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

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### **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.

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## 1 **1. Introduction**

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

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

26 Generally these systems are operated continuously with a constant flow rate, but also

1 intermittent operation has been evaluated. Gwerder et al. [4] showed that with a pulse width  
2 modulation control (PWM), which operates the TABS zone pump in an intermittent way,  
3 energy savings are obtained and operation periods of the plant can be shifted to times with  
4 high energy generation efficiency. Due to the large thermal inertia of TABS, instant  
5 correction of the room temperature cannot be achieved, however day-to-day room  
6 temperature compensation is promising [4]. Furthermore, Sourbron et al. [5] demonstrated  
7 that room temperature feedback control strategies can be inadequate for TABS because they  
8 cause frequent switching between heating and cooling with a dramatic impact on the energy  
9 performance. De Wit and Wisse [3] stated that the operating mode can be controlled by the  
10 room air temperature if a dead band is applied between the air temperature set point for the  
11 heating mode and the air temperature set point for the cooling mode, so that the system is  
12 more stable. It is possible to control different rooms with different comfort requirements by  
13 dividing the building into several zones with similar features and control each zone  
14 separately. Not only the division in zones, but also the hydraulic circuit topology has a  
15 paramount importance on the operating conditions and energy demand of TABS [1, 3].  
16 In order to determine the water supply temperature the UBB (Unknown-But-Bounded)  
17 approach has been proposed by Gwerder et al. [2]. It takes into account the dynamic  
18 behaviour of the system and the influence of internal and external gains on the heating and  
19 cooling loads. Such gains have an important role for the achievement of the required indoor  
20 thermal comfort, as demonstrated by Saelens et al. [6], who analyzed the energy and comfort  
21 performance of TABS under different occupant behaviour. Kolarik et al. [7] showed that the  
22 application of the TABS decreases the primary energy use in comparison with traditional  
23 systems without a significant decrement of occupants' performance. Moreover another recent  
24 topic of research about TABS concerns the positive role of model predictive control to  
25 increase their energy efficiency [8, 9].  
26 The purpose of this paper is to examine in depth TABS control strategies and their potential

1 for load shifting on demand. In particular the aim is to analyze, by means of a sample case,  
2 the influence of demand side management (DSM) mechanisms on the performance of a  
3 thermally activated commercial building.

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

16

## 17 **2. Methods**

18 The analysis is performed by means of a sample case, represented and simulated with a  
19 dynamic simulation tool (TRNSYS [13]). The study of this commercial building was part of  
20 the activities of the GEOTABS project [14]. In this paper first the performance of a  
21 conventional TABS control strategy is investigated, then the possible implementation of DSM  
22 mechanisms are analyzed by means of sensitivity analysis and multi-objective optimization.

23 As far as the conventional control strategy is concerned, the influence of the supply water  
24 temperature on the building performance is evaluated, in order to understand the robustness of  
25 the system as it is. Secondly, the TABS behaviour under three different demand side  
26 management mechanisms is assessed: (i) a peak shaving strategy (DSM1), (ii) a random

1 request of switching on/off the system (DSM2) and (iii) a night load shifting strategy  
2 (DSM3).

3

#### 4 **2.1 The sample case**

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

1 The production plant can work in heating mode, active cooling mode or passive cooling  
2 mode. In the latter the cold is extracted from the ground through direct heat exchange between  
3 the brine and the cold storage tank and the heat pump is switched off. The operative mode is  
4 chosen by a control algorithm on the basis of the last 3 days average outdoor temperature: the  
5 switch between heating and cooling mode is set at 14°C with a hysteresis of  $\pm 1^\circ\text{C}$ . For active  
6 cooling to be allowed, the outside air temperature must be higher than 26°C. The TABS  
7 supply water temperature set points (Figure 2) depends on the running average outdoor  
8 temperature of the six previous hours. Each floor of the building is divided into four control  
9 zones. Each of these zones is controlled with a binary two-way valve, that will open for  
10 approximately 10 minutes every hour of the day. When, at the end of this period, the  
11 temperature difference between the supply and return temperature for that zone is higher than  
12 2°C, the valve is kept open for the rest of the hour, and so on.

13 The variable air volume (VAV) boxes of the AHU are on/off controlled based on time  
14 schedules (on 8:00 – 18:00 hours). The supply air set temperature equals 22°C when the  
15 outside air temperature is below 19°C and 20°C when the outside air temperature is above  
16 20°C and is linearly interpolated in between.

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

19

## 20 **2.2 The simulation model**

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

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



1 energy ( $E_{pr}$ ) and the overheating and underheating hours were calculated as it follows:

2

$$3 \quad E_{build} = E_{TABS} + E_{AHU} \quad (1)$$

$$4 \quad E_{el} = E_{HP} + E_{fan} + E_{Pumps} \quad (2)$$

$$5 \quad E_{pr} = \frac{E_{el}}{\eta} + \frac{E_{boiler}}{\varepsilon} \quad (3)$$

6

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

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

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

19 In order to calculate the primary energy ( $E_{pr}$ ) a coefficient for the grid production and  
20 transmission loss ( $\eta= 0.4$ ) and a combustion efficiency for the natural gas fuelling the boiler  
21 ( $\varepsilon= 0.95$ ) were considered.

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

24 The overheating hours ( $h_{over}$ ) are defined as the number of working hours when the indoor  
25 temperature is higher than 26°C, while the underheating hours ( $h_{under}$ ) when the indoor

1 temperature is lower than 19°C. Both the average building temperature and the temperatures  
2 in the 12 different zones considered were evaluated.

