pump (E_{HP}) that heats/cools the water for the TABS and for the coil of the AHU, considering an average seasonal COP = 4;
- the electricity for the fans of the AHU (E_{fan}), assessed with performance specifications by the manufacturer (Table 2);
- the electricity of the main pumps of the water distribution system to the TABS and to the AHU (E_{Pumps}), assessed with performance specifications by the manufacturer (Table 2).

The share of this electricity due to the TABS is named $E_{el,\ TABS}$ and accounts for the power demand of the heat pump and of the distribution pump related only to TABS operation.

In order to calculate the primary energy (E_{pr}) a coefficient for the grid production and transmission loss (η= 0.4) and a combustion efficiency for the natural gas fuelling the boiler (ε= 0.95) were considered.

The electricity and natural gas costs were assessed considering Belgian tariffs, that are respectively 0.23€/kWh and 0.058€/kWh taxes included [18].

The overheating hours (h_{over}) are defined as the number of working hours when the indoor temperature is higher than 26°C, while the underheating hours (h_{under}) when the indoor temperature is lower than 19°C. Both the average building temperature and the temperatures in the 12 different zones considered were evaluated.

2.3 DSM mechanisms

As previously mentioned, DSM includes all strategies designed to influence the customer's energy use, focusing on changing the shape of the load and thereby helping to optimize the whole power system from generation to delivery, to end use [10]. Considering that buildings account for 40% of the total energy consumption in the European Union (mainly for space heating and hot water [19]), there are relatively large heating, cooling and hot water demands that can be controlled, adapted and/or enhanced to perform a DSM function. DSM is particularly interesting in the context of smart grids because it is an useful tool for managing the dynamics and reliability of electricity infrastructure and for helping the integration of non-dispatchable renewable energy. DSM strategies mainly involve the implementation of four types of component: (i) energy-efficient end-use devices; (ii) additional equipment, systems and controls to enable load shaping; (iii) standard control systems for turning end-use devices on/off as required; and (iv) communication systems between end-users and external parties [20]. In the considered building an energy efficient device (ground coupled heat pump) and control systems to switch on/off the electrical devices (heat pump and TABS distribution pumps) are present. This paper focuses on DSM strategies implemented to manage the energy consumption of the reference building on the basis of the external request of the grid with the purpose of evaluating the TABS potential for load shifting on demand while maintaining the required level of indoor thermal comfort.

In general, DSM strategies can be aimed at peak clipping, valley filling, load shifting and strategic conservation [21]. Several options can be implemented to make the energy demand follow the energy production, more or less dynamic, among them three different types of

DSM mechanisms were considered in this paper: (i) a peak shaving strategy, (ii) a random request of switching on/off the system and (iii) a night load shifting strategy:

i. The peak shaving strategy is aimed at reducing the energy consumption during peak hours for the electricity demand. It is particularly useful to reduce or preserve the maximum generation capacity of power plants and thus to limit the electricity production cost. In Belgium the peak periods are 11:00-13:00 and 16:00-18:00 [22].
ii. The random request strategy, instead, wants to show what happens when the grid asks for short switching off periods with several repetitions during the working hours of the day. This strategy represents the intermittent behaviour of renewable energies (particularly wind energy) that ask for allocation of variable loads and if integrated in the production mix could cause unbalanced production or shortages periods, so that the utility needs a backup generation facility and storage systems or it can request to the final users to adapt their demand on the basis of energy availability. In the latter case, generally the utility sends different signals to turn on/off those end users devices suitable for such operating conditions [23]. For the case study a switch off time of 15 minutes per hour, randomly positioned, was assumed for the TABS.
iii. The night load shifting strategy allows the TABS to work only at night time, while being off from 8:00 to 20:00 so that to reduce the daytime load and increase the night time one. This helps a more uniform load distribution during the whole day and consequently a more stable power production.

In order to implement demand side management strategies, it is necessary to promote their application and make the consumers aware about the achievable benefits. Among the possible promotion options there is the demand response (DR), defined as changes in the electricity consumption patterns of end consumers to reduce the instantaneous demand in times of high electricity prices by means of a change in the price of electricity or of incentive payments [24]. The purpose of DR is that if the marginal peak load price is higher than the value that a consumer gets out of the services derived from the electricity, he would be willing to modify the demand in exchange of a discounted rate [25]. Typical discounted rates are time-of-use (TOU) tariffs or real-time-pricing (RTP). In the first case the tariff is structured in different fixed bands, charging more when electricity generation is more expensive; in the latter, the electricity payment is minimized in response to the variable real-time prices. In this study, a discounted rate (10% less than the normal price) was used for the electricity consumption encouraged by the demand side management strategies in order to assess the possible economic benefit for the final user.

3. Results and discussion

3.1 Analysis of the existing control strategy

The existing control strategy of the TABS is designed for year-round operation and is based on a supply water temperature curve (Figure 2) depending on the outdoor temperature of the six previous hours (see section 2.1 for the detailed description). The curve follows the guidelines for control of thermally activated building systems available in literature [2]: it is composed of a curve for heating mode and a curve for cooling mode linked in the transition temperature range, thus it works for year-round operation. The curve was determined on the basis of building features and, tested on site within GEOTABS project [14], it produced good results in terms of thermal comfort. This aspect was also demonstrated by the simulation results, reported in Table 3, which show no underheating or overheating problems (considering the building average temperature and the temperatures in the 12 zones of the first floor). The results show that the maximum discomfort hours are lower than 5% of the yearly working hours in winter and summer (the design practice is to keep this value lower than 10% of the yearly working hours, i.e. 250 hours).

Considering our purpose of analysing the effect of superimposing an external control on the TABS operation by means of DSM strategies, it is of paramount importance to have a deep knowledge about the existing control strategy. Thus, in order to understand the influence of the setting of the control parameters, a sensitivity analysis was performed. The variables considered are: the supply water temperature set-points (Tset1, Tset2, Tset3) and the external air temperature set-points (Ta1, Ta2, Ta3, Ta4) of the curve in Figure 2, and the opening duration (t_ctrl) of the two-way valve of the TABS distribution system. The effect of the abovementioned parameters variations on the primary energy consumption and on the overheating/underheating hours was evaluated.

A Monte Carlo technique was adopted, using latin-hypercube sampling to generate a plausible distribution of parameters values. These techniques have been widely used in thermal modelling field for uncertainty and sensitivity analysis (UA/SA) and it has been shown that only marginal improvements in accuracy can be obtained after 60-80 simulations [26]. In particular for all the parameters a normal distribution with a standard deviation of 20% around the mean was considered. The mean and the minimum and maximum values of the variation range for each parameter are specified in Table 4. Mean values are referred to the reference supply water temperature curve (Figure 2).

