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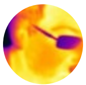

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Thermal comfort evaluation in HVAC Demand Response control

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Abstract

A novel idea, the Daily Discomfort Score (DDS) is developed to assess Demand Response (DR) and thermal comfort in a University building. HVAC set-point control is exercised as a way to reduce the cost of energy and improve thermal comfort. The Daily Discomfort Score employs operative temperature as the key input parameter to take into account radiative and air temperature conditions in each thermal zone. A penalty mechanism is introduced to account for temperature deviation outside the comfort zone and consecutive hours of discomfort. Baseline and preconditioning scenarios are tested to demonstrate the effectiveness of the Daily Discomfort Score in evaluating thermal comfort and Demand Response HVAC control.

Keywords: thermal comfort, demand response; adaptive comfort ;

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1. Introduction

Demand Response (DR) refers to the technical, operational and market framework allowing consumers change their power demand in exchange for financial or other type of rewards. It provides the space for adding flexibility and smartness in the new era electrical power generation and distribution grid. In the smart grid, requirements for higher generation capabilities are lower and overall system efficiency is improved. In DR, consumers can become 'prosumers' and export energy to the grid in response to control signals aiming to accomplish an integrated harmonic performance of the overall electrical distribution power system. Since manageable loads are a valuable resource,

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consumers may employ various techniques related to the operation of their Distributed Energy Resources (DER) to shift their consumption in time, lower power peaks and overall reduce the cost of the energy they consume. At EU level considerable progress in implementing DR programs has been made including regulatory and statutory reforms. However, the EU DR market is at an early stage with investments targeted mainly at the rollout of smart metering and Advanced Metering Infrastructure (AMI) while barriers have not in most cases been fully removed to allow new business models such as aggregators establish their role and potential (1).

Advanced control of HVAC systems can be exploited to shift power peaks, reduce energy consumption and associated costs while adhering to indoor thermal comfort desired conditions. Specific techniques such as global temperature adjustment, passive thermal storage, fan variable frequency drive limit, supply air temperature adjustment etc. have been identified for commercial buildings and also can be applied depending on the installed systems in other building types (2). Passive thermal mass storage refers to the precooling or preheating of the building that can be used to reduce thermal loads in peak hours. In mild climates preconditioning strategies can result in total energy savings i.e. when free ventilation cooling is exploited. On the other hand, preconditioning may increase total energy consumption depending on weather conditions, building envelope and preconditioning schedule.

DR control strategies related to the operation of the HVAC system can be effectively implemented provided that indoor thermal comfort is not compromised. This is a crucial aspect of DR as indoor thermal comfort is related to users' health workplace satisfaction and productivity. This paper proposes a framework for analyzing DR preconditioning strategies in terms of financial performance and impact on thermal comfort.

1.1. Methodology

The Daily Discomfort Score (DDS) introduced hereafter is part of a wider framework for evaluating Demand Response HVAC control measures in smart buildings. The control measure tested in this case study refers to the time varying HVAC set-point temperature for heating and cooling. Set-point temperature control is a typical way to implement preconditioning of the building. In this case preconditioning is tested to evaluate whether it can be used to simultaneously establish cost of energy savings and thermal comfort improvements.

Moreover, preconditioning is a technique which may be exploited to minimize high power demand peaks by storing energy in the building's thermal mass. Stored energy in the building's thermal mass has as a result lower HVAC demand power required for desired indoor comfort temperatures to be reached during standard working hours. On the other hand, preconditioning could at the same time improve indoor comfort and avoid discomfort i.e. in early hours of HVAC operation during the day, when indoor temperature has not yet approached set point values.

The Daily Discomfort Score is developed to provide a decision support tool for assessing the impact of Demand Response HVAC operating strategies, modes or specific measures in indoor thermal comfort. The DDS can be used as a stand-alone indicator or in multi-criteria optimisation schemes. Evaluating DR cost savings is of limited practical value if the potential impact in terms of the thermal comfort is not taken into account. The Daily Discomfort Score aims to provide a valid criterion in evaluating the impact of a DR event in indoor thermal comfort conditions.

