Potential benefits in terms of thermal comfort and energy use of adding a control loop to an existing multizone Air Handling Unit in a hospital setting

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Abstract

Hospital Virgenlas Nieves currently features a multizone air handling unit (AHU) that provides ventilation and space conditioning to 4 spaces. It is a very old, non-standard unit with 2 stages of conditioning that heavily relies on manual control. The system will soon be upgraded with a connection to the main building management system, which will allow automatic control. A TRNSYS model was used to evaluate the potential benefits of AHU control strategies in terms energy use and thermal comfort. A control logic based on constant air temperature setpointsafter the 2 conditioning stages results in 24% heating energy savings and 57% decrease in overall heating degree-hours. Benefits in cooling mode are smaller.A second control strategy uses a fuzzy controller of Matlab to continuously set variable setpoints of plenum temperatures and supply air to the zones. While energy results are similar, comfort results are much more satisfactory.

1 Introduction

Hospital Virgen de las Nieves (hereafter referred to as HVN) located in Granada (Spain) uses a multizone air handling unit (AHU) as the sole means to provide ventilation and space conditioning to 4 zones (2 of which include a surgery room). The system is not currently connected to the main building management system, and heavily relies on manual control. The system operators receive frequent comfort complains from the occupants. The system is to be connected to main building automation system, which will allow implementing control strategies to improve thermal comfort and energy use. HVN has the exact same system set up in 5 additional floors in which the control solutions developed here could be easily replicated.

Objective

The objective of this study is to define control strategies for the air handling unit to improve system performance in terms of thermal comfort and energy use. Control strategies will be pre-evaluated using energy modeling tools (TRNSYS and Matlab).

2 Background

Advanced Air Handling Unit controls

Advanced control techniques of Air handling units have been developed in the latest years, and have been test based on experiments as presented by Kolokotsa et al. (Kolokotsa et al., 2002). In their publication fuzzy controllers are presented for controlling the air conditioning system and the dampers based on an interface using LON protocol.

A different application in a test chamber has been presented by Kolokotsa et al. (Kolokotsa et al., 2006), in which the internal conditions are controlled using a fuzzy controller which is installed in a computer and the commands are sent to the chamber's controller using an OPC Server. In the installation, the operation of the air handling unit and the external window are controlled based on inputs from temperature, humidity and air quality sensor.

A review on the available controllers for heating and cooling plants have presented by Dounis et al. (Dounis and Caraiscos, 2009) in which the classical controllers are compared to more advanced ones such as fuzzy based ones, and neural network controllers.

Dounis et al. (Dounis et al., 2011) have used the interconnection between TRNSYS and Matlab (type 155) to exchange information. Thus the TRNSYS thermal model has been used to verify the proper operation of the Matlab controller.

Thermal comfort assessment in surgery rooms

Indices to evaluate general thermal comfort in buildings found in literature are typically based on the Fanger model (Fanger, 1970), which introduced "Predicted Mean Vote" (PMV) and "Predicted Percentage of Dissatisfied" (PPD) as comfort indices. These indices are also used in standards EN ISO 7730:2005 (CEN European Committee for Standardization, 2005) and EN 15251:2007 (CEN European Committee for Standardization, 2007). Carlucci and Pagliano (2012) provided a detailed review of thermal comfort indices for general use spaces.

However, due to their unique characteristics, "Fanger-based" indices are not used in standards and guidebooks for surgery room design and operation. ASHRAE Standard 170 (ASHRAE, 2008) requires design temperature and relative humidity ranges to be 20-24ºC and a 30-60% respectively. The same values are recommended in the HVAC Design Manual for Hospitals and Clinics (ASHRAE, 2003), while and the Applications Handbook (ASHRAE, 1999) recommends a narrower range for relative humidity (45-55%) and a wider range for temperature (16.7-26º.7C) design. It must be stressed that these are system design ranges. However, this does not imply that their setpoints either during operation or when not in use must fall within these ranges.

3 Method

System description

The AHU in the surgery rooms of HVN is a multizone system that provides ventilation (fresh air) and space conditioning (either heating or cooling) to 4 zones (2 of which include surgery rooms). Figure 1 shows the SketchUp model of the spaces served by the AHU and the relevant shading elements.