The sensitivity was quantified by means of the Pearson's correlation coefficient [27], that expresses the relationship between variables with a number between -1 and 1: positive values indicate that if values for one variable increase, values for the other variable also increase, vice-versa for negative values. If there is no correlation or a weak correlation, the correlation coefficient is close to 0. The simulations were performed separately during a typical winter and summer week and for the whole year.

In Figure 5 the results of the sensitivity analysis are reported. It shows the influence of the selected parameters on primary energy, underheating hours evaluated on the building average temperature ($h_{under,avg}$) and on the temperature of the North-facing zone with the highest discomfort value ($h_{under,max}$, zone 7 for this example), overheating hours evaluated on the building average temperature ($h_{over,avg}$) and on the temperature of the South-facing zone with the highest discomfort value ($h_{over,max}$, zone 4 for this example).

In winter (Figure 5a) the first observation is that the opening duration (t_ctrl) of the two-way valve is the only parameter with a sensitivity coefficient greater than 0.5, meaning that there is a fairly strong relation between the variables. The increase in time of the valve opening increases the energy consumption, but reduces comfort problems. All the other parameters have a weaker relationship among themselves. As far as the supply water temperatures, Tset1 and Tset2, are concerned, they have to be properly set in order to avoid underheating problems and their increase asks for more energy to supply to the building so that it is important to find the right trade-off between the opposite needs. In particular increasing Tset2, and/or the correspondent external air temperature set point Ta2, decreases the underheating having a limited effect on the energy demand increase.

In summer (Figure 5b) the same behaviour as in winter for the opening duration (t_ctrl) of the two-way valve towards the energy consumption is observed. Furthermore only the increase of Tset2 temperature set point has a considerably high impact on the decrease of energy consumption to the detriment of the overheating of South-facing zones. All the other parameters have a correlation coefficient lower than 0.5, that reveals a low influence on the considered performance indicators. This means that the supply water temperature curve is well designed for summer operation and slight improvements can be achieved.

The sensitivity analysis referred to the whole year (Figure 5c) confirms the main findings of the previously presented seasonal evaluations:

- decrease the valve opening duration to reduce the energy consumption;
- increase the Tset1 set point to reduce the underheating hours;
- find the right trade off for the Tset2 set point in order to balance underheating and overheating hours, without worsening the energy consumption.

3.2 Analysis of the control strategy within the DSM framework

The building performance under the three DSM mechanisms considered (section 2.3) was evaluated through the performance indicators presented in section 2.2.

The focus of this paper is on the TABS behaviour, for this reason the signal to switch off the distribution system, reducing consequently the energy demand and the energy consumption, has to be addressed only to the TABS. Moreover it is not possible in such commercial building to switch off the AHU without negatively affecting the indoor air quality.

Nevertheless, the analysis is meaningful even if only the TABS are subject to the external requests from the electricity grid since it accounts for about half of the electricity consumption of the whole building, as shown in Figure 6. Figure 7 instead shows how the AHU and TABS contribute to the energy demand of the first floor simulated. The role of the TABS is predominant in satisfying the energy demand (Figure 7a), both in heating and in cooling mode (the latter including also the passive cooling). Nevertheless, the two systems have been designed to work together and eliminating one of them would produce a detriment to the thermal comfort (Figure 7b): without the AHU the maximum overheating hours are 466 h and the maximum underheating hours are 29 h; without the TABS the maximum overheating hours are 770 h and the maximum underheating hours are 1130 h. These values highlight that the AHU helps especially to face the overheating problems during the warmest days of the year.

In Figure 8a the simulation results of the electric power trend referred to a typical winter day is shown for the reference system as it is: the AHU is on during the working hours, while the TABS operate along the whole day, typically for the first 10 minutes of every hour and where necessary also for the rest of the hour. It is possible to notice that the most busy period for the TABS is the first half of the day, while in the second half the system generally does not work because of the positive effect of the thermal mass activated during the previous operation time. In Figure 8b, 8c and 8d the electric loads under the three DSM strategies (DSM1, DSM2 and DSM3 respectively) are shown. Switching on/off periods of the systems are highlighted: the DSM1 strategy does not modify the reference electric load unless during the peak hours, while the DSM2 strategy tends to better distribute the load during day time and the DSM3 strategy during night time. Table 5 shows in detail how the electricity consumption of TABS distributes during different time slots of the day throughout the whole year: these findings are in agreement with the electric power trend represented in Figure 8 and highlight that the more consistent energy shifting is due to DSM3 strategy.

Table 3 summarizes the simulation results: the energy consumption, discomfort hours and energy costs for a year are reported. It shows that superimposing the three DSM strategies to the existing TABS control strategy produces a slight variation of the energy consumption (both energy demand, electric energy and primary energy); the night load shifting mechanism (DSM3) shows the highest energy consumption reduction (7% reduction of the electricity consumption and 6% of the primary energy). As far as the thermal comfort is concerned, it is evident that while the underheating ($h_{under,avg}$, $h_{under,max}$) is always limited and the average overheating ($h_{over,avg}$) is zero, the maximum overheating ($h_{over,max}$) can reach considerably high values, also in the reference case. This first finding highlights the relevance of rooms size and orientation for the thermal comfort. With more detail, while the DSM1 strategy almost does not affect the comfort, the DSM3 strategy worsens the overheating problem and reaches the maximum value of about 250 hours. Instead DSM2 strategy solves the thermal issue in the warmer zones. Thus long switching off periods during the working hours can cause discomfort on the summer time, while short switching off periods affecting the overall load distribution could also improve the thermal comfort. In any case, all the considered strategies keep the discomfort below the design prescription (<10% of the yearly working hours).

These results emphasize the limited influence of the DSM mechanisms superimposed to the existing control strategy of TABS, mainly thanks to the high thermal inertia of such systems, that allows them to use the stored energy when the heating/cooling system is off. The limited influence on the indoor temperature is also related to the presence of the AHU that is not subject to the demand side logic. The main issue of the thermal comfort of the TABS is the overheating during summer, because of the negative influence of internal and external gains in presence of a cooling system with low reaction time to the thermal demand.