For verifying the DDS concept, the validated thermal model of K1 building of Technical University of Crete, developed as part of the Camp IT project (3), is exploited. In addition, a model of the existing cost of energy scheme (4) at Technical University of Crete is deployed to identify potential cost savings from implementing DR measures.

The methodological framework linked with this research work consists of the following steps:

1. Development of thermal dynamic simulation model of the building under study
2. Energy cost model implementation taking into account different energy tariff zones
3. HVAC DR control assessment based on the following criteria
    a. Cost of annual energy consumption
    b. Thermal comfort evaluation based on Daily Discomfort Score (DDS)

2. Design of the Discomfort Score

The idea of the discomfort score (DS) is based on the Adaptive Comfort Standard (ACS) ASHRAE Std. 55(5)(6), which represents an alternative to the PMV-based method. The standard, as shown in Figure 1, relates the outdoor temperature T_{out} to the indoor operative temperature T_{op}. In particular, the optimum comfort indoor operative temperature is given by the regression (blue dotted line):

$$T_{comf} = 17.8 + 0.31T_{out}$$

The area between the green dashed lines represents the 90% acceptability area, that is, the temperature accepted by by 90% of the people that participated in the experiment for the design of the standard. This area includes all the points $T_{comf} \pm 2.5°C$ that differ from the corresponding optimal temperature, as given by the regression relationship. Respectively, the red lines limit the 80% acceptability area and have a distance of up to $\pm 3.5°C$ from the optimal line. The standard then considers "uncomfortable" all those temperature that fall out of the latter. Although the ASHRAE ACS standard has been developed for naturally ventilated buildings, it is applied in this case to provide recommendations for thermal comfort in mixed-mode buildings of opening windows and locally controlled HVAC systems. This is considered to be a viable assumption provided that in all considered scenarios, EN 15251 (7) compliant set points for controlling indoor temperature are used to prevent overheating or overcooling of the building. Furthermore, in the proposed methodology, hourly values of outdoor air temperature are exploited to allow an extended band of indoor operative temperatures similar to that defined by the ACS ASHRAE standard.

To calculate T_{comf} we calculate the vertical difference $\Delta = T_{op} - T_{comf}$, as shown in Figure 1, based on hourly indoor operative temperature and measured hourly outdoor temperature. At any hour interval $h \in \{1, \ldots 24\}$, a

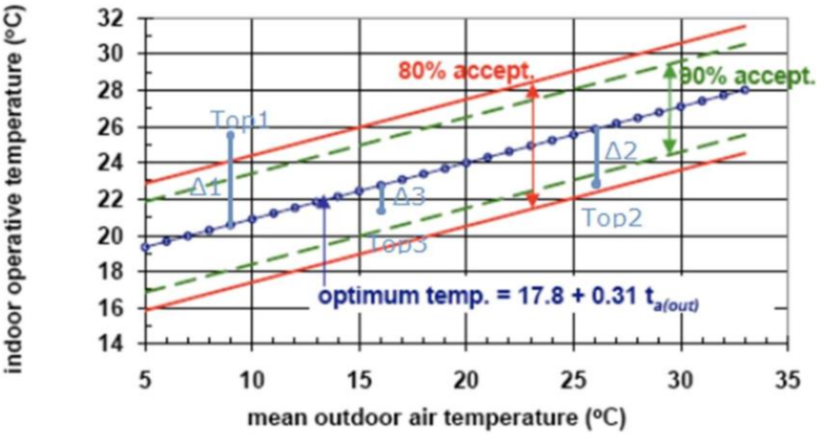

Figure 1: Correlation of indoor operative temperature and mean outdoor air temperature

Hourly Discomfort Score (HDS) is assigned based on Equation 1:

$$HDS = \begin{cases} 1, |\Delta| \geq 3.5 \\ 0.5, |\Delta| \geq 2.5 \; and \; |\Delta| < 3.5 \\ 0, \; otherwise \end{cases} \text{(eq.1)}$$