3

### 4 **2.3 DSM mechanisms**

5 As previously mentioned, DSM includes all strategies designed to influence the customer's  
6 energy use, focusing on changing the shape of the load and thereby helping to optimize the  
7 whole power system from generation to delivery, to end use [10]. Considering that buildings  
8 account for 40% of the total energy consumption in the European Union (mainly for space  
9 heating and hot water [19]), there are relatively large heating, cooling and hot water demands  
10 that can be controlled, adapted and/or enhanced to perform a DSM function. DSM is  
11 particularly interesting in the context of smart grids because it is an useful tool for managing  
12 the dynamics and reliability of electricity infrastructure and for helping the integration of non-  
13 dispatchable renewable energy. DSM strategies mainly involve the implementation of four  
14 types of component: (i) energy-efficient end-use devices; (ii) additional equipment, systems  
15 and controls to enable load shaping; (iii) standard control systems for turning end-use devices  
16 on/off as required; and (iv) communication systems between end-users and external parties  
17 [20]. In the considered building an energy efficient device (ground coupled heat pump) and  
18 control systems to switch on/off the electrical devices (heat pump and TABS distribution  
19 pumps) are present. This paper focuses on DSM strategies implemented to manage the energy  
20 consumption of the reference building on the basis of the external request of the grid with the  
21 purpose of evaluating the TABS potential for load shifting on demand while maintaining the  
22 required level of indoor thermal comfort.

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

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

3 i. The peak shaving strategy is aimed at reducing the energy consumption during peak  
4 hours for the electricity demand. It is particularly useful to reduce or preserve the  
5 maximum generation capacity of power plants and thus to limit the electricity  
6 production cost. In Belgium the peak periods are 11:00-13:00 and 16:00-18:00 [22].

7 ii. The random request strategy, instead, wants to show what happens when the grid asks  
8 for short switching off periods with several repetitions during the working hours of the  
9 day. This strategy represents the intermittent behaviour of renewable energies  
10 (particularly wind energy) that ask for allocation of variable loads and if integrated in  
11 the production mix could cause unbalanced production or shortages periods, so that  
12 the utility needs a backup generation facility and storage systems or it can request to  
13 the final users to adapt their demand on the basis of energy availability. In the latter  
14 case, generally the utility sends different signals to turn on/off those end users devices  
15 suitable for such operating conditions [23]. For the case study a switch off time of 15  
16 minutes per hour, randomly positioned, was assumed for the TABS.

17 iii. The night load shifting strategy allows the TABS to work only at night time, while  
18 being off from 8:00 to 20:00 so that to reduce the daytime load and increase the night  
19 time one. This helps a more uniform load distribution during the whole day and  
20 consequently a more stable power production.

21 In order to implement demand side management strategies, it is necessary to promote their  
22 application and make the consumers aware about the achievable benefits. Among the possible  
23 promotion options there is the demand response (DR), defined as changes in the electricity  
24 consumption patterns of end consumers to reduce the instantaneous demand in times of high  
25 electricity prices by means of a change in the price of electricity or of incentive payments  
26 [24]. The purpose of DR is that if the marginal peak load price is higher than the value that a

1 consumer gets out of the services derived from the electricity, he would be willing to modify  
2 the demand in exchange of a discounted rate [25]. Typical discounted rates are time-of-use  
3 (TOU) tariffs or real-time-pricing (RTP). In the first case the tariff is structured in different  
4 fixed bands, charging more when electricity generation is more expensive; in the latter, the  
5 electricity payment is minimized in response to the variable real-time prices. In this study, a  
6 discounted rate (10% less than the normal price) was used for the electricity consumption  
7 encouraged by the demand side management strategies in order to assess the possible  
8 economic benefit for the final user.

9

### 10 **3. Results and discussion**

#### 11 **3.1 Analysis of the existing control strategy**

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

25 Considering our purpose of analysing the effect of superimposing an external control on the  
26 TABS operation by means of DSM strategies, it is of paramount importance to have a deep

1 knowledge about the existing control strategy. Thus, in order to understand the influence of  
2 the setting of the control parameters, a sensitivity analysis was performed. The variables  
3 considered are: the supply water temperature set-points ( $T_{set1}$ ,  $T_{set2}$ ,  $T_{set3}$ ) and the external  
4 air temperature set-points ( $T_{a1}$ ,  $T_{a2}$ ,  $T_{a3}$ ,  $T_{a4}$ ) of the curve in Figure 2, and the opening  
5 duration ( $t_{ctrl}$ ) of the two-way valve of the TABS distribution system. The effect of the  
6 abovementioned parameters variations on the primary energy consumption and on the  
7 overheating/underheating hours was evaluated.

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

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

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

1 the highest discomfort value ( $h_{\text{over,max}}$ , zone 4 for this example).

2 In winter (Figure 5a) the first observation is that the opening duration ( $t_{\text{ctrl}}$ ) of the two-way  
3 valve is the only parameter with a sensitivity coefficient greater than 0.5, meaning that there  
4 is a fairly strong relation between the variables. The increase in time of the valve opening  
5 increases the energy consumption, but reduces comfort problems. All the other parameters  
6 have a weaker relationship among themselves. As far as the supply water temperatures,  $T_{\text{set1}}$   
7 and  $T_{\text{set2}}$ , are concerned, they have to be properly set in order to avoid underheating  
8 problems and their increase asks for more energy to supply to the building so that it is  
9 important to find the right trade-off between the opposite needs. In particular increasing  
10  $T_{\text{set2}}$ , and/or the correspondent external air temperature set point  $T_{\text{a2}}$ , decreases the  
11 underheating having a limited effect on the energy demand increase.