The thermal heaviness of a building can be quantified by means of the building's thermal time constant (τ), defined as the ratio of the heat capacity inside the insulation and the thermal conductance of the envelope [28]. For our case study a thermal time constant of about 650 h was assessed (only the first floor was considered in the calculation). It corresponds to a cooling down period of about 40 hours to reduce the temperature of 1.5°C when the modelled building is left in a cold climate without heating (the same as in the model calibration with experimental measures performed in the GEOTABS project [16]), that is a considerably long time. Thus the high thermal time constant confirms that the overall system is only slightly affected by external requests of switching off the heating/cooling system at least in the absence of fast and big gains. In fact in the case of DSM3 strategy, when in summer the system has to stay off during 12 daytime hours, the overheating problem of the South facing zones is worsened. In order to try to solve this issue, it could be convenient to act on the TABS supply water temperature when the DSM3 strategy works. Considering the results of the sensitivity analysis (Figure 5), a possible action is to lower the Tset2 temperature in order to reduce the overheating problem. A simulation with 1°C decrease of the set-point (Tset2=20°C) was performed. The maximum overheating hours were reduced to 100 h (the same as the reference case), while the electricity consumption reduction is 11% and the primary energy reduction is 6% (the auxiliary boiler of the AHU steps in and asks for more natural gas if the heat pump is not working) keeping almost the same energy cost saving (-12%). During a middle season day, instead, when the external temperature is pretty warm (maximum daily temperature around 20°C), the DSM3 strategy could cause light overheating problems as well. In Figure 9 the temperature of the warmer South facing zone is drawn for a week of middle May and it is possible to see that, when the DSM3 strategy is in action, few hours of overheating are present on the midday hours of the central day of the week. In this case the overheating can be easily eliminated by natural ventilation: the simulation results show that a natural ventilation of 0.7 ACH with the same schedule as the AHU, allows to keep the inside temperature under 26°C. The natural ventilation could even substitute the mechanical ventilation in middle season if the same air flow rate is guaranteed throughout the whole day (1.3 ACH), exploiting also the night chilled air, with evident benefits in terms of energy efficiency.

The abovementioned simulation shows how TABS can cope easily with demand side management strategies: slight modifications of the TABS control strategy acting on the supply water temperature allows the system to work under externally imposed conditions keeping unchanged the internal comfort. Unfortunately in terms of energy reduction the advantage is limited because the thermal mass needs to be recharged after switching off periods when the stored energy is used and causes thermal losses. This aspect makes modest the interest for final users in participating to DSM projects, unless proper time-of-use tariffs and/or incentives are introduced. In this case a discounted electricity rate (-10%) was assumed for the DSM programs which results in energy bill savings of about 11% for DSM1 and DSM3 (Table 3). The DSM2 strategy does not consider long switch off periods, therefore the energy cost does not change compared to the reference case.

The analysis is deepened by looking for system configurations that also allow energy consumption reduction. For this purpose the system configuration is optimized using a multi-objective optimization algorithm (MOGA-II [29]) with the following objectives: minimizing energy consumption and minimizing underheating and overheating hours. The same variables as in the sensitivity analysis were considered and a separate optimization for a typical winter week and summer week was run. In Figure 10 the optimum supply water temperature curves are shown: they belong to the Pareto frontier of the optimized values and they correspond to the minimum primary energy consumption when the acceptable level of the discomfort hours was set to 5% of the yearly working hours. In accordance with the findings from the sensitivity analysis, in winter (the heating mode is "on" for ambient temperature <13°C) the temperature set-point Tset1 and Tset2 are higher than the reference case, while in summer (the cooling mode is "on" for ambient temperature >15°C) the temperature set-point Tset2 is lower than the reference case and also Tset3 is generally slightly lower. Instead the opening duration of the two-way valve (t_ctrl) for the optimized controls is close to the reference case value (±2 min). The energy consumption reduction achievable with these configurations is around 20% less than the reference case value. Anyway, considering that the supply water temperature curve is used for a year-round operation, the seasonal optimization does not correspond necessarily with the yearly optimization. This is shown in Figure 11 where the supply water temperature for the reference case is compared with the yearly, winter and summer optimum curves. In the case of the yearly optimum curve the energy consumption reduction drops to 6%.

Concluding, the TABS seem very interesting instruments in the demand side management framework, their control strategy can work properly under external superimposed requests or can be easily adapted to them. No significant energy reductions are expected when DSM mechanisms are applied, but energy costs savings are achievable by introducing discounted tariffs in order to involve final consumers within such programs. From the utility point of view, TABS represent flexible energy demand systems because they allow a significant load control without requesting for particular design specifications on the original systems.

4. Conclusions

The purpose of this paper was to analyze the influence of demand side management control strategies on TABS. Considering a reference case study, first an in-depth analysis of the existing control strategy was performed and afterwards the effect of external superimposed demand side management strategies was evaluated. Three different DSM mechanisms were considered: (i) a peak shaving strategy, (ii) a random request of switching on/off the system and (iii) a night load shifting strategy.

Main conclusions that can be drawn are:

- the TABS control strategy based on a year-round supply water temperature curve depending on the external ambient temperature can cope well with superimposed external requests to manage the energy demand, asking in case only for slight modifications of the water temperature set points.
- While the DSM strategies do not affect the performance of the TABS in terms of thermal comfort, at the same time they do not realize considerable energy consumption reduction. Optimization techniques could be used to draw an optimum supply water temperature curve, but for a year-round operation limited improvements are expected because the activation of the thermal mass asks for more energy and increases thermal losses, as highlighted also in other studies [30].
- Final users could be involved in DSM projects with proper incentives mechanisms or discounted rates aimed at reducing the energy bill, considering that scarce energy consumption reduction is achievable.
- TABS are flexible demand systems and they allow a good load control from the utility point of view.

Acknowledgments

This research was carried out in the framework of the EU project GEOTABS "Towards optimal design and control of geothermal heat pumps combined with thermally activated building systems in offices" (01/02/2011 - 31/01/2013).

References

[1] B. Lehmann, V. Dorer, M. Gwerder, F. Renggli, J. Tödtli, Thermally activated building systems (TABS): Energy efficiency as a function of control strategy, hydronic circuit topology and (cold) generation system, Applied Energy 88 (2011) 180–191.

[2] M. Gwerder, B. Lehmann, J. Todtli, V. Dorer, F. Renggli, Control of thermally-activated building systems (TABS), Applied Energy 85 (2008) 565-581.

[3] A.K. de Wit, C.J. Wisse, Hydronic circuit topologies for thermally activated building systems – design questions and case study, Energy and Buildings 52 (2012) 56–67.

[4] M. Gwerder, J. Tödtli, B. Lehmann, V. Dorer, W. Güntensperger, F. Renggli, Control of thermally activated building systems (TABS) in intermittent operation with pulse width modulation, Applied Energy 86 (2009) 1606–1616.

[5] M. Sourbron, R. De Herdt, T. Van Reet, W. Van Passel, M. Baelmans, L. Helsen, Efficiently produced heat and cold is squandered by inappropriate control strategies: A case study, Energy and Buildings 41 (2009) 1091–1098.

[6] D. Saelens, W. Parys, R. Baetens, Energy and comfort performance of thermally activated building systems including occupant behavior, Building and Environment 46 (2011) 835-848.

