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The Effects of Set-Points and Dead-Bands of the HVAC System on the Energy Consumption and Occupant Thermal Comfort

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SUMMARY

A building is a complex system where many components interact with each other therefore the control system plays a key role regarding the energy consumption and the occupant thermal comfort.
This study is concerned with a detached, one-storey, single family, energy-plus house. It is equipped with a ground heat exchanger, a ground coupled heat pump, embedded pipes in the floor and in the ceiling, a ventilation system (mechanical and natural), a domestic hot water tank and photovoltaic/thermal panels on the roof.
Preliminary evaluations showed that for Madrid, change of indoor set-point in cooling season from 23°C to 25°C (±1 K) can decrease the cooling need by 23%. Hence, an interest arose in order to quantify the energy saving potential with respect to different set-points and dead-bands. However occupant comfort should not be neglected for the sake of energy savings.
This study focuses on the effects of the set-points and dead-bands of different components on the energy consumption together with the occupant thermal comfort. Evaluations are carried out with TRNSYS for Copenhagen and Madrid in order to compare climatic effects.

INTRODUCTION

As the fossil fuels are gradually depleting, focus on the renewable energy resources and their integration into various systems has been increasing. Even though replacing fossil fuels with renewable energy resources is an important step, energy efficiency should not be neglected. People spend most of their time indoors [1] therefore providing a comfortable and healthy indoor environment should be placed in the center of every HVAC system design. This goal should be achieved as efficiently and as effectively as possible.
This study is concerned with the house, Fold, which Technical University of Denmark competed in the worldwide student competition Solar Decathlon Europe 2012 [2]. During the design of the HVAC system of the house, the above mentioned points were studied.
The house was designed to be energetically self-sufficient and in fact it performs as an energy-plus house [3]. It is equipped with a ground heat exchanger (GHX), a ground coupled heat pump, embedded pipes in the floor and in the ceiling, a ventilation system (mechanical and natural), a domestic hot water (DHW) tank and photovoltaic/thermal (PV/T) panels.
It was observed during the design and operation phases that in order to obtain optimal performance, it is not enough for one component to perform optimally but all of the components should perform optimally and interact with each other in the best possible way. Hence set-points and dead-bands of different components emerge as crucial parameters. This study is concerned with the indoor temperature set-point and dead-band, set-point of supply

temperature to the embedded pipes and mass flow rate in the ground loop and their effects on energy demand, energy consumption and occupant thermal comfort. Evaluations are carried out for Copenhagen and Madrid, with commercially available simulation software, TRNSYS.

CASE STUDY DESCRIPTION

The house is a detached, one-storey, single family, energy-plus house with an interior area of 66,2 m^2 and with a conditioned volume of 213 m^3. The house's largest glazing façade is oriented to the North, with a 19˚ turn towards West. The house can be seen in Figure 1:

Figure 1: Southwest and North sides of the house

The glazing surfaces in North and South sides are covered by the overhangs which eliminate direct solar radiation to the house during summer. During winter direct solar radiation enters the house and creates a favorable effect. Only active shading system was for the skylight window. Inside the house, there is one space combining kitchen, living room and bedroom. The surface areas and the thermal transmittance values are presented in Table 1:

Table 1: Construction details of the house [3]

External walls	South	North	East	West	Floor	Roof
Area [m^2]	-	-	19,3	37,2	66,2	53
U-value [W/m^{2}K]	-	-	0,09	0,09	0,09	0,09
Windows	South	North	East	West	Floor	Roof
Area [m^2]	21,8	36,7	-	-	-	0,74
U-value [W/m^{2}K]	1,04	1,04	-	-	-	1,04
Solar transmission	0,3	0,3	-	-	-	0,3

The design conditions required for the house to be fully functioning in two different climates: Denmark (Copenhagen) and Spain (Madrid). Summer maximum, summer average and winter average temperatures are taken for Madrid while winter minimum temperature is taken for Copenhagen. Design temperatures and respective loads are as follows:

- Summer maximum 40,0°C 52,0 W/m^2 (cooling)
- Summer average 26,0°C 35,2 W/m^2 (cooling)
- Winter minimum -12,0°C 45,6 W/m^2 (heating)
- Winter average 2,6°C 26,6 W/m^2 (heating)

Cooling and heating system of the house is water based with a low temperature heating and high temperature cooling concept, enabling the integration of renewable resources, ground in this case. It is a dry radiant system, piping grid is installed under the wooden layer. Space heating is obtained by the embedded pipes in the floor and space cooling is obtained by embedded pipes in the ceiling and, if necessary, in the floor. A mixing station is installed between ground and embedded pipes in order to control the water flow and temperature.