The Daily Discomfort Score (DDS) is obtained from the HDS by adding the various Hourly Discomfort Scores within each day plus a penalty in the case of consecutive hours of discomfort. More precisely, if there is a series of consecutive positive hours, HDSs are summed in an arithmetic progression fashion to take into account that the perception of discomfort increases with time. For example if the heating system stops working during a cold winter day for an hour, the impact on discomfort is limited compared to a two or more hours' period.

$$DDS = \sum_{i=1}^{24} X_i \sum_{j=0}^{J} HDS_j * (j+1)$$

(eq.2)

Where

$$X_i = \begin{cases} 0, when\ HDS = 0 \\ 1, when\ HDS > 0 \end{cases}$$

$$i\ is\ the\ number\ of\ hours\ for\ which\ HDS > 0$$

$$j\ is\ the\ number\ of\ consecutive\ hours\ for\ which\ HDS > 0$$

3. Case Study

As a case study, K1 building of Environmental Engineering department at TUC is explored. The thermal model was developed in CampIT project (8) and involved 3D design in Google SketchUp (9), parameterisation through Open Studio (10) and EnergyPlus (11) as the simulation engine. For the calculation of cost and DDS Matlab (12) is used. Indoor temperature measurements in several thermal zones were exploited for model validation and fine tuning. K1 is a building of 3 floors with dimensions (length (m) / width (m) / height (m)) 86.40/15.20/12.00, 2,032m^2 of conditioned and 1,135m^2 of non-conditioned spaces. K1 hosts 14 laboratories, 20 offices, 1 meeting room, mechanical rooms, stairs, WC, elevators etc.

Table 1: Structural components and materials of K1 building

Exterior walls a) Double plasterboard (width:18 mm each) b) Insulation: 5 cm rockwool, d = 80 kg/m3 c) Cement board: 12 mm	**Ground and first floors ceilings** a) Uncoated concrete: 2 cm b) Insulation: 5 cm rockwool, d = 80 kg/m3 c) Ceramic tiles: 10 mm.
Second floor ceilings a) Uncoated concrete: 2 cm. b) Insulation: 10 cm c) Asphalt membrane: 10 mm.	**Windows (104 windows)** a) Double pane windows b) Aluminum frames c) Exterior lamellas
Floor top coating a) Ceramic tiles: 10 mm (in all spaces) b) Industrial flooring: 20 mm (Chemistry lab)	

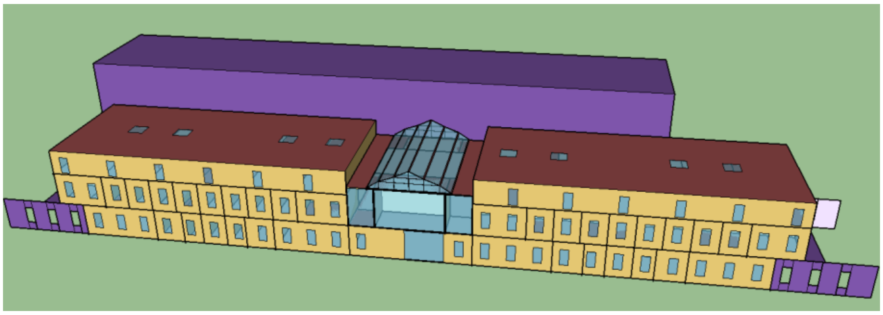

Figure 2: K1 building 3D thermal simulation model in SketchUp/Open Studio

In broad terms the baseline schedule is defined as a set point for the HVAC in heating mode of 20°C and 25°C in cooling mode during typical working days and hours 08:00-18:00 (weekends excluded, Figure 3).