[7] J. Kolarik, J. Toftum, B.W. Olesen, K.L. Jensen, Simulation of energy use, human thermal comfort and office work performance in buildings with moderately drifting operative temperatures, Energy and Buildings 43 (2011) 2988–2997.

[8] M. Sourbron, C. Verhelst, L. Helsen, Building models for model predictive control of office buildings with concrete core activation, Journal of Building Performance Simulation 6 (2013) 175-198.

[9] C.D. Corbin, G.P. Henze, P. May-Ostendorp, A model predictive control optimization environment for real-time commercial building application, Journal of Building Performance Simulation 6 (2013) 159-174

[10] A. Faruqui, Chamberlin J.H., Principles and practice of demand-side management, EPRI, Palo Alto, 1992.

[11] H. Chao, Price-Responsive Demand Management for a Smart Grid World, The Electricity Journal 23 (2010) 7-20.

[12] A. Arteconi, N.J. Hewitt, F. Polonara, State of the art of thermal storage for demand-side management, Applied Energy 93 (2012) 371-389.

[13] S.A. Klein et al, TRNSYS manual, University of Wisconsin-Madison, 2009.

[14] GEOTABS 2011, "Towards optimal design and control of geothermal heat pumps combined with thermally activated building systems in offices", www.geotabs.eu (last access 20/11/2013)

[15] Hollandsch Huys sample case, http://www.geotabs.eu/Database/Buildingflyer_HollandschHuys_120921.pdf

[16] A. Dentel, M. Franz, WP 5: Model Simulation, 2013, http://www.geotabs.eu/Publication/wp5/system_perfo/view(last access 20/11/2013)

[17] W. Paris, WP 5: Model Simulations, Deliverable 5.2. Reference building model (test case), http://www.geotabs.eu/Publication/wp5/1_D/view (last access 20/11/2013)

[18] Europe's energy portal www.energy.eu (last access 20/11/2013)

[19] European Parliament, EU Directive on the Energy Performance of Buildings (recast) (2010/31/EU), 19 May 2010.

[20] C. W. Gellings, The smart grid. Enabling energy efficiency and demand response. The Fairmont Press, 2009.

[21] C.W. Gellings, W.M. Smith, Integrating Demand-Side Management into Utility Planning, Proceedings of the IEEE, vol. 77, No. 6, June 1989.

[22] www.belpex.be (last access 20/11/2013)

[23] C. Cecati, C. Citro, P. Siano, Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid, IEEE Transaction on Sustainable Energy, Vol. 2, n. 4,

2011.

[24] J. M. Lujano-Rojas, C. Monteiro, R. Dufo-López, J.L. Bernal-Agustín, Optimum residential load management strategy for real time pricing (RTP) demand response programs, Energy Policy, 45 (2012) 671-679.

[25] P.S. Moura, A.T. de Almeida, The role of demand side management in the grid integration of wind power, Applied Energy 87 (2010) 2581-2588.

[26] K. J. Lomas, H. Eppel, Sensitivity Analysis Techniques for Building Thermal Simulation Programs, Energy and Buildings, 19 (1992) 21-44.

[27] J. L. Rodgers, W. A. Nicewander, Thirteen ways to look at the correlation coefficient. The American Statistician, vol. 42, February 1988, pp.59–66.

[28] J. Karlsson, L. Wadsö, M. Öberg, A conceptual model that simulates the influence of thermal inertia in building structures, Energy and Buildings 60 (2013) 146–151.

[29] S. Poles, MOGA-II An improved Multi-Objective Genetic Algorithm, Technical Report, Esteco 2003.

[30] G. Reynders, T. Nuytten, D. Saelens, Potential of structural thermal mass for demand-side management in dwellings, Building and Environment 64 (2013) 187-199.

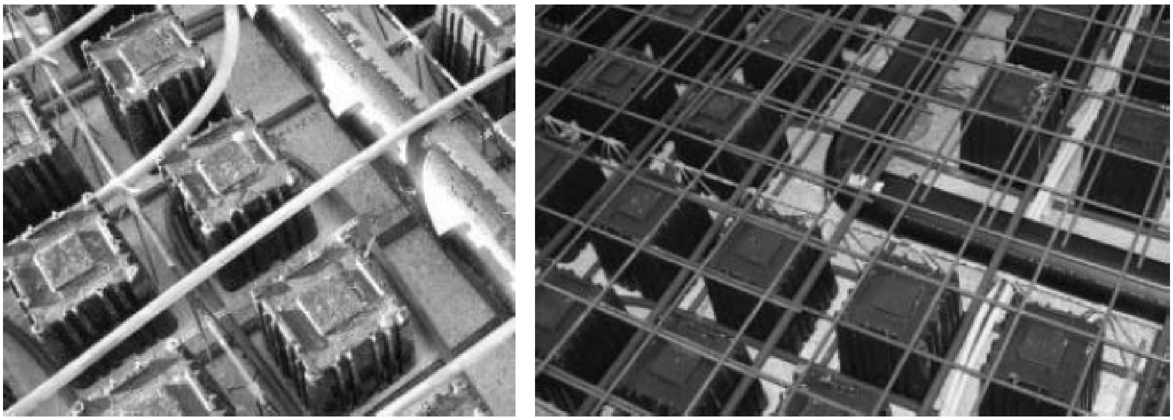


Figure 1. Representation of TABS used in the reference building (Airdeck).