12 In summer (Figure 5b) the same behaviour as in winter for the opening duration ( $t_{\text{ctrl}}$ ) of the  
13 two-way valve towards the energy consumption is observed. Furthermore only the increase of  
14  $T_{\text{set2}}$  temperature set point has a considerably high impact on the decrease of energy  
15 consumption to the detriment of the overheating of South-facing zones. All the other  
16 parameters have a correlation coefficient lower than 0.5, that reveals a low influence on the  
17 considered performance indicators. This means that the supply water temperature curve is  
18 well designed for summer operation and slight improvements can be achieved.

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

- 21 • decrease the valve opening duration to reduce the energy consumption;
- 22 • increase the  $T_{\text{set1}}$  set point to reduce the underheating hours;
- 23 • find the right trade off for the  $T_{\text{set2}}$  set point in order to balance underheating and  
24 overheating hours, without worsening the energy consumption.

25

### 1 **3.2 Analysis of the control strategy within the DSM framework**

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

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

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

20 In Figure 8a the simulation results of the electric power trend referred to a typical winter day  
21 is shown for the reference system as it is: the AHU is on during the working hours, while the  
22 TABS operate along the whole day, typically for the first 10 minutes of every hour and where  
23 necessary also for the rest of the hour. It is possible to notice that the most busy period for the  
24 TABS is the first half of the day, while in the second half the system generally does not work  
25 because of the positive effect of the thermal mass activated during the previous operation  
26 time. In Figure 8b, 8c and 8d the electric loads under the three DSM strategies (DSM1, DSM2

1 and DSM3 respectively) are shown. Switching on/off periods of the systems are highlighted:  
2 the DSM1 strategy does not modify the reference electric load unless during the peak hours,  
3 while the DSM2 strategy tends to better distribute the load during day time and the DSM3  
4 strategy during night time. Table 5 shows in detail how the electricity consumption of TABS  
5 distributes during different time slots of the day throughout the whole year: these findings are  
6 in agreement with the electric power trend represented in Figure 8 and highlight that the more  
7 consistent energy shifting is due to DSM3 strategy.

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

24 These results emphasize the limited influence of the DSM mechanisms superimposed to the  
25 existing control strategy of TABS, mainly thanks to the high thermal inertia of such systems,  
26 that allows them to use the stored energy when the heating/cooling system is off. The limited



1 influence on the indoor temperature is also related to the presence of the AHU that is not  
2 subject to the demand side logic. The main issue of the thermal comfort of the TABS is the  
3 overheating during summer, because of the negative influence of internal and external gains  
4 in presence of a cooling system with low reaction time to the thermal demand.

5 The thermal heaviness of a building can be quantified by means of the building's thermal time  
6 constant ( $\tau$ ), defined as the ratio of the heat capacity inside the insulation and the thermal  
7 conductance of the envelope [28]. For our case study a thermal time constant of about 650 h  
8 was assessed (only the first floor was considered in the calculation). It corresponds to a  
9 cooling down period of about 40 hours to reduce the temperature of 1.5°C when the modelled  
10 building is left in a cold climate without heating (the same as in the model calibration with  
11 experimental measures performed in the GEOTABS project [16]), that is a considerably long  
12 time. Thus the high thermal time constant confirms that the overall system is only slightly  
13 affected by external requests of switching off the heating/cooling system at least in the  
14 absence of fast and big gains. In fact in the case of DSM3 strategy, when in summer the  
15 system has to stay off during 12 daytime hours, the overheating problem of the South facing  
16 zones is worsened. In order to try to solve this issue, it could be convenient to act on the  
17 TABS supply water temperature when the DSM3 strategy works. Considering the results of  
18 the sensitivity analysis (Figure 5), a possible action is to lower the Tset2 temperature in order  
19 to reduce the overheating problem. A simulation with 1°C decrease of the set-point  
20 ( $T_{set2}=20^{\circ}\text{C}$ ) was performed. The maximum overheating hours were reduced to 100 h (the  
21 same as the reference case), while the electricity consumption reduction is 11% and the  
22 primary energy reduction is 6% (the auxiliary boiler of the AHU steps in and asks for more  
23 natural gas if the heat pump is not working) keeping almost the same energy cost saving (-  
24 12%). During a middle season day, instead, when the external temperature is pretty warm  
25 (maximum daily temperature around 20°C), the DSM3 strategy could cause light overheating  
26 problems as well. In Figure 9 the temperature of the warmer South facing zone is drawn for a

1 week of middle May and it is possible to see that, when the DSM3 strategy is in action, few  
2 hours of overheating are present on the midday hours of the central day of the week. In this  
3 case the overheating can be easily eliminated by natural ventilation: the simulation results  
4 show that a natural ventilation of 0.7 ACH with the same schedule as the AHU, allows to  
5 keep the inside temperature under 26°C. The natural ventilation could even substitute the  
6 mechanical ventilation in middle season if the same air flow rate is guaranteed throughout the  
7 whole day (1.3 ACH), exploiting also the night chilled air, with evident benefits in terms of  
8 energy efficiency.