In the ceiling, there is foam board system with aluminum heat conductive plates and PEX pipes (12x1,7 mm). There are 6 circuits, with maximum flow rate in one circuit of 0,07 m^3/h. In the floor, there is chipboard system with aluminum heat conducting plates and PEX pipes (17x2,0 mm). There are 4 circuits, with maximum flow rate in one circuit of 0,07 m^3/h for the cooling case and 0,15 m^3/h for the heating case.
In order to regulate the indoor air quality, mechanical and natural ventilation systems are installed. The distribution system consists of 2 supply diffusers and 4 exhausts (kitchen hood, bathroom, toilet and clothes dryer). Maximum flow rate that could be provided by the air handling unit, AHU, is 320 m^3/h and this capacity fully covers the design value. AHU has two heat recovery systems; passive (cross flow heat exchanger) and active (reversible heat pump coupled with the DHW tank). Ventilation system is utilized to control humidity and indoor air quality expressed by CO_2 levels. Mechanical ventilation is shut off when the outside air temperature is suitable for natural ventilation. Natural ventilation is possible via two windows in South and North façades and the operable skylight window.
The only electrical energy source of the house is solar energy, utilized via PV/T panels placed on the entire roof area. The electrical system is designed to be grid-connected. The solar thermal system is coupled with the PV part of the PV/T panels. Thermal part absorbs the heat produced by PV panels and utilizes it in the DHW tank.
Heat source/sink for space heating/cooling is the ground, utilized via a borehole heat exchanger. Free cooling is obtained during the cooling season and ground coupled heat pump is only used during the heating season. The ground heat exchanger is a borehole with a depth of 120 meters, single U-tube configuration and with a diameter of 0,12 m.

METHODS and INVESTIGATIONS

Presented results are from the commercially available dynamic building simulation software, TRNSYS [4]. Simulations were carried out for Copenhagen and Madrid, International Weather for Energy Calculations (IWEC) and Spanish Weather for Energy Calculations (SWEC) weather files were used, respectively.
Same load profiles for occupants, lighting and equipment were implemented for Copenhagen and Madrid. There are 2 occupants in the house with 1,2 met. Occupants are assumed to be away from 8:00 to 16:00 during the weekdays and from 12:00 to 17:00 during the weekends. The lighting load is 222 W (3,4 W/m^2). Lights are assumed to be ON from 05:00 to 08:00 and from 16:00 to 22:00 every day. Electrical power of the installed home appliances is 1,5 kW. Different equipment is ON and OFF during the day. The values are expressed with respect to the maximum value. For the weekdays, load is 5% all the time except from 02:00 to 03:00 where load is 20% and except from 19:00 to 20:00 where load is 62%. For Saturday, from 7:00 to 8:00 the load is 15%, from 8:00 to 9:00 the load is 34% and for Sunday from 2:00 to 3:00 the load is 20%.
Ventilation rate is 0,8 ach and infiltration is 0,1 ach. Natural ventilation is not taken into account in the simulations.
G-value of the windows was taken as 0,28 (difference from the actual case is due to the available material library).
May to September was the cooling season and the rest of the months were the heating season. In the reference case, set-points for the operative temperature has been defined as 21°C±1 K for heating and 25°C±1 K for cooling seasons, following category II of EN 15251:2007 [5]. The supply temperature set-points to the embedded pipes were 34°C and 16°C, for heating and cooling modes, respectively. The flow rates were determined according to EN 15377-2:2008 [6], design values were 619 kg/h for floor heating, 336 kg/h for floor cooling and 317

kg/h for ceiling cooling. The circulation pump in the ground loop has a design flow rate of 650 kg/h and a power of 68 W corresponding to this flow rate.
The heat pump is water-to-water type. The performance data of the heat pump is presented in the following Figure 2 (heat pump is not used in the cooling season due to free cooling):