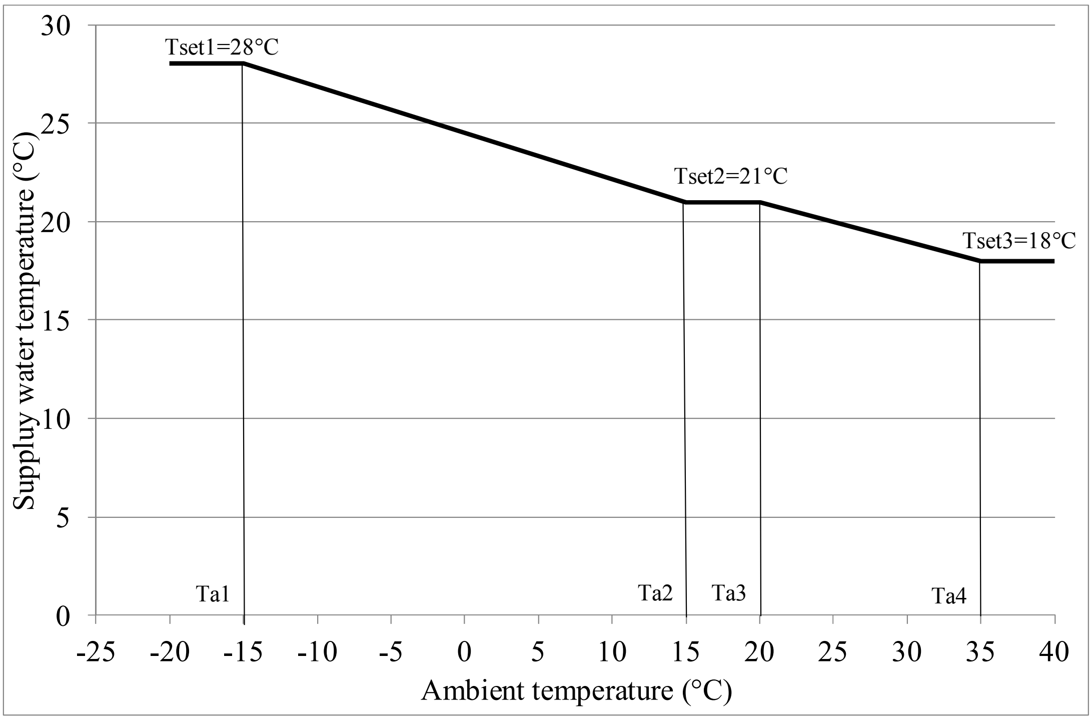


Figure 2. Supply water temperature curve.

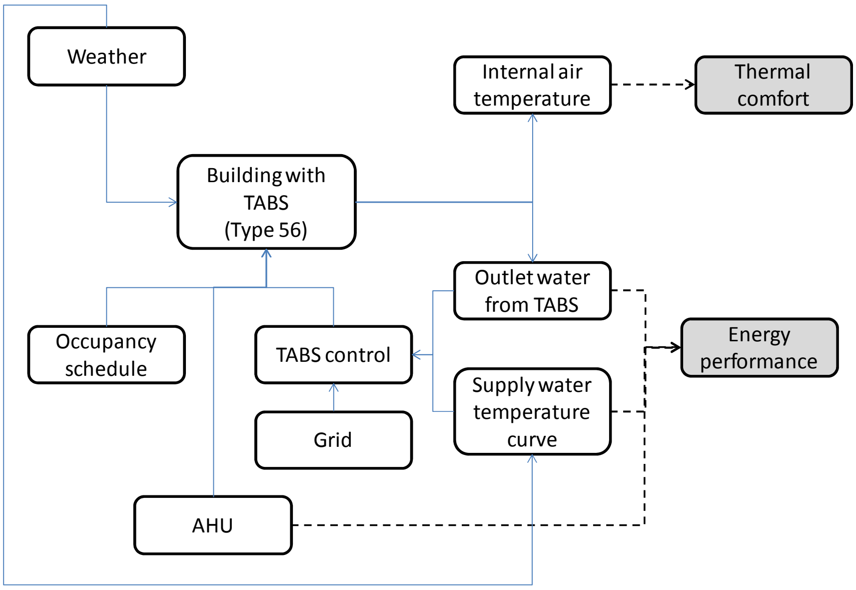


Figure 3. Conceptual schematic of the TRNSYS model.

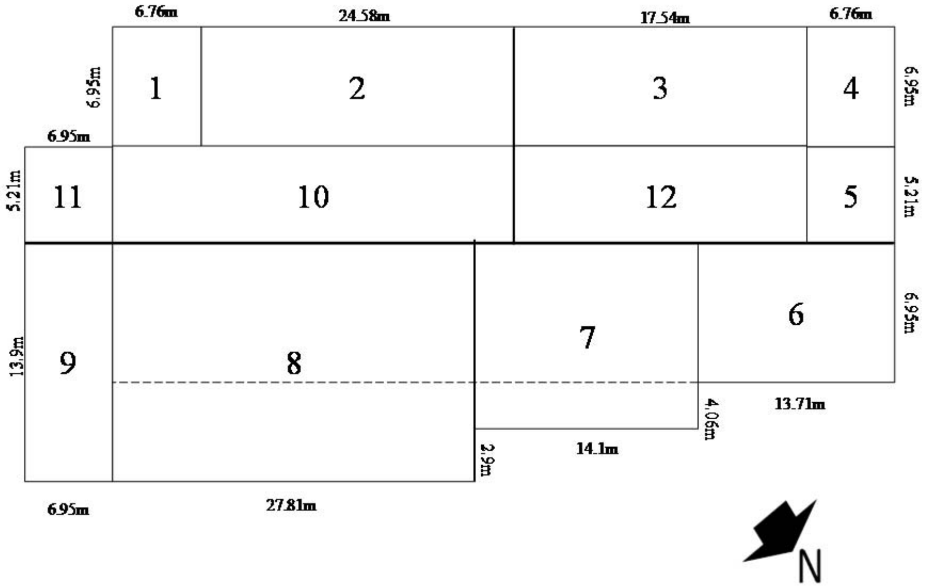
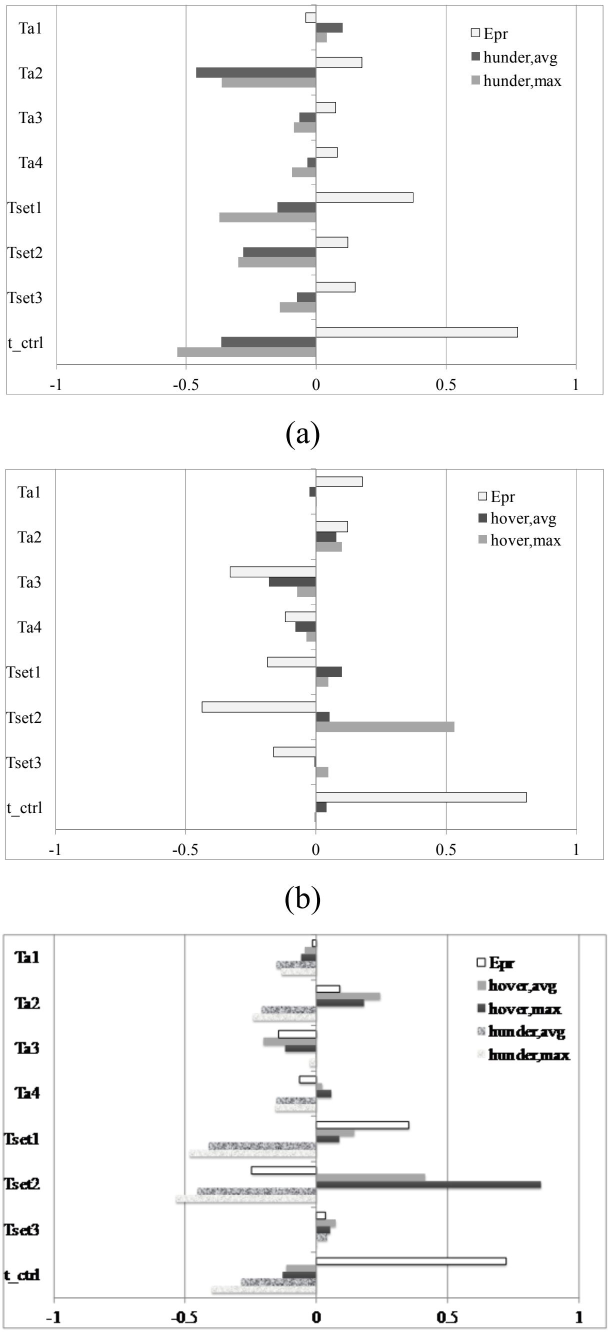


Figure 4. Layout of the first floor and subdivision in zones.