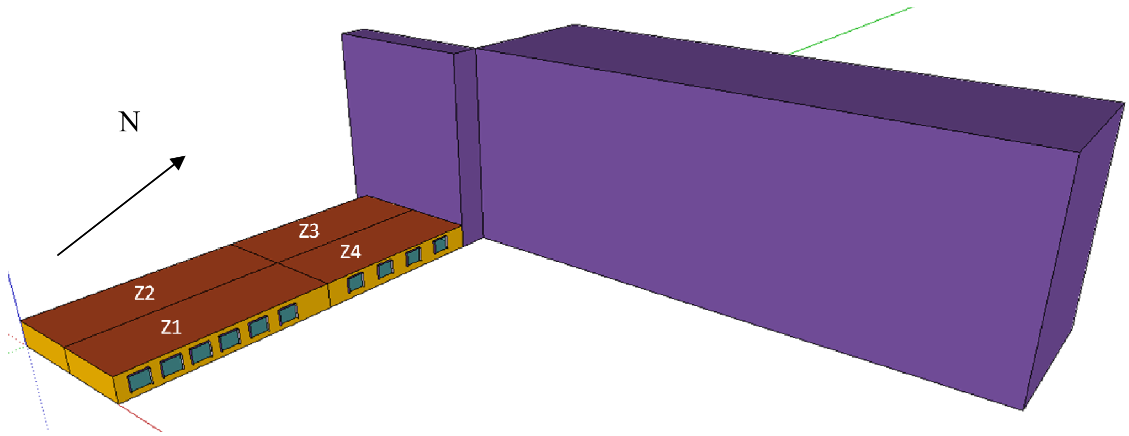

Figure 1 – SketchUp model - Zone layout

This AHU is a dedicated system (100% outdoor air) with no heat recovery. There is an independent supply duct for each of the 4 zones with an independent control damper for each of them. Figure 2 shows the AHU schematic.