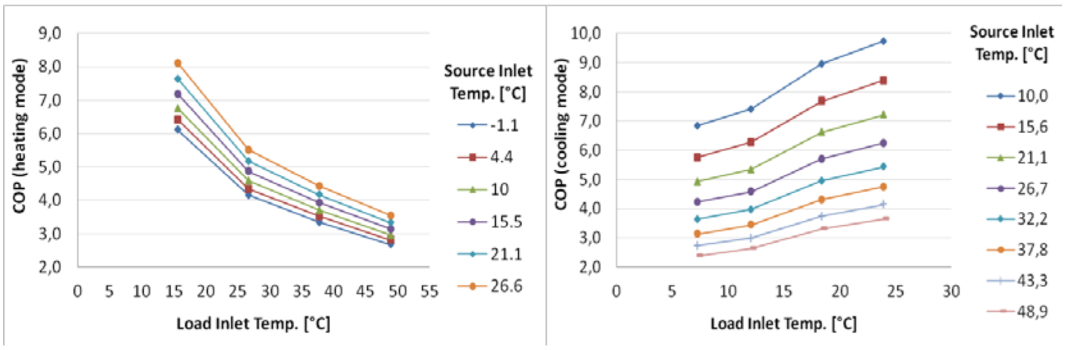

Figure 2: Heat pump efficiency curves for heating and cooling modes

In the above figure, load side represents flow coming from the house and source side represents flow coming from the ground. The nominal thermal output of the heat pump is 3 kW with an electrical power of 600 W.
The results from annual simulations are presented in Table 2:

Table 2: Energy consumption by house needs

Application [kWh/m^2] / Location	Copenhagen	Madrid
	Need/consumption	Need/consumption
Heating	100,7/30,6	54,2/17,3
Cooling	23,4/0,6	28,2/1,0
Ventilation	1,5/0,7	5,3/5,2
DHW	32,2/7,1	32,2/3,7
Rest of the electricity consumption	5,4	4,0
Total electricity consumption	44,4	31,3
Total primary energy consumption	111,0	93,8
Energy balance (electricity)	67,9	141,0

In the above table, need indicates thermal need and consumption indicates electricity consumption. Rest of the electricity consists of consumptions of the pump of the embedded pipe loops and of the two pumps for the PV/T panels. Energy balance is consumption subtracted from production and it indicates that the house is an energy-plus house. The primary energy factor has been taken as 2,5 for Denmark [7] and as 3 for Spain [8].

RESULTS

Results of the simulations

In the following tables, values next to the temperatures indicate set-point temperatures. Values in the parentheses next to the flow rates indicate pump power. EN 15251:2007 has been used as the indicator of the occupant thermal comfort and results are shown in the percentage of time that the conditions fulfill respective comfort categories. During the simulations, indoor temperature set-points are adjusted according to the comfort categories.

Dead-band analyses were not applied to all of the parameters; it was implemented on the indoor temperature set-point as a representative case of its effects.
Coefficient of Performance (COP) values correspond to the COP of the heat pump (ratio of heat delivered to electricity consumed) and COP_{sys} is the ratio of heat delivered to the sum of the electricity consumption of heat pump and the circulation pump. Free Cooling Coefficient (FCC) represents the ratio of cooling effect to circulation pump consumption.
Presented results are only the embedded pipe system and do not consider ventilation however this is considered not to have a significant effect due to the design strategy (ventilation system is only intending to control humidity and CO_2 levels).
Results of the simulations are presented in the following tables, for each location and season:

Table 3: Heating season, Copenhagen (CC is the comparison of consumption to the reference)

	Demand [kWh/m^2]	Consumption [kWh/m^2]	CC [-]	COP [-]	COP_{sys} [-]	Cat. I [-]	Cat. II [-]	Cat. III [-]
Reference,21°C±1 K	100,7	30,6	-	3,29	3,05	52%	90%	100%
T_{indoor}, 19°C	79,9	23,5	-23,2%	3,4	3,15	16%	26%	95%
T_{indoor}, 20°C	90,6	27,1	-11,5%	3,35	3,1	24%	54%	99%
T_{indoor}, 21°C ±2K	97,7	29,7	-3,1%	3,29	3,05	48%	69%	100%
T_{indoor}, 22°C	109,7	33,9	10,7%	3,24	3	84%	98%	100%
T_{indoor}, 23°C	118,3	37,1	21,3%	3,19	2,96	96%	99%	100%
T_{supply}, 30°C	90,6	27,0	-11,9%	3,36	2,99	32%	62%	98%
T_{supply}, 31°C	95,2	28,5	-6,7%	3,34	3,01	38%	78%	99%
T_{supply}, 32°C	98,4	29,7	-2,9%	3,31	3,02	46%	86%	100%
T_{supply}, 33°C	100,2	30,4	-0,6%	3,3	3,04	52%	90%	100%
ṁ, 400 kg/h (63 W)	100,9	30,8	0,8%	3,27	3,05	52%	91%	100%
ṁ, 900 kg/h (74 W)	100,5	30,5	-0,5%	3,3	3,04	52%	89%	100%
ṁ, 1150 kg/h (79 W)	100,5	30,4	-0,6%	3,31	3,02	52%	89%	100%
ṁ, 1400 kg/h (84 W)	100,5	30,4	-0,7%	3,31	3,01	52%	89%	100%
ṁ, 1650 kg/h (87 W)	100,5	30,4	-0,8%	3,31	3	52%	89%	100%