(a)

(b)

(c)

Figure 5. Sensitivity analysis results for a typical winter week (a), summer week (b) and year-round operation (c): correlation among the selected parameters (y-axis) and the primary energy consumption (E_{pr}), average overheating hours ($h_{over,avg}$), maximum overheating hours ($h_{over,max}$), average underheating hours ($h_{under,avg}$), maximum underheating hours ($h_{under,max}$).

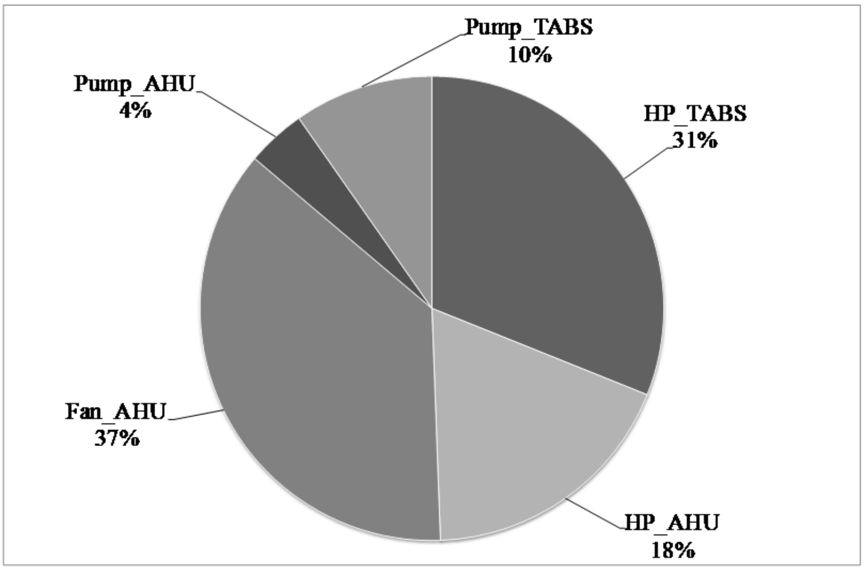
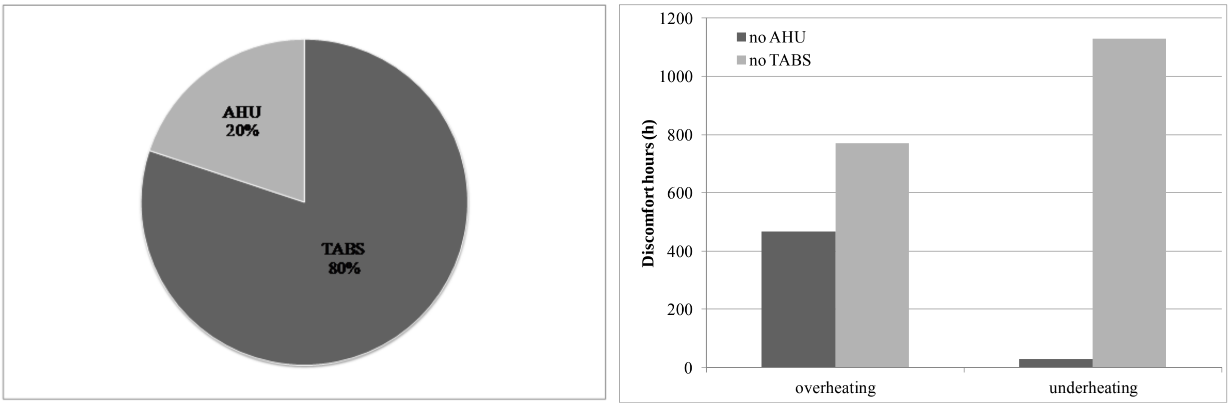


Figure 6. Electric energy consumption breakdown for the reference building.



(a) (b)

Figure 7. TABS and AHU contribution to the energy demand of the first floor (a) and discomfort hours caused by keeping off separately the two systems all the year round (b).