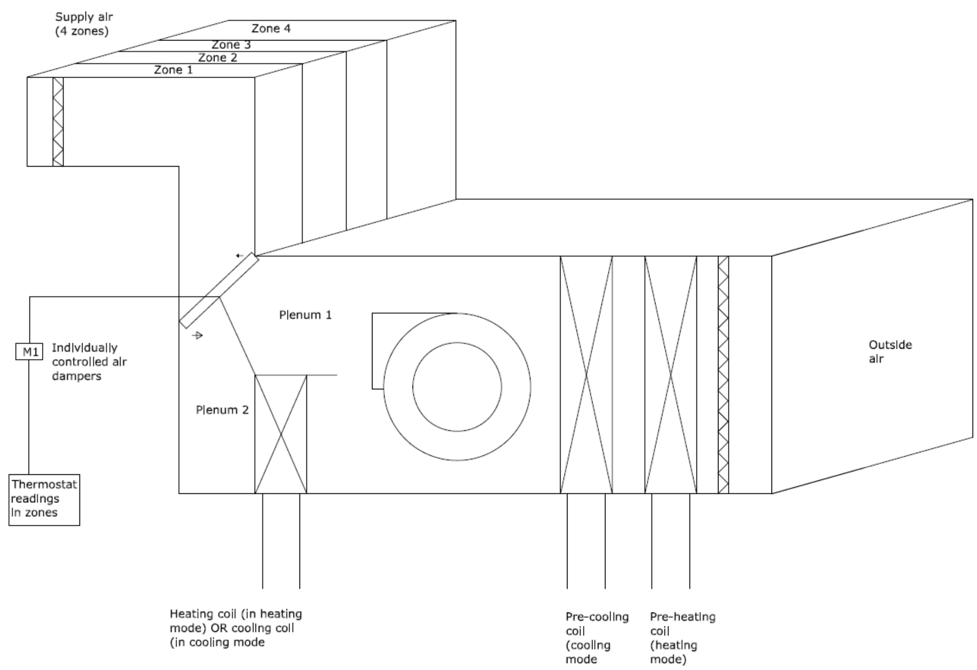

Figure 2 – Schematic of the multizone AHU in Hospital Virgen de las Nieves

The amount of supply air to the 4 zones is constant (constant volume system); the dampers change the ratio of air that comes from the 2 available plenums (at different temperatures): it could be 100% from one of the two sides, or a mix of the two. Air in Plenum 1 runs only through one pair of pre-conditioning coils ("1 stage conditioning", there are 2 coils heating/cooling in series, but only one active at a time), while air in Plenum 2 runs through an additional conditioning coil ("2-stage conditioning", 1 coil that is either heating or cooling depending on the season). This AHU is connected to a 2 pipe system - therefore, all the water in the coils is eitherheating or cooling.

The control system is currently not integrated in the central building management system.

- Room temperature set-points are manual control inputs by the occupants (through thermostats).
- Room temperature set-point drives the individual dampers position (through an internal control).
- Valve positions of the 3 coils (the 2 stages of conditioning) are manually operated. There is no automatic control over coil water flow rates, and therefore, no control over air temperature in the 2 plenums.

The air handling unit has no humidity control capabilities (neither humidification nor dehumidification) and the spaces have no humidity sensors. Therefore, none of the models considered humidity control (although outdoor air relative humidity was accounted for in the heating and cooling coils energy exchange).

The HVAC Design Manual for Hospitals and Clinics (ASHRAE 2003) recommends variable air volume (VAV) systems in spaces where there are significant unoccupied hours (such as surgery rooms). While a VAV would likely enhance energy efficiency in this case study, HVN is postponing measures that imply hardware purchase and installation.

Baseline model

Both the building and the system were modeled in TRNSYS version 17 (University of Wisconsin et al., 2013). Version 17 features a new building model that contains 3D geometric surface information that is used for the detailed radiation calculations. The building model included only a single storey (which corresponds to the service space of the air handling unit), and assumed no heat transfer to/from the adjacent stories (which was considered a reasonable simplification, as the adjacent stories have the same space use and lay-out). Heating and cooling coils were modeled with TESS types 670 (heating) and 508 (cooling), which calculate outlet temperatures of air and water based on their respective inlet temperatures, flow rates, and a user defined by-pass factor (which was adjusted based on monitored data, as explained below). Zone geometry and envelope characteristics were modeled based on the documentation provided by Hospital Virgen de las Nieves. The weather file for Granada was obtained from the Meteonorm Database (METEOTEST).

Internal gains in the selected areas were calculated based on approximate values of occupancy density, lighting, and equipment use provided by Hospital Virgen de las Nieves personnel. Zones 1 and 2 have the same floor area ($158m^2$) and space type distribution; therefore, they also have the same (assumed) internal gains. The same is true for Zones 3 and 4 (floor area = $136m^2$). Note, however, that total gains in the 4 zones are different due to the differences in orientation and exterior wall and window area. Table 1 summarizes the assumed internal gains in the zones. Table 2 summarizes zone characteristics.

Table 1 – Occupancy and internal gains in the zones

Time interval	Gains	Zones 1 and 2	Zones 3 and 4
Morning	Occupants (#)	9	4
(8:00-15:00)	Radiant (W)	2741	1852
	Convective (W)	1133	744
	Latent (W)	855	380
Afternoon	Occupants (#)	10	0
(15:00-22:00)	Radiant (W)	2773	1369
	Convective (W)	1191	152
	Latent (W)	950	0
Night	Occupants (#)	5	0
(22:00-8:00)	Radiant (W)	2615	1369
	Convective (W)	899	152
	Latent (W)	475	0

As part of the work developed within the EC-funded Green@Hospital project (Green@Hospital), the AHU was recently equipped with monitoring equipment that allowed for the adjustment of some of the system parameters in the model. An energy meter was installed in each of the heating and cooling coils of the AHU. According to the data sheet (Kamstrup), thermal energy metering error was:

$$Error = \pm\left(0.15 + \frac{2}{\Delta\theta}\right)\% \quad (1)$$

Where $\Delta\theta$ is the difference between inlet and outlet water temperature in the coil.

Model validation was basically done based on data corresponding to the period between October 4 and 7, 2013 (cooling season).