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

20 The analysis is deepened by looking for system configurations that also allow energy  
21 consumption reduction. For this purpose the system configuration is optimized using a multi-  
22 objective optimization algorithm (MOGA-II [29]) with the following objectives: minimizing  
23 energy consumption and minimizing underheating and overheating hours. The same variables  
24 as in the sensitivity analysis were considered and a separate optimization for a typical winter  
25 week and summer week was run. In Figure 10 the optimum supply water temperature curves  
26 are shown: they belong to the Pareto frontier of the optimized values and they correspond to

1 the minimum primary energy consumption when the acceptable level of the discomfort hours  
2 was set to 5% of the yearly working hours. In accordance with the findings from the  
3 sensitivity analysis, in winter (the heating mode is "on" for ambient temperature  $<13^{\circ}\text{C}$ ) the  
4 temperature set-point  $T_{\text{set1}}$  and  $T_{\text{set2}}$  are higher than the reference case, while in summer  
5 (the cooling mode is "on" for ambient temperature  $>15^{\circ}\text{C}$ ) the temperature set-point  $T_{\text{set2}}$  is  
6 lower than the reference case and also  $T_{\text{set3}}$  is generally slightly lower. Instead the opening  
7 duration of the two-way valve ( $t_{\text{ctrl}}$ ) for the optimized controls is close to the reference case  
8 value ( $\pm 2$  min). The energy consumption reduction achievable with these configurations is  
9 around 20% less than the reference case value. Anyway, considering that the supply water  
10 temperature curve is used for a year-round operation, the seasonal optimization does not  
11 correspond necessarily with the yearly optimization. This is shown in Figure 11 where the  
12 supply water temperature for the reference case is compared with the yearly, winter and  
13 summer optimum curves. In the case of the yearly optimum curve the energy consumption  
14 reduction drops to 6%.

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

22

#### 23 **4. Conclusions**

24 The purpose of this paper was to analyze the influence of demand side management control  
25 strategies on TABS. Considering a reference case study, first an in-depth analysis of the  
26 existing control strategy was performed and afterwards the effect of external superimposed

1 demand side management strategies was evaluated. Three different DSM mechanisms were  
2 considered: (i) a peak shaving strategy, (ii) a random request of switching on/off the system  
3 and (iii) a night load shifting strategy.

4 Main conclusions that can be drawn are:

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

20

21

## 22 **Acknowledgments**

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

26

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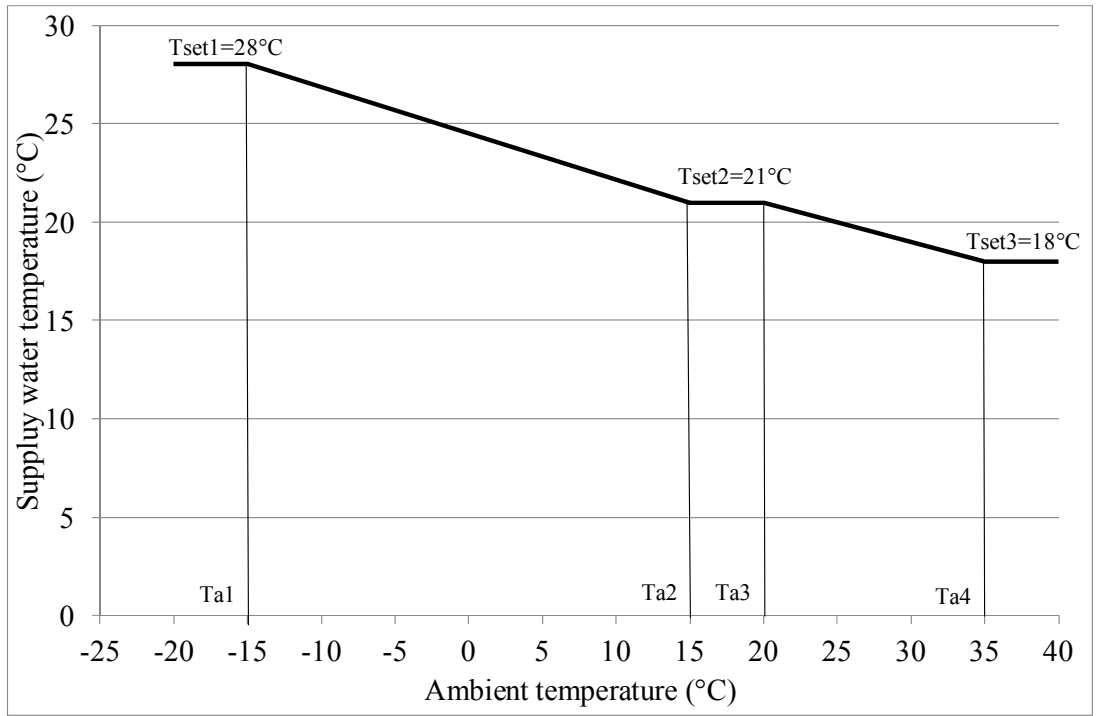
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Figure 1. Representation of TABS used in the reference building (Airdeck).

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Figure 2. Supply water temperature curve.