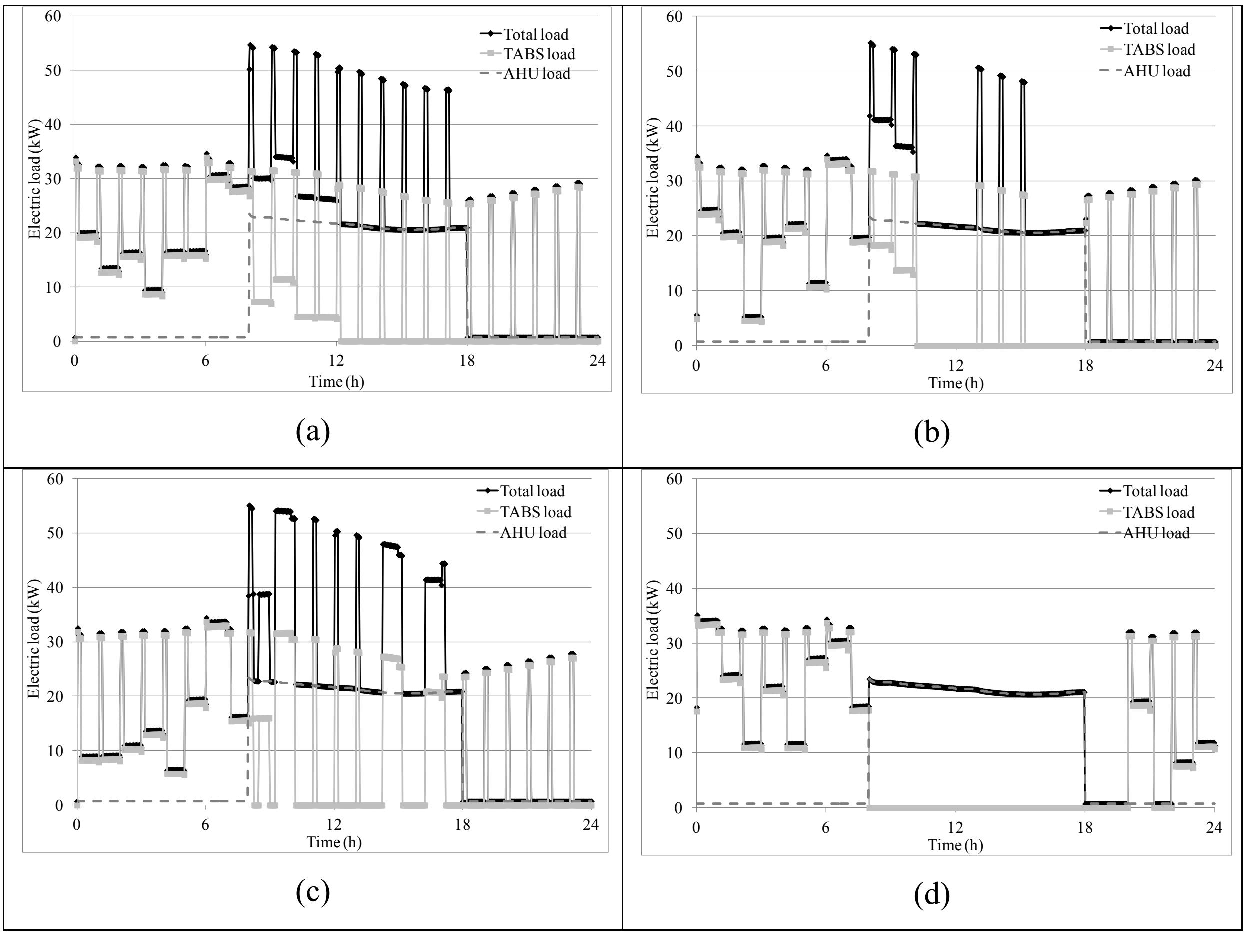


Figure 8. Electric load during a typical winter day for the reference system (a) and under the different DSM strategies implemented: peak shaving strategy DSM1 (b), random strategy DSM2 (c) and night load shifting strategy DSM3 (d).

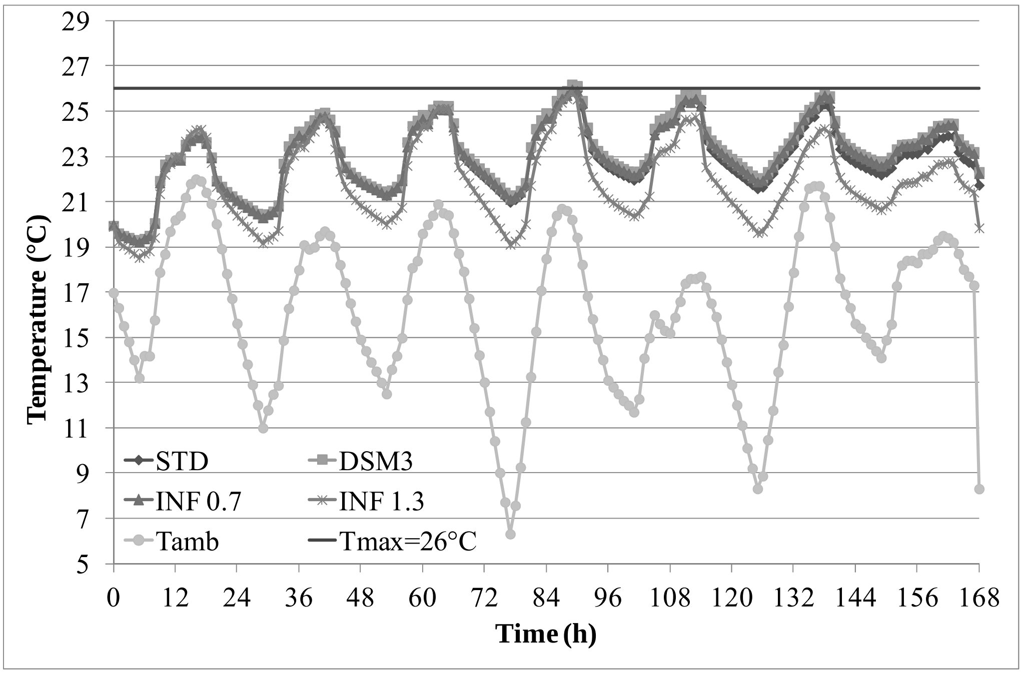
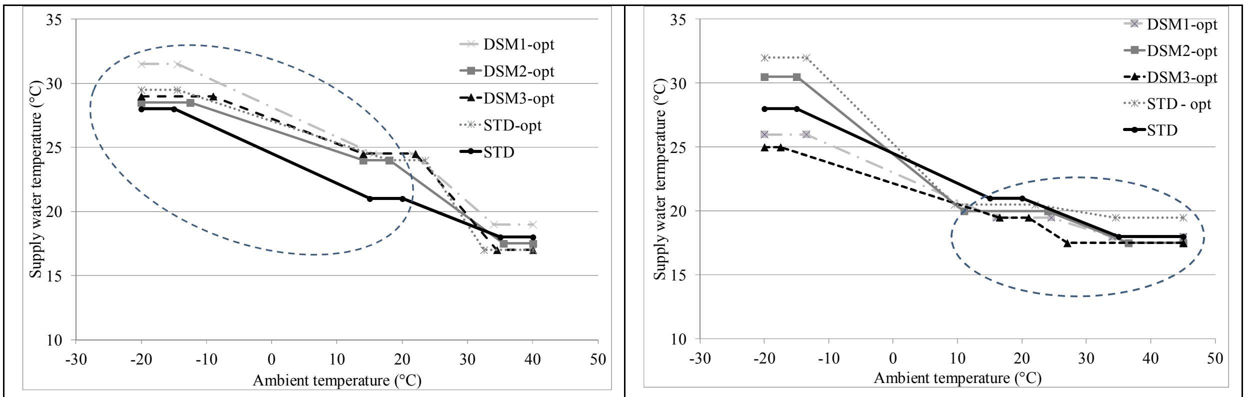


Figure 9. Temperature of the warmer South facing zone during a week in middle May for the reference case (STD); for the case with the DSM3 strategy in action (DSM3); for the case with the DSM3 strategy in action having a natural ventilation of 0.7 ACH with the same schedule as the AHU (INF 0.7); for the case with the DSM3 strategy in action having a natural ventilation of 1.3 ACH throughout the whole day (INF 1.3) that substitutes the AHU. Tmax=26°C represents the temperature limit for overheating.



(a) (b)

Figure 10. Comparison of the supply water temperature curve for the reference case (STD) with the optimum curves for the reference case (STD-opt) and for the demand side management strategies in action (DSM1-opt, DSM2-opt, DSM3-opt) in winter (a) and summer (b). The dotted circle highlights that part of the curve of interest in the heating (<13°C) or cooling mode (>15°C).