Total supply airflow rate was adjusted based on the heat transfer balance in the first conditioning coil (a monitoring input). The adjusted total supply airflow was 7700kg/h. It must be noted that this value is similar to the initial assumption, which was based on the results of air velocity spot measurements carried out by HVN personnel (8200kg/h).

The adjusted total supply airflow was used as a model input for the precooling coil. Precooling coil bypass factor was adjusted until the model outlet temperatures of both air and water showed close results compared to the monitoring values. The resulting by-pass factor (i.e., fraction of air that does not interact with the conditioning coil) was 75%, which is very large yet consistent with a very old air handling unit.

The same method was used to adjust the model of the second conditioning coil (recooling coil, in cooling mode), although only periods in which the 4 air dampers were fully closed could be used (necessary condition to know the corresponding airflow rate). The by-pass factor was adjusted to 85%, which provided a good match for both air and water side outlet temperatures.

Distribution of total supply airflow into the 4 zones was based on the relative size of duct section at the outlet of the AHU, which carries the implicit assumption that the pressure drop in the 4 distribution ducts is roughly the same.

Table 2 – Zone characteristics

Parameter	Zone 1	Zone 2	Zone 3	Zone 4
Floor area (m^2)	158	158	136	136
Exterior wall (m^2)	71	0	0	45
Window area (m^2)	16	0	0	11
Fraction of supply airflow (%)	52	26	7	15

Waterflow values for the two stages of conditioning were obtained from monitoring. There was only 12 days' worth of reliable data. Waterflow through the conditioning coils was not constant due to hydraulic instabilities (this AHU does not have a dedicated water supply loop), however, variations were relatively small (see Table 3). Because of the lack of more representative information, the 12-day waterflow profiles were used as a constant modeling input throughout the year (i.e., the same data series were repeated over and over). This assumption imposes a strong limitation on model reliability, as in reality the system operators would occasionally adjust coil valves based on comfort complains. Nonetheless, the authors decided to repeatedly use these waterflow profiles because they were not able to find more reliable data/method to describe operator's manual adjustments.Furthermore, while the results derived from this hypothesis may not accurately represent reality, they are a good illustration of the performance limitations of the currently implemented control system.

Table 3 – Water flow through conditioning stages. Monitoring results

Parameter	1st Stage	2nd Stage
Minimum flow (kg/h)	5460	1396
Average flow (kg/h)	6997	1772
Maximum flow (kg/h)	8436	2073
Standard Deviation (kg/h)	444	130

The supply air temperature control (i.e., damper position) was implemented in the model according to the following logic:

- Room air temperatures (readings from the building module) and room temperature setpoints (assumed 23ºC both for summer and winter, based on the expertise of HVN personnel) are compared. The default supply air temperature setpoints are set as the room air temperature setpoints (occupant input). When there is a >1ºC difference between room temperature reading and the corresponding temperature setpoint, a proportional control modifies supply air temperature setpoint to a lower or higher value depending on the zone cooling/heating requirements. This results in a set of "ideal" supply air temperature set-points for the 4 zones.
- The ideal supply air set-points are modified to fall within the feasible limits of the 2 stages of conditioning (in heating mode min = PHC Temp, max = RHC temp, where PHC is air at "preheating coil" outlet and RHC is air at the "reheating coil" outlet, the two plenums).
- The modified supply air temperature set-points for the individual zones are used as inputs for the flow diverters and mixers, which correspond to the air dampers in the multizone AHU.
- Supply air outputs of the AHU model are inputs for the zones in the building model.

Energy performance evaluation was based on the thermal energy use in the conditioning stages (both in heating and cooling). This is thermal energy (heating and cooling) provided by the conditioning coils, and does not account for the efficiency of the central heating and cooling plant. Fan electricity use was not included in the analysis because it is a constant volume system (i.e., fan energy use remains constant regardless of the control strategy).