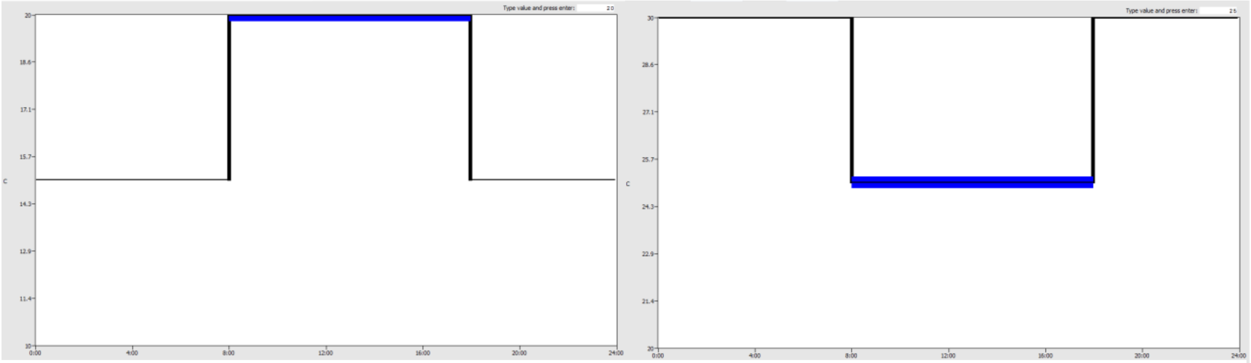

Figure 3: Heating (left) / Cooling (right) schedule for HVAC system in baseline scenario

For the preheating and precooling scenarios various different settings were tested. In figure 4 a preheating (Figure 4, left) and a precooling scenario (Figure 4, right) is presented in terms of the associated HVAC schedules. It is noted that the same set points for heating (20°C) and cooling (25°C) are applied in both baseline and preconditioning scenarios during working hours. The difference is in the heating and cooling hours within working days extended to initiate earlier in the morning for both heating and cooling to take advantage of the low cost tariff between 23:00-07:00. In specific, the preheating schedule starts at 04:00 when set point is increased from 15°C to 16°C. For every hour after that, the set point is increased by 1°C one until 20°C set point is reached at 08:00.
Precooling schedule (Figure 4, right) is also initiated at 04:00 when the set point is lowered from 30°C to 29°C. Following this, the set point is reduced by 1°C for every hour to the value of 25°C at 08:00.

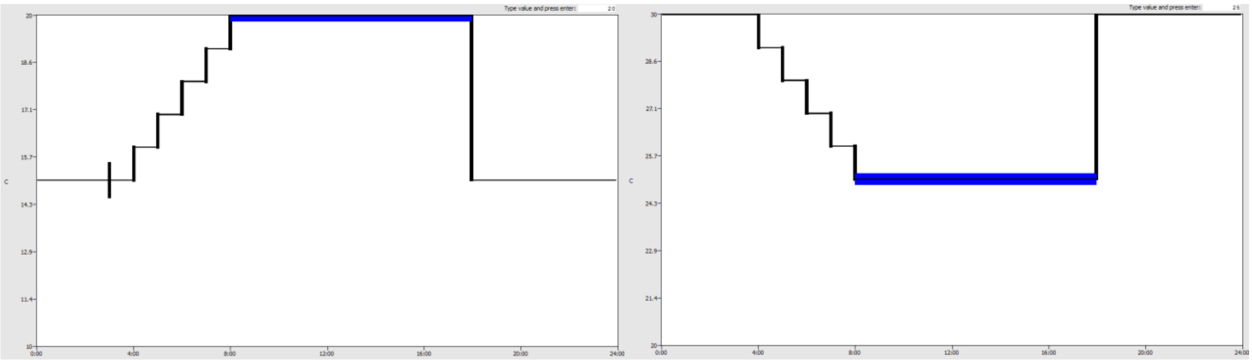

Figure 4: Heating (left) / Cooling (right) set point schedule for HVAC system in preconditioning scenario

4. Results

In Figure 5 a comparison based on the annual cost of energy between the baseline and the preconditioning scenario is illustrated. Although the performance in both of these scenarios appears to be quite similar (Figure 5, left), it is important to note that the extended hours of HVAC operation in the preconditioning scenario result in lower running costs on an annual basis. Although cost reduction is relatively small, it demonstrates that there is a potential for higher financial gains if a more elaborate control technique is utilized. The fact that preconditioning results in lower running costs is justified due to the significant percentage of the energy consumption during the off-peak energy tariff (4).