Table 4: Heating season, Madrid (CC is the comparison of consumption to the reference)

	Demand [kWh/m^2]	Consumption [kWh/m^2]	CC [-]	COP [-]	COP_{sys} [-]	Cat. I [-]	Cat. II [-]	Cat. III [-]
Reference,21°C±1 K	54,2	17,3	-	3,13	2,94	71%	99%	100%
T_{indoor}, 19°C	36,1	11,5	-33,7%	3,14	2,95	37%	51%	99%
T_{indoor}, 20°C	45,5	14,5	-16,2%	3,14	2,95	50%	72%	100%
T_{indoor}, 21°C ±2K	48,7	15,6	-10,2%	3,13	2,94	57%	76%	100%
T_{indoor}, 22°C	63,2	20,2	16,9%	3,12	2,93	98%	100%	100%
T_{indoor}, 23°C	71,6	23,0	32,9%	3,11	2,92	100%	100%	100%
T_{supply}, 30°C	50,7	16,2	-6,6%	3,13	2,85	62%	94%	100%
T_{supply}, 31°C	52,1	16,6	-3,9%	3,13	2,88	65%	97%	100%
T_{supply}, 32°C	53,1	17,0	-2,1%	3,13	2,91	68%	99%	100%
T_{supply}, 33°C	53,8	17,2	-0,8%	3,13	2,93	70%	99%	100%
ṁ, 400 kg/h (63 W)	54,4	17,5	0,9%	3,11	2,94	71%	99%	100%
ṁ, 900 kg/h (74 W)	54,4	17,3	0,0%	3,14	2,93	71%	99%	100%
ṁ, 1150 kg/h (79 W)	54,3	17,3	-0,2%	3,14	2,92	71%	99%	100%
ṁ, 1400 kg/h (84 W)	54,4	17,3	-0,2%	3,15	2,91	71%	99%	100%
ṁ, 1650 kg/h (87 W)	54,4	17,3	-0,3%	3,15	2,9	71%	99%	100%

Table 5: Cooling season, Copenhagen (CC is the comparison of consumption to the reference)

	Demand [kWh/m^2]	Consumption [kWh/m^2]	CC [-]	FCC [-]	Cat. I [-]	Cat. II [-]	Cat. III [-]

Reference,25°C±1 K	23,4	0,6	-	38,22	93%	96%	99%
T_{indoor}, 22°C	35	1,2	101,6%	28,43	96%	98%	99%
T_{indoor}, 23°C	30,2	1,0	70,5%	29,17	95%	96%	98%
T_{indoor}, 24°C	27,2	0,8	27,9%	34,72	95%	97%	99%
T_{indoor}, 25°C ±2K	21,2	0,6	-6,6%	37,13	89%	93%	97%
T_{indoor}, 26°C	19,8	0,5	-21,3%	41,17	89%	92%	97%
T_{supply}, 17°C	22,6	0,7	9,8%	33,45	92%	95%	98%
T_{supply}, 18°C	21,6	0,7	18,0%	29,89	91%	94%	97%
T_{supply}, 19°C	21	0,7	23,0%	27,89	90%	93%	97%
T_{supply}, 20°C	19,4	0,8	36,1%	23,42	88%	91%	96%
$\dot{m}$, 400 kg/h (63 W)	23,1	0,6	-3,3%	39,24	92%	95%	98%
$\dot{m}$, 900 kg/h (74 W)	23,4	0,7	9,8%	35,15	93%	96%	99%
$\dot{m}$, 1150 kg/h (79 W)	23,4	0,7	16,4%	32,92	93%	96%	99%
$\dot{m}$, 1400 kg/h (84 W)	23,2	0,8	27,9%	29,89	93%	95%	99%
$\dot{m}$, 1650 kg/h (87 W)	23,1	0,8	31,1%	28,75	93%	95%	99%