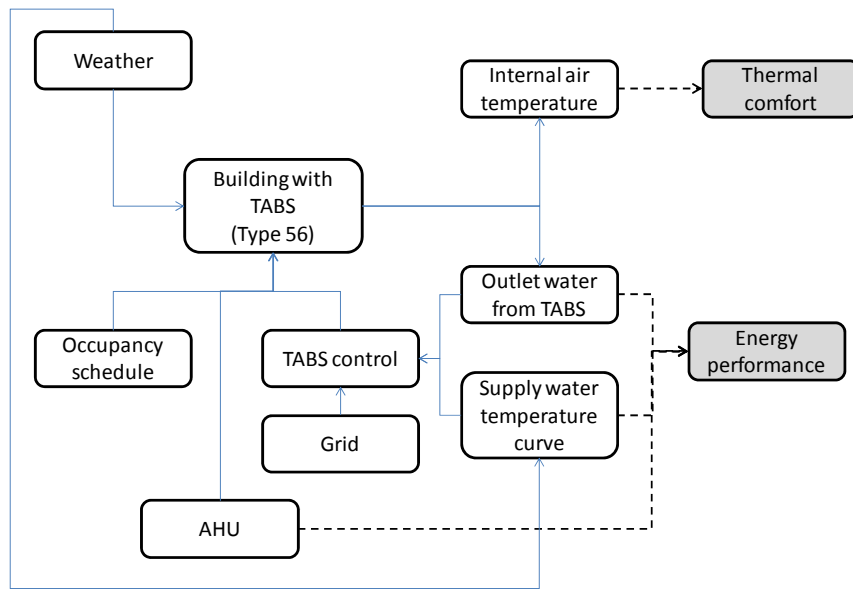


Figure 3. Conceptual schematic of the TRNSYS model.

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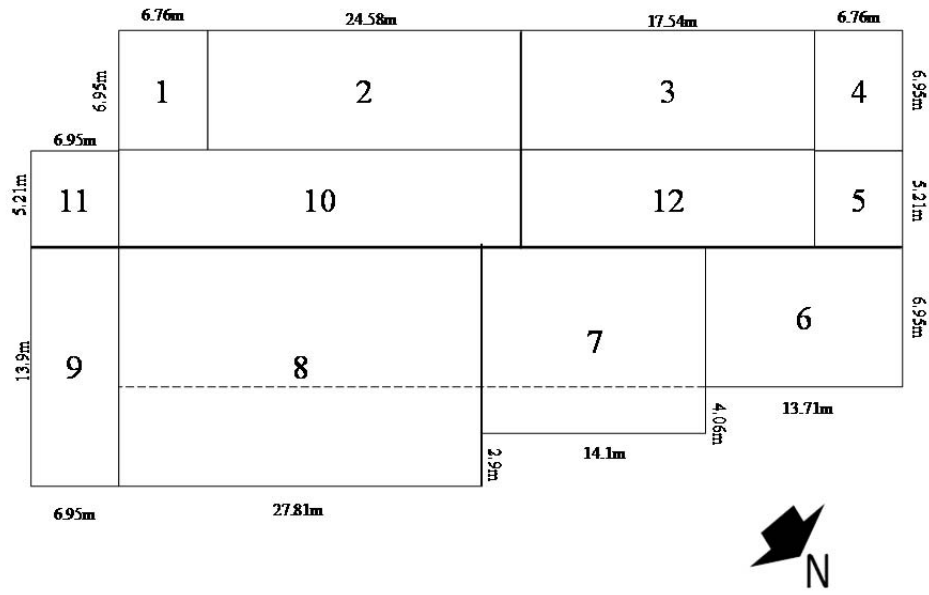
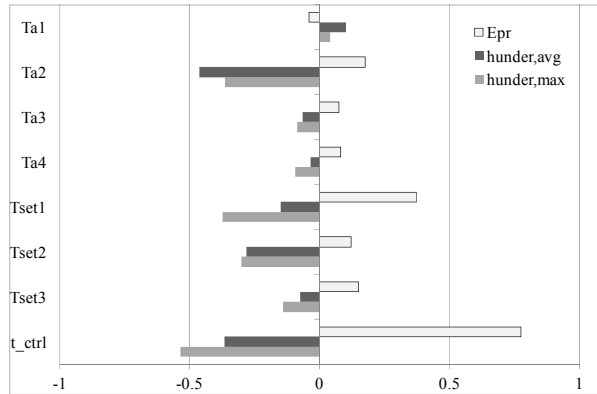


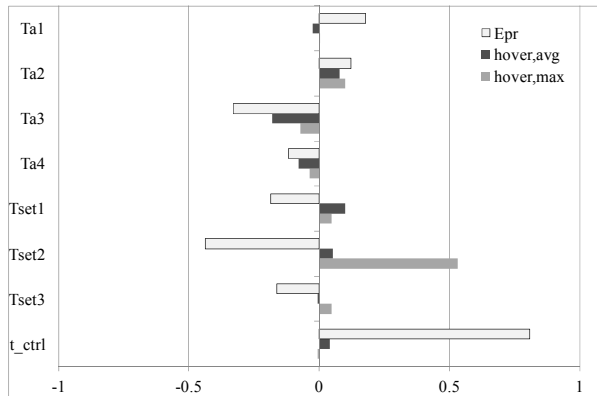
Figure 4. Layout of the first floor and subdivision in zones.

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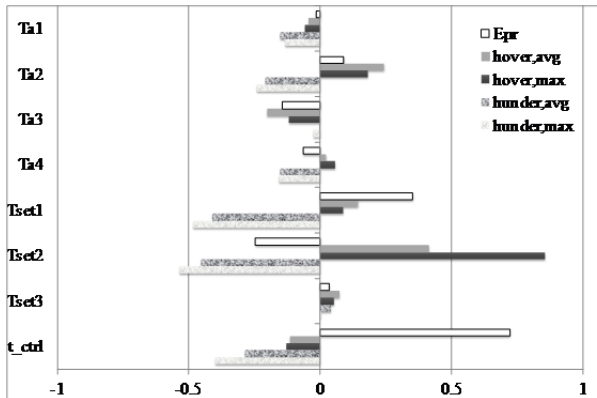
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(a)