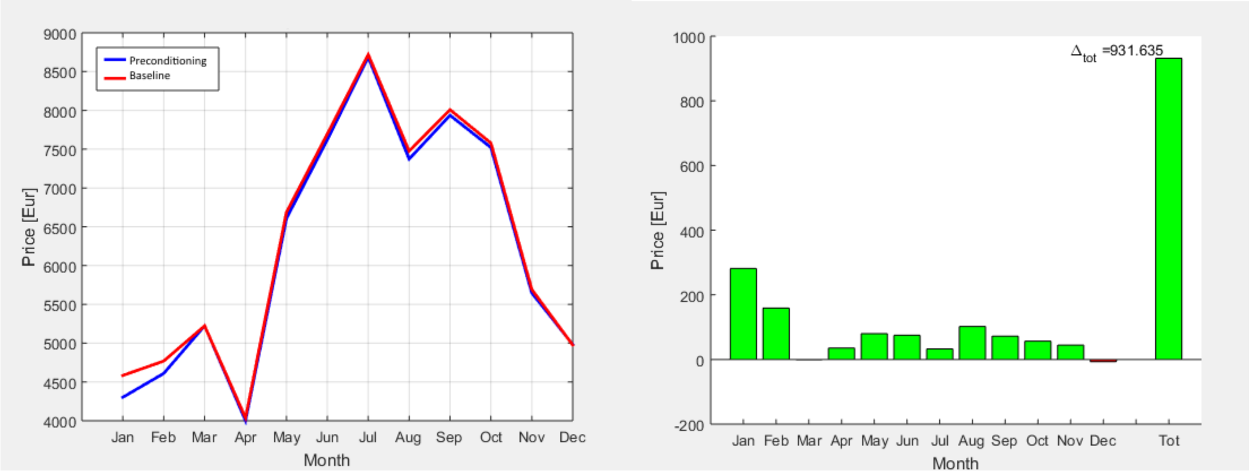

Figure 5: Cost of energy comparison in baseline and preconditioning scenarios

In Figure 6, DDS of the building for thermal zone 2 in the baseline and preconditioning scenario is illustrated. In both baseline and preconditioning scenarios there is a significant amount of days throughout the year during which discomfort conditions occur. However, as anticipated, the preconditioning scenario results in improved thermal comfort conditions compared to the baseline.

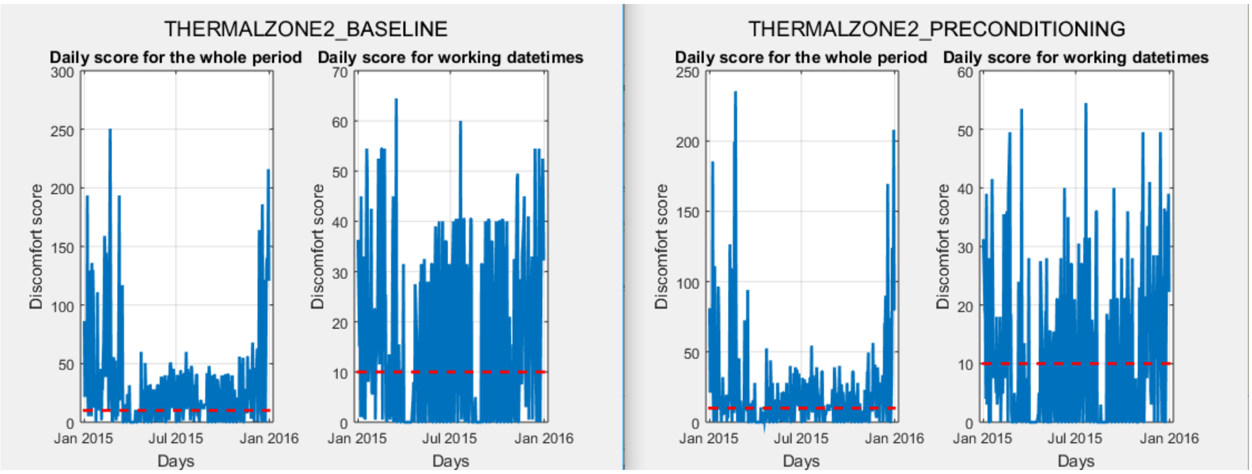

Figure 6: Daily Discomfort Score in Thermal Zone 2 baseline and preconditioning scenarios