Table 6: Cooling season, Madrid (CC is the comparison of consumption to the reference)

	Demand [kWh/m^2]	Consumption [kWh/m^2]	CC [-]	FCC [-]	Cat. I [-]	Cat. II [-]	Cat. III [-]
Reference,25°C±1 K	28,2	1,0	-	27,19	90%	97%	100%
T_{indoor}, 22°C	41,9	1,9	83,7%	21,89	100%	100%	100%
T_{indoor}, 23°C	36,7	1,5	45,2%	24,34	99%	100%	100%
T_{indoor}, 24°C	31,1	1,2	16,3%	25,56	98%	100%	100%
T_{indoor}, 25°C ±2K	26,9	1,0	-1,9%	26,45	80%	87%	99%
T_{indoor}, 26°C	26,3	0,9	-16,3%	30,18	79%	87%	99%
T_{supply}, 17°C	28,3	1,0	0,0%	27,25	90%	97%	100%
T_{supply}, 18°C	27,9	1,1	1,9%	26,37	89%	97%	100%
T_{supply}, 19°C	27	1,1	3,8%	24,98	88%	96%	100%
T_{supply}, 20°C	25,5	1,2	12,5%	21,84	85%	93%	99%
$\dot{m}$, 400 kg/h (63 W)	28,2	1	-3,8%	28,27	89%	96%	100%
$\dot{m}$, 900 kg/h (74 W)	28	1,2	10,6%	24,39	89%	97%	100%
$\dot{m}$, 1150 kg/h (79 W)	27,7	1,2	18,3%	22,56	89%	96%	100%
$\dot{m}$, 1400 kg/h (84 W)	27,7	1,3	26,9%	21,04	89%	96%	100%
$\dot{m}$, 1650 kg/h (87 W)	27,5	1,4	32,7%	19,95	89%	96%	100%

Energy performance

The indoor temperature set-points have the greatest influence on the energy demand and consumption. In the heating season, higher indoor temperature set-points result in higher demand and consumption (21% and 33% higher for 2°C increase for Copenhagen and Madrid, respectively) followed by a decrease in COP and COP_{sys}. Changes in COP and COP_{sys} are more pronounced in Copenhagen. In the cooling season, higher indoor temperature set-points result in lower demand (15% and 7% lower for 1°C increase for Copenhagen and Madrid, respectively) and consumption. Free Cooling Coefficient increases with higher indoor set-points.

Dead-band increase (from ±1 K to ±2 K) results in a more flexible, less precise control, and its effects are visible in the decreased demand and consumption values for all cases. COP and COP_{sys} are almost not affected while Free Cooling Coefficient is affected slightly.

Due to the low temperature heating and high temperature cooling concept, when investigating the effects of different supply temperatures, lower temperatures than the design temperatures were investigated in the heating season. A similar approach was utilized in the cooling case in order to investigate the possibility of higher supply temperatures (also due to dew-point).

In the heating season, energy demand and consumption (12% and 7% lower for 4°C lower supply temperature for Copenhagen and Madrid, respectively) tend to decrease with the decrease of the supply temperature set-point. This results in higher COP but lower COP_{sys}. COP is not affected in Madrid. In the cooling season, cooling demand decreases with increased supply temperature set-point (17% and 10% lower for 4°C higher supply temperature for Copenhagen and Madrid, respectively) but this is not reflected to the consumption values due to the longer operation of the circulation pump. This trend is reflected to the Free Cooling Coefficient values.
The results show that flow rate in the ground loop doesn't have a significant effect on the demand and the consumption for the heating case. For the cooling case, effects are more pronounced on the consumption due to the free cooling concept (direct interaction of the house with the GHX). COP_{sys} and Free Cooling Coefficient values tend to decrease with increasing flow rate mainly due to the higher consumption of the circulation pump.