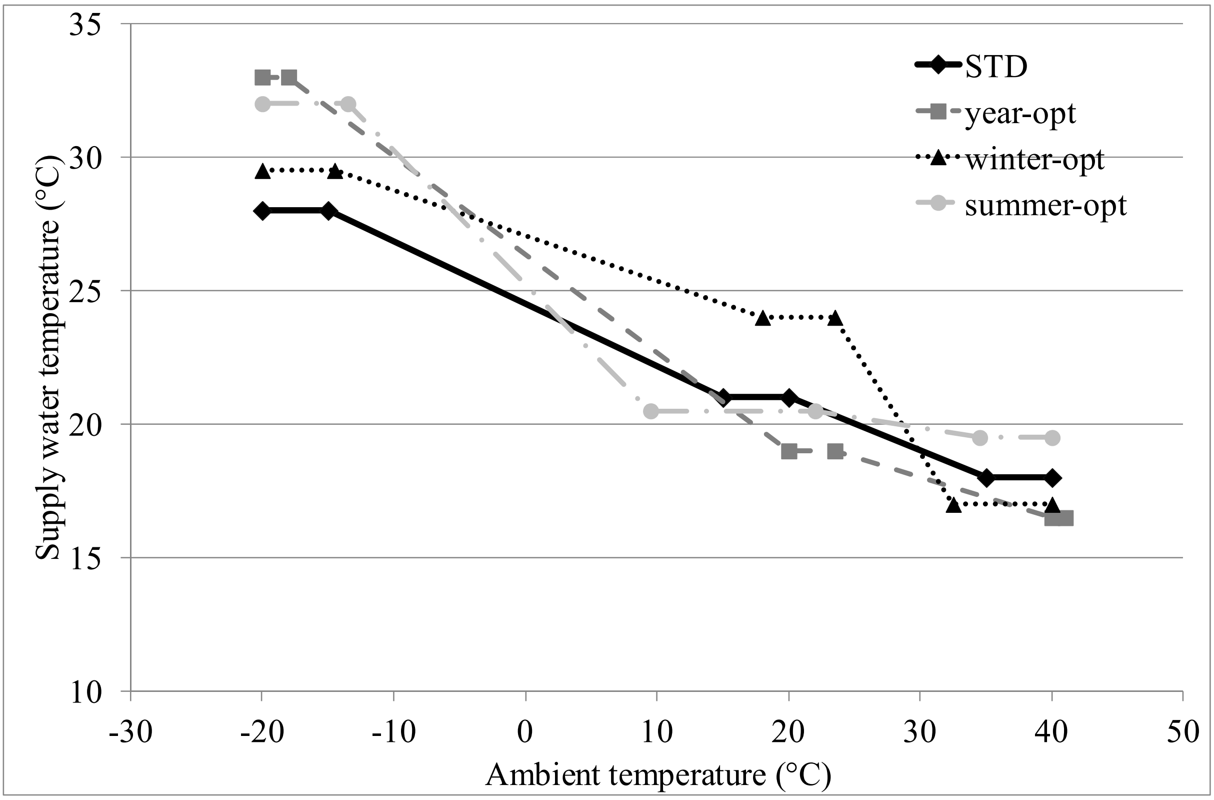


Figure 11. Supply water temperature curve for the reference case and yearly, winter and summer optimum curve.

Table captions

Table 1 – Thermophysical properties of the building envelope of the first floor simulated.

Table 2 – Technical specifications of the TABS and AHU supply systems.

Table 3 – Performance in terms of energy consumption, discomfort hours and energy costs for the reference case (STD) and with the three DSM strategies in action.

Table 4. Mean and minimum and maximum values of the variation range of the sensitivity analysis parameters.

Table 5 – Distribution of the electricity consumption of the TABS during different time slots of the day (expressed as percentage of the yearly electricity consumption of the TABS).

Table 1 – Thermophysical properties of the building envelope of the first floor simulated.

Wall	**Material**	**Thermal conductivity [W/m K]**	**Thickness [m]**
External walls	external bricks	1.35	0.115
	air cavity	0.36	0.650
	wood fibre board	0.06	0.018
	cellulose thermal insulation/wood frame	0.05	0.184
	OSB	0.13	0.012
	air cavity	0.28	0.050
	gypsum board	1.25	0.013
Wall between zones	plaster board	1.25	0.013
First floor- concrete slab	Airdeck concrete floor	Ref [17]	0.350
	XPS acoustical insulation	0.03	0.050
	finishing layer	1.00	0.080
	carpet	0.06	0.005
Windows	**g**	**U [W/m^2 K]**	**Area (m^2)**
	0.81	0.65	178.02

Table 2 – Technical specifications of the TABS and AHU supply systems.

TABS		
supply water flow rate - 1st floor	l/h	35'400
supply water flow rate - total building	l/h	47'800
pump nominal power	kW	3.78
AHU		
air flow rate – 1st floor	m^3/h	5'615
air flow rate - total building	m^3/h	14'670
supply water flow rate	l/h	26'400
pump nominal power	kW	1.09
Fan (exhaust + supply fans nominal power)	kW	26

Table 3 – Performance in terms of energy consumption, discomfort hours and energy costs for the reference case (STD) and with the three DSM strategies in action.

		STD	DSM1		DSM2		DSM3	
				var%		var%		var%
E_{build}	kWh	215,535	211,740	-2%	217,285	1%	200,848	-7%
E_{el}	kWh	69,185	68,013	-2%	69,575	1%	64,355	-7%
$E_{el,TABS}$	kWh	28,225	27,025	-4%	28,639	1%	23,225	-18%
E_{pr}	kWh	187,240	184,326	-2%	188,196	1%	175,295	-6%
$h_{over,avg}$	h	0	0		0		0	
$h_{over,max}$	h	100	135	+35%	61	-39%	254	+154%
$h_{under,avg}$	h	1	1		1		2	
$h_{under,max}$	h	10	11	+11%	9	-10%	17	+73%
Total energy cost	€	16,702	14,829	-11%	16,263	-3%	14,807	-11%

Table 4. Mean and minimum and maximum values of the variation range of the sensitivity analysis parameters.

	Tset1	Tset2	Tset3	Ta1	Ta2	Ta3	Ta4	t_ctrl
	°C	°C	°C	°C	°C	°C	°C	min
mean value	28	21	18	-15	15	20	35	10
variation range	25÷30	18÷25	16÷20	-18÷0	-17÷20	15÷25	25÷40	1÷59

Table 5 – Distribution of the electricity consumption of the TABS during different time slots of the day (expressed as percentage of the yearly electricity consumption of the TABS).

Time slot	h	0-8	8-11	11-13	13-16	16-18	18-20	20-24
STD	%	42	19	7	8	6	6	12
DSM1	%	47	20	0	11	0	9	13
DSM2	%	40	20	7	10	7	5	11
DSM3	%	72	0	0	0	0	0	28