In terms of thermal comfort, the difference between room air temperature and room air temperature setpoint was used to evaluate the effectiveness of the control strategy in delivering the desired comfort. The difference between delivered and desired supply air temperatures was integrated over time, and presented in terms of "degree-hours". As acknowledged in Section 2, thermal comfort in general use spaces is often evaluated with indices based on the work by Fanger. However, the authors chose to use degree-hours because 1) the system is only capable of controlling (and only to some extend) one of the comfort parameters: temperature, 2) surgery rooms do not have standard conditions of interior setpoints, clothing level, or metabolic rate that are required for the assessment of PMV and PPD, and 3) the purpose of the study is to assess how well the system can match the local temperature setpoints. Previous studies (Stephan et al., 2011) have used degree-hours to assess systems based on a single control parameter (temperature).

Control logic 1 – Constant plenum temperatures

The first improvement to the AHU control was to add control loops in the conditioning coil flow rates so that air temperature in the two plenums remained "constant". It must be noted that this is a 2-pipe system, and therefore, control capabilities of the AHU are limited: supply air temperature cannot be higher than outdoor air temperature in cooling mode, and cannot be lower in heating mode.

This strategy was modeled by using ideally controlled heating and cooling coils. These provide the required heating/cooling for the outlet air to exactly match a given temperature setpoint, however, they are still limited by the 2-pipe constraint (i.e., cooling is only possible in cooling season, and heating is only possible in heating season). A parametric analysis was run to evaluate the performance of the system under a variety of plenum temperature setpoints.

Control logic 2 – Dynamic plenum temperature setpoints based on readings from indoor temperature

An advanced controller is developed in Matlab's environment. The specific programming environment is selected because it contains several toolboxes for advanced control techniques development. In order to initiate an interface between Matlab & TRNSYS, type 155 is used. Using the specific type, data are exchanged between Matlab and TRNSYS, so that Matlab is called after the convergence of the TRNSYS model. This condition reflects the approach followed in real-time implementation when a sensor is reading a condition, and then the controller is sending a command to the systems. Each time-step, TRNSYS sends selected data to Matlab, which in return sends back control commands to TRNSYS. Inside Matlab's environment a smart controller for the surgery room air handling unit, based on fuzzy logic, is called.

Fuzzy logic architecture is selected because it contains, in the form of rules, the knowledge of the personnel which is currently adjusting the system manually. The input to the controller is the difference between the current temperature in each room separately from the defined setpoint. Thus, the controller is trying to minimize the error between these two values. Due to the installation and operation of a PID controller for basic control the smart controller is designed to adjust the supply air set-point of the 4 air streams. The architecture and the characteristics of the developed fuzzy controller can be seen in Table 4.

Table 4 - Architecture and characteristics of the fuzzy controller

Type of fuzzy controller	'Mamdani'
N. of inputs	4: error between current and desired indoor temperature
N. of outputs	4: change of supply air set-point
Fuzzification membership functions	5
De-fuzzification membership functions	5

The fuzzification parameters are similar for all 4 rooms and they can be re-adjusted if it required in case one of the rooms has different performance. Similarly, the de-fuzification parameters can be re-adjusted if required.

Moreover the system can only provide heating or cooling based on the season of the year (2 pipe system). Thus, the controller has to be adjusted in order to operate for both heating and cooling season. In order to prevent an un-normal operation of the controller, the supply air temperature set-points has to be limited between some upper and lower boundaries. The boundaries for the set-points can be seen in Table 5.

Table 5: Boundaries of supply air temperature set-point

Seasons	Boundaries	Values
Cooling mode	Upper limit	25°C
	Lower limit	13°C
Heating mode	Upper limit	30°C
	Lower limit	13°C

In cooling mode supply air temperature should be above 13 C to avoid local discomfort (draft). Similarly, the minimum setpoint for heating cannot be below 13 C. The upper limits are selected based on the response of the system to the controller's commands. Each time-step the output of the controller (positive or negative) is added to the previous stored value and the new one is sent to the TRNSYS model. Thus, if the upper limit for cooling mode is higher than 25°C, it will take more time-steps to find the required supply air temperature set point which will balance indoor temperature close to the set point.