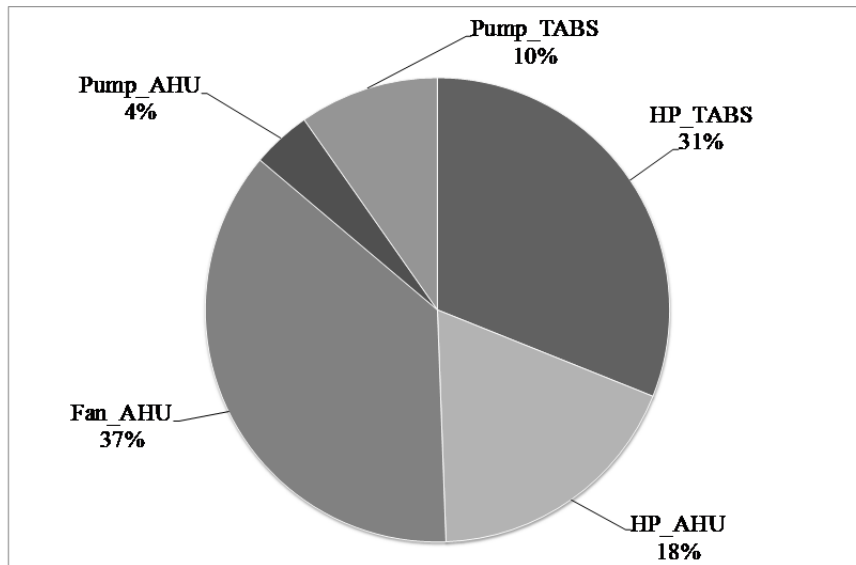
(b)



(c)

3 Figure 5. Sensitivity analysis results for a typical winter week (a), summer week (b) and year-  
4 round operation (c): correlation among the selected parameters (y-axis) and the primary  
5 energy consumption (E<sub>pr</sub>), average overheating hours (h<sub>over,avg</sub>), maximum overheating hours  
6 (h<sub>over,max</sub>), average underheating hours (h<sub>under,avg</sub>), maximum underheating hours (h<sub>under,max</sub>).  
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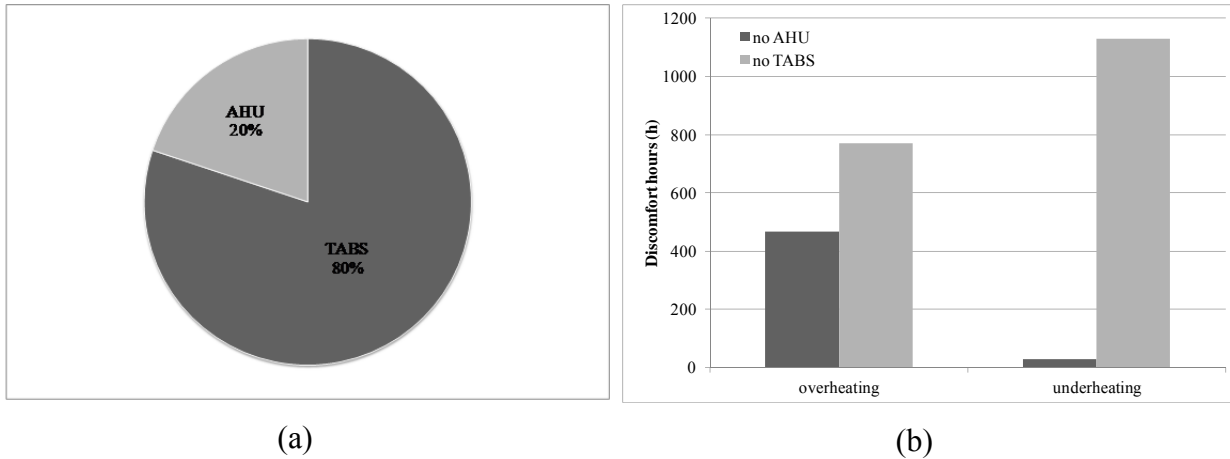
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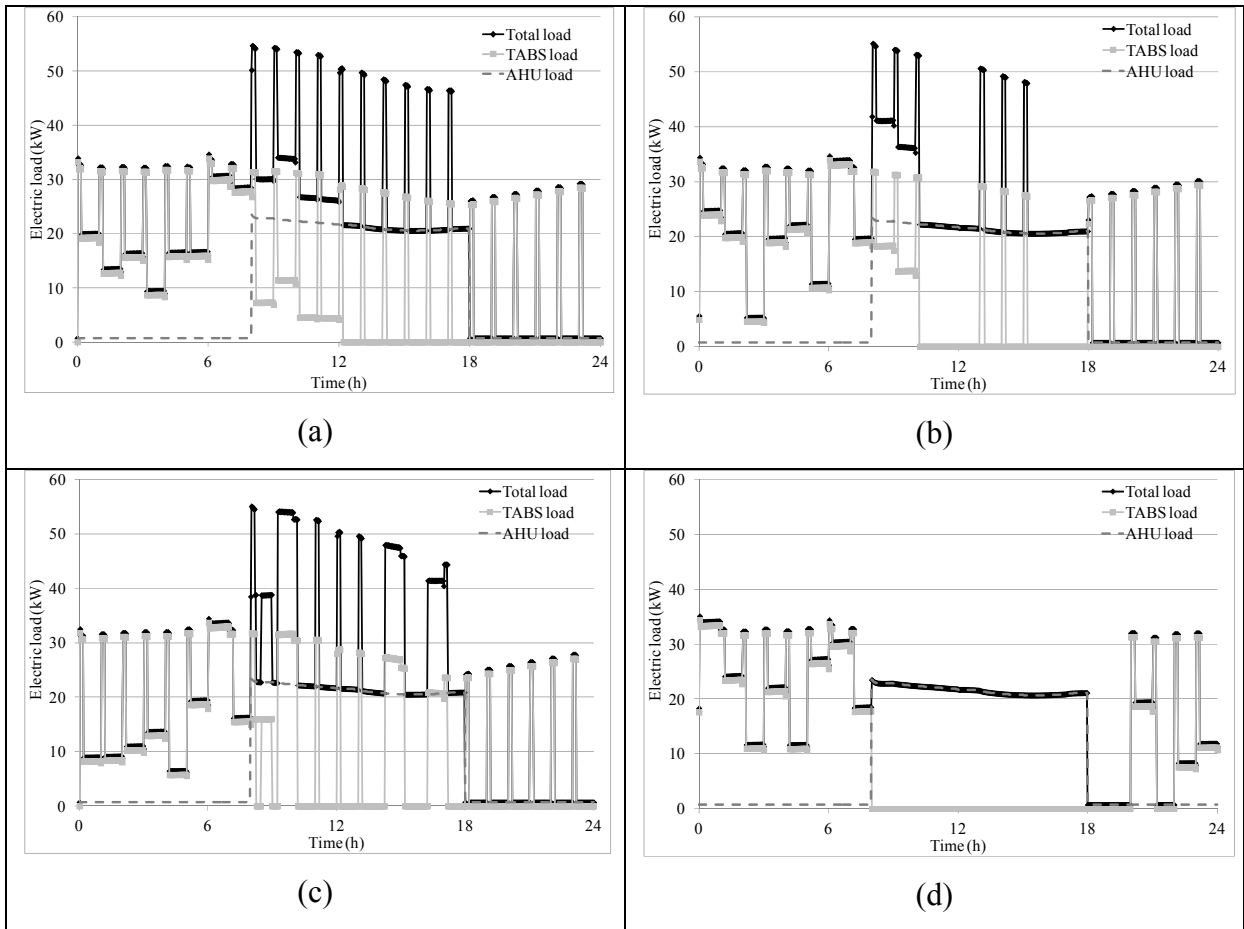
Figure 6. Electric energy consumption breakdown for the reference building.