Comfort conditions

The thermal comfort is most sensitive to the indoor temperature set-points. The effect of increased dead-band is more visible in the heating season. Increase of the dead-band results in a less strict control over the respective parameter therefore the comfort conditions tend to get worse (due to less operating hours of the heat pump and/or the circulation pump).
In the cooling season, increased dead-band has a similar effect on the comfort conditions to an increased indoor temperature set-point.
Comfort categories are less sensitive to the indoor temperature set-point changes during cooling season than in heating season. This could be explained with the higher heating demand than cooling demand. The same behavior is also observable for supply temperatures.
The supply temperatures to the embedded pipes have more effect on the comfort conditions than the flow rate in the ground loop but less effect than the indoor temperature set-point.
The results show that the flow rate in the ground loop doesn't have a significant effect on the occupant thermal comfort neither in the heating season nor in the cooling season.
Climatic effects can be observed in the case that Copenhagen is more sensitive to the supply temperatures in the heating case (different heating needs) however in the cooling case this effect is not possible to observe directly.
Indoor operative temperatures are presented in the following figure for both of the locations during a representative week in July for Copenhagen and Madrid respectively (outdoor dry bulb temperature is shown on the right axis):

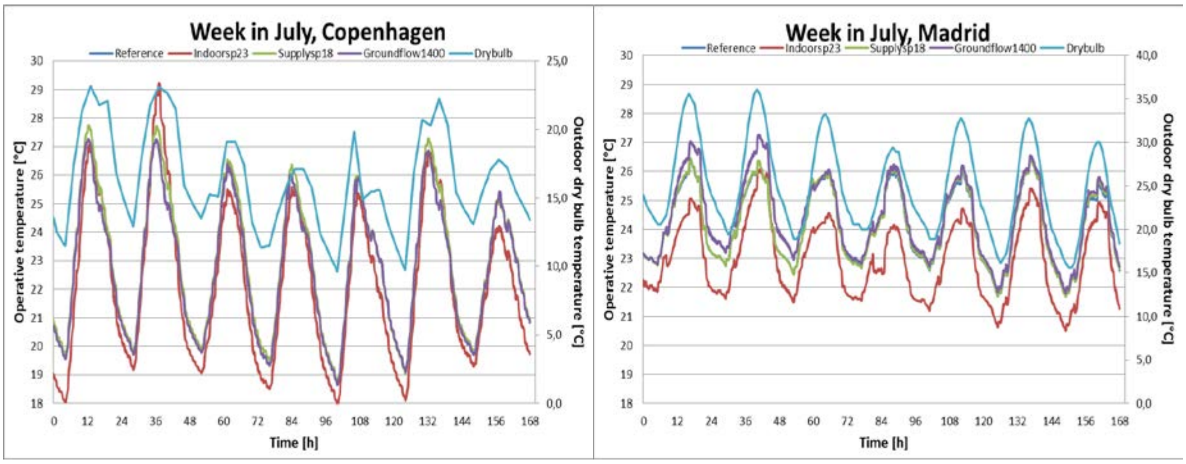

Figure 3: Operative temperatures during a week in July for both of the locations

It is important to bear in mind that comfort categories only consider operative temperature but thermal comfort is a function of other parameters such as humidity. Therefore Predicted Mean Vote (PMV) could have been used in order to evaluate the occupant thermal comfort. Local thermal discomfort issues should also be considered.
Every simulation software has its own advantages and limitations therefore the results presented in this paper will be validated with the full scale experiments in the near future.

DISCUSSION and CONCLUSION

Among the investigated parameters, the indoor temperature set-point is the most dominant parameter with respect to energy demand, consumption and occupant thermal comfort. Energy consumption and thermal comfort are also sensitive to the supply temperature to the embedded pipe loops but not as much as indoor temperature set-points. Flow rate in the ground has very low influence on energy consumption and occupant thermal comfort. This effect could be explained as closer the component/parameter to the indoors, higher the sensitivity (more components in between less the effect). When the indoor temperature set-point is changed, every component in the system has to be adjusted accordingly but when the set-point of a component is changed, this change does not affect the system as much because the effects get dampened and not all of the other components need to be adjusted accordingly. It is possible to save 23% and 34% of energy consumption during heating season in Copenhagen and Madrid, respectively. In the cooling season, it is possible to reduce cooling demand by 17% and 10% in Copenhagen and Madrid, respectively. While these reductions result in fewer hours within Category I and II, Category III is satisfied for all of the cases for more than 95% of the time. Climatic differences are observable via different effects of modifications on the results. Increased dead-band results in lower energy consumption and demand but it also results in decreased occupant thermal comfort.
It is possible to achieve 1°C reduction in supply temperature in the heating mode and 1°C increase in supply temperature in the cooling season with almost no change in the comfort conditions. However all of the other energy saving measures other than supply temperature modifications are accompanied with lower comfort for the occupants. Due to this trade-off between energy consumption and occupant thermal comfort, an optimum system operation point should be chosen based on the priority.

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