Furthermore, the controller is adjusting the temperature set-point of the 2 chambers (pre-heating/cooling, re-heating/cooling). The values of these set-points depends on the minimum and maximum values of the new supply air set-points. For heating mode the pre-heating chamber is having as set-point temperature the minimum value of the supply air temperature and the re-heating chamber is having the maximum value. Thus, the rooms which require these temperature can be pleased while the other 2 rooms can be pleased adjusting the dampers internally. Similarly for cooling mode, the pre-cooling chamber is having the maximum value of new supply air set-points while the re-cooling chamber is having the minimum value.

4 Results and discussion

Baseline Results

Figure 3 and Figure 4 show monthly profiles of heating and cooling thermal energy use, respectively. Both figures show the relative contributions of the 2 conditioning stages. Since this is a 2-pipe system, there is no simultaneous heating and cooling energy use. Based on the experience of Hospital Virgen de las Nieves personnel, the heating/cooling mode change dates were assumed to be June 1st and October 15th (hence, there is both heating and cooling energy use in October).

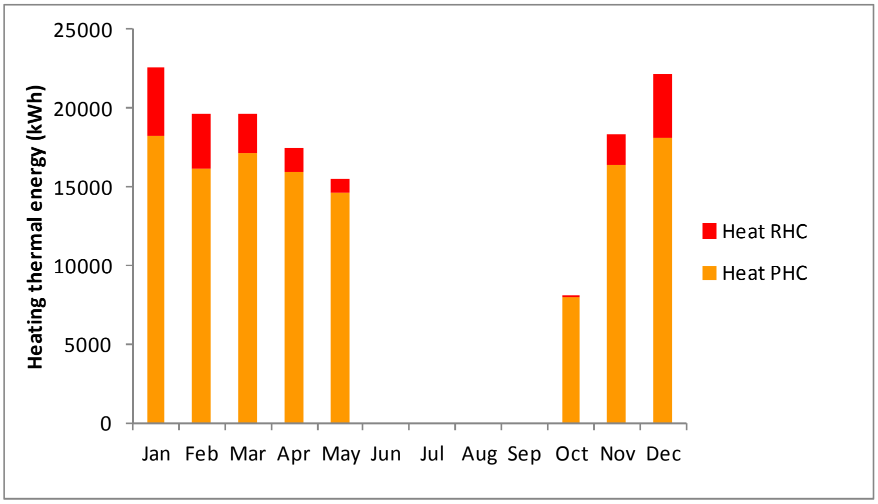

Figure 3 – Baseline results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

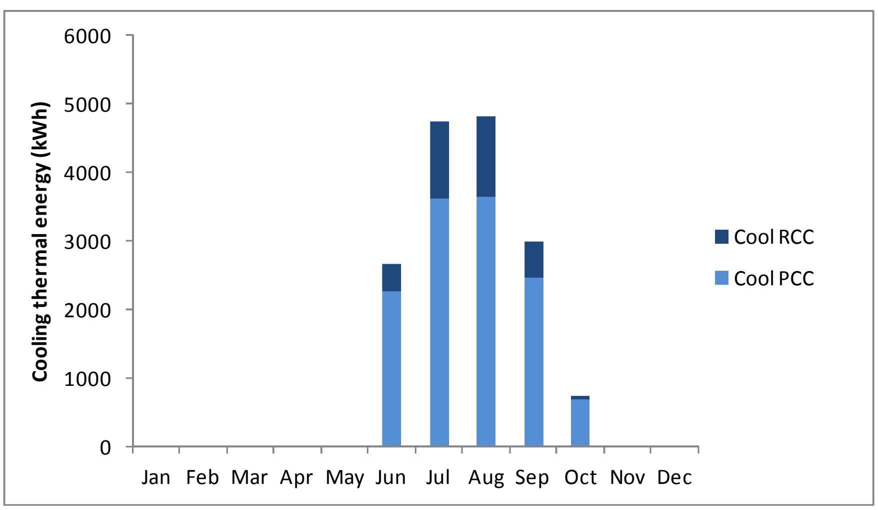

Figure 4 – Baseline results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Although total heating and cooling thermal energy use follow the expected profile (larger heating energy use in the coldest months, larger cooling energy use in the hottest), heating energy use in the first stage of conditioning remains fairly constant throughout the heating season. The contribution of the first conditioning stage (both in heating and cooling) is largely dominant over the second stage of conditioning. Considering that the second stage of conditioning provides flexibility to adjust supply air temperatures according to the different requirements in the 4 zones, itsvery low energy contribution suggests that it is often by-passed due to a too hot (in heating mode) or too cold (in cooling mode) air temperature after the first stage of conditioning.

Figure 5 andFigure 6show monthly profiles of degree-hours (cumulative deviation between air temperature and room temperature setpoint) in heating and cooling season, respectively. Both figures show the degree-hours break-down by zone.

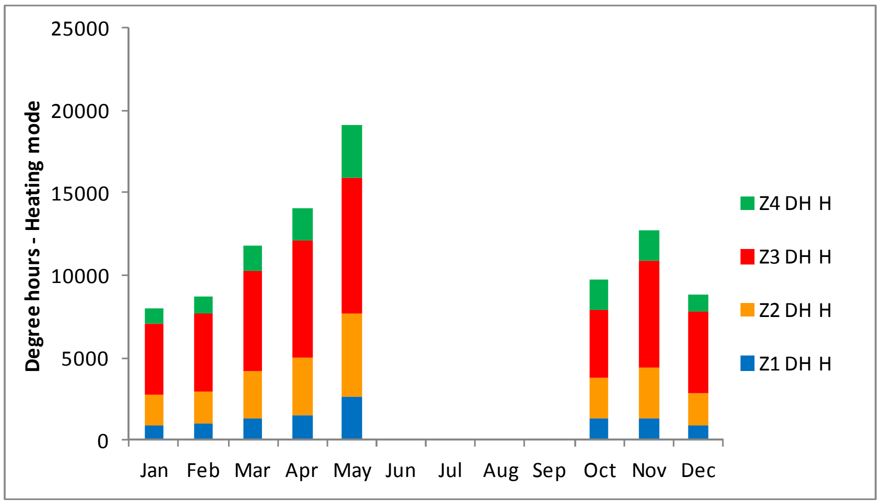

Figure 5 – Baseline results. Degree hours in heating mode

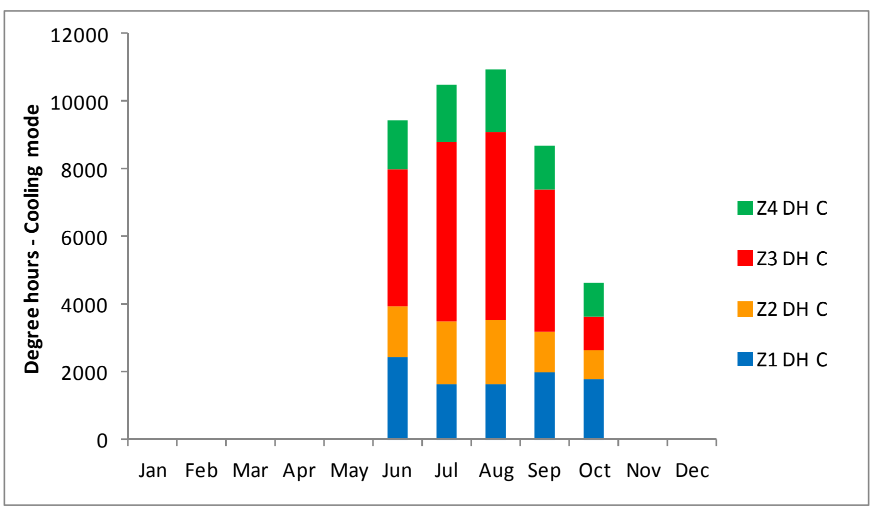

Figure 6 – Baseline results. Degree hours in cooling mode

The figures above show increasing thermal discomfort in the shoulder seasons (i.e., near the mode-change dates), which is typical of 2-pipe systems. It must be noted that these periods correspond to the lowest thermal energy contributions of the second conditioning coil. This suggests that the lower flexibility of the system to adjust supply air temperatures results in increased thermal discomfort.

Monthly values of degree-hours are high, and generally larger in the heating season. Interior zones (Zones 2 and 3) are the most uncomfortable.

Control logic 1 Results

Figure 7 and Figure 8 show cumulative values of heating thermal energy use and degree-hours in heating mode, respectively. Both figures compare baseline (BL) vs. control 1 strategy results for a variety of combinations of plenum temperature setpoints (PHC ranges 10-14ºC, RHC ranges 26-30ºC).

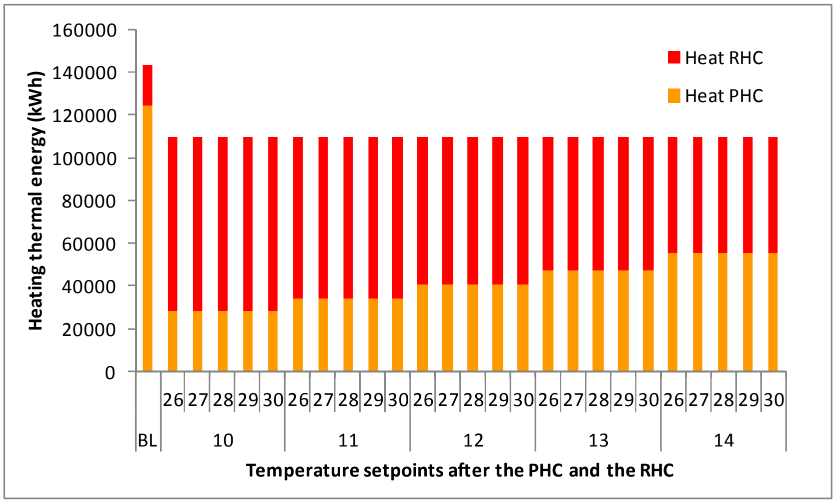

Figure 7 – Control logic 1 results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

While the relative energy contributions of the two stages of conditioning largely vary with PHC temperature setpoint, the total thermal heating energy use with control strategy 1 is basically constant across the tested spectrum of PHC and RHC setpoints. Total heating energy use is roughly 110,000kWh/yr, which translates into 24% savings compared to the baseline scenario. It must be noted that, compared with the baseline, all the tested combinations show a much lower contribution of PHC to the overall heating thermal energy use.

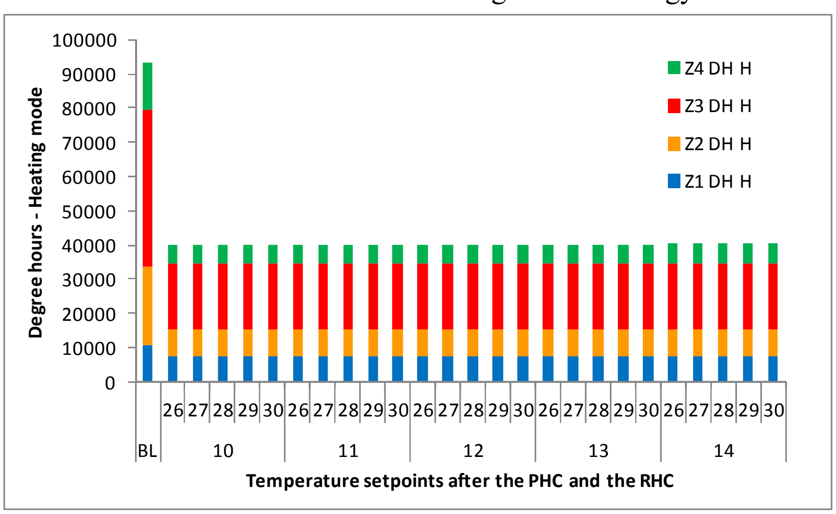

Figure 8 – Control logic 1 results. Degree hours in heating mode

Simulation results show that (within the tested ranges) temperature setpoints in the two plenums seem to have almost no impact on thermal comfort in heating mode. The overall degree-hours with control strategy 1 in heating mode drop from roughly 93,000 in the baseline to 40,000, which is a very significant (55%) reduction.

Figure 9 and Figure 10 show cumulative values of cooling thermal energy use and degree-hours in cooling mode, respectively. Both figures