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1            Figure 7. TABS and AHU contribution to the energy demand of the first floor (a) and  
 2            discomfort hours caused by keeping off separately the two systems all the year round (b).  
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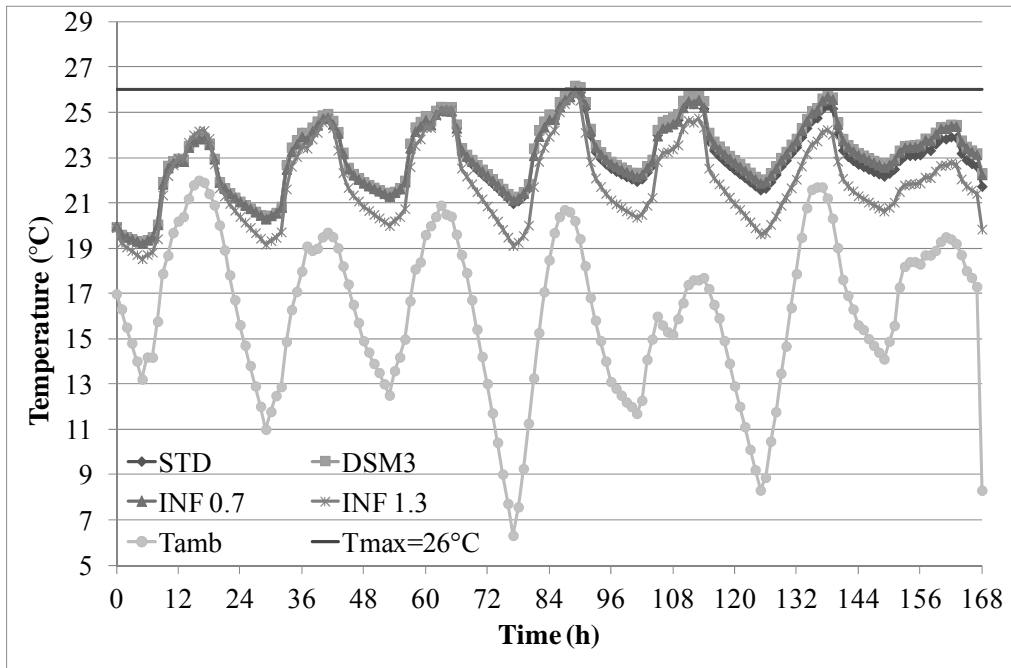
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Figure 8. Electric load during a typical winter day for the reference system (a) and under the different DSM strategies implemented: peak shaving strategy DSM1 (b), random strategy DSM2 (c) and night load shifting strategy DSM3 (d).