Figure 7 refers to thermal zone 19 baseline and preconditioning scenarios. Observations in this case indicate that preconditioning results in clearly superior thermal comfort compared to the baseline scenario. In preconditioning, DDS is very high during a limited number of days throughout the year. On the contrary, according to the baseline scenario thermal discomfort conditions are frequent in both heating and cooling periods despite the fact that standard set points are used.

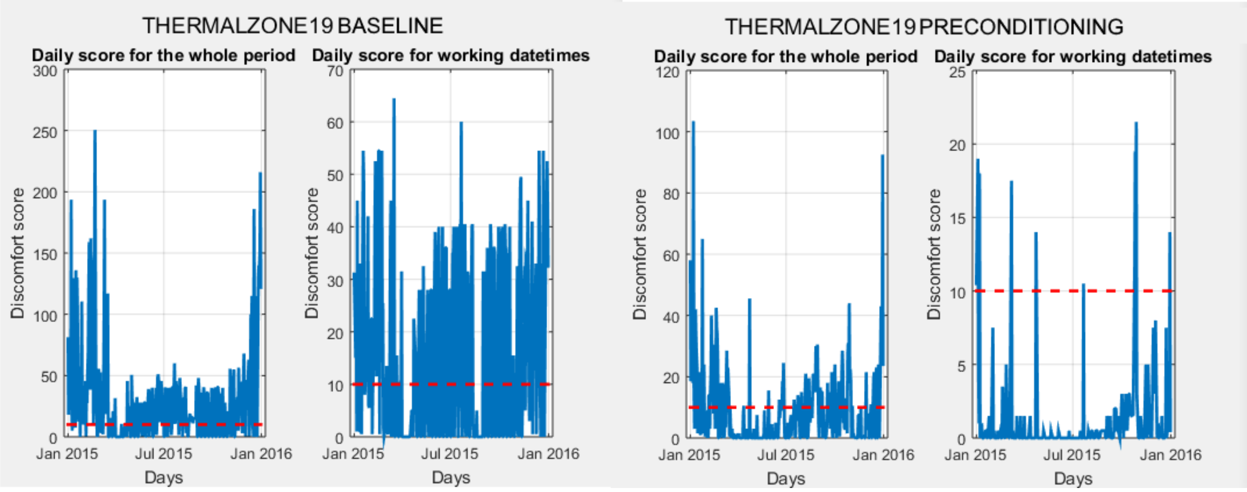

Figure 7: Daily Discomfort Score in Thermal Zone 19 baseline and preconditioning scenarios

5. Conclusions

Evaluating demand response strategies in buildings is a complex task linking dynamic weather and energy consumption parameters with the cost of energy and indoor thermal comfort. In this case a simplified preconditioning scenario has been assessed in terms of the annual cost of energy and indoor thermal comfort. The analysis in this case demonstrated that relatively low cost reductions can be obtained simultaneously with improved thermal comfort levels. This is a strong indication that more elaborate HVAC control strategies can be used to exploit the real potential for energy and cost savings in buildings as the energy market becomes more transparent, open and efficient. With regards to the evaluation of the indoor thermal comfort, the adaptive comfort standard was used to develop the Daily Discomfort Score, a benchmark, providing the valuable and user friendly graphical insight of thermal indoor conditions at any point in time. The DDS can be modified to address various features or parameter adjustments as appropriate for different applications. As a general remark this work emphasized that in DR HVAC control, thermal comfort co-assessment is a prerequisite to ensure comfort conditions are not deteriorated. In buildings of substantial size, each thermal zone needs to be examined separately as indoor conditions may vary substantially due to differences in geometry, orientation, internal gains etc.

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