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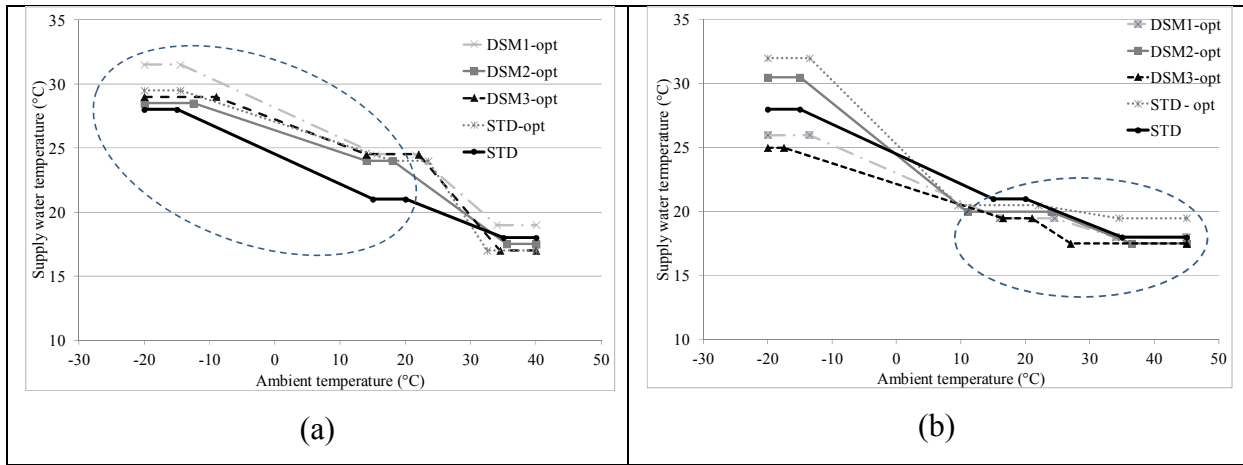
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3 Figure 9. Temperature of the warmer South facing zone during a week in middle May for the  
4 reference case (STD); for the case with the DSM3 strategy in action (DSM3); for the case  
5 with the DSM3 strategy in action having a natural ventilation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

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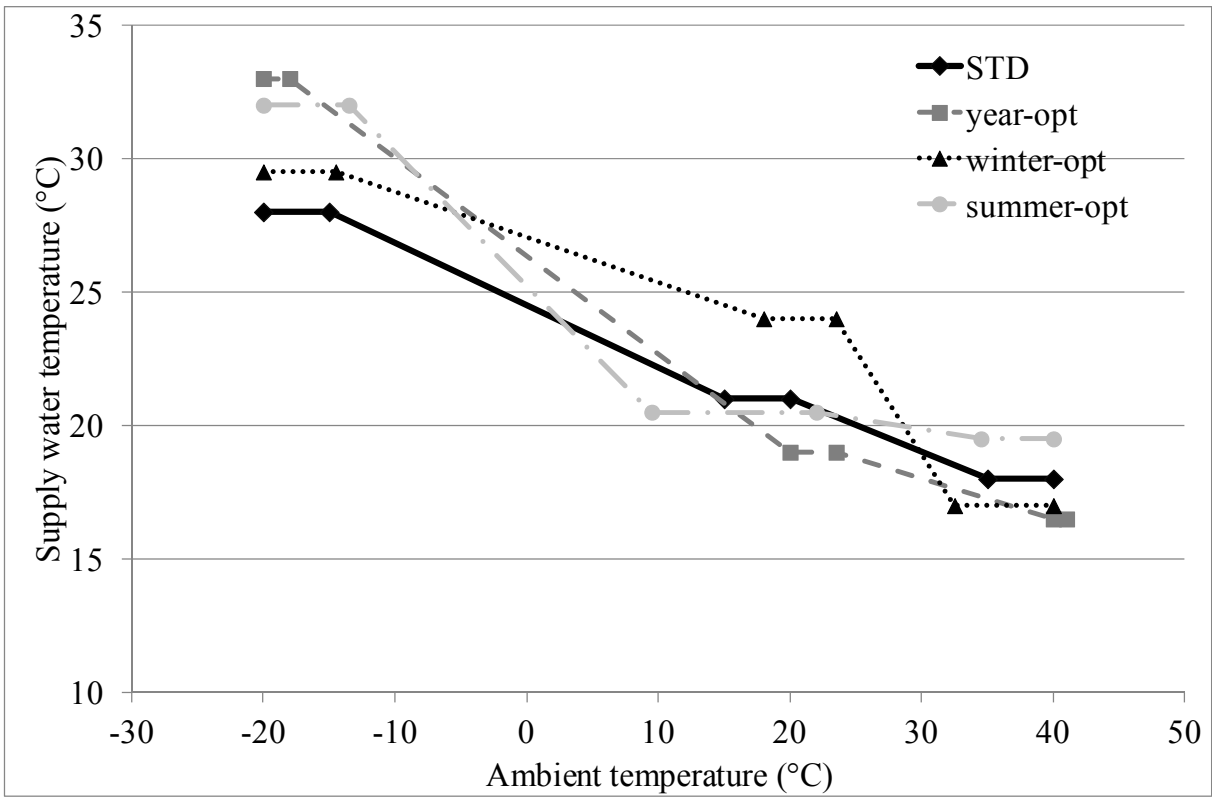


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5 Figure 10. Comparison of the supply water temperature curve for the reference case (STD)  
6 with the optimum curves for the reference case (STD-opt) and for the demand side  
7 management strategies in action (DSM1-opt, DSM2-opt, DSM3-opt) in winter (a) and  
8 summer (b). The dotted circle highlights that part of the curve of interest in the heating  
9 (<math><13^{\circ}\text{C}</math>) or cooling mode (>math>>15^{\circ}\text{C}</math>).

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

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**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).

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

<b>Wall</b>	<b>Material</b>	<b>Thermal conductivity [W/m K]</b>	<b>Thickness [m]</b>
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
	plaster board	1.25	0.013
Wall between zones			
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
<b>Windows</b>	<b>g</b>	<b>U [W/m<sup>2</sup> K]</b>	<b>Area (m<sup>2</sup>)</b>
	0.81	0.65	178.02

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

<b>TABS</b>		
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
<b>AHU</b>		
air flow rate – 1st floor	m <sup>3</sup> /h	5'615
air flow rate - total building	m <sup>3</sup> /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

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

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

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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

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

3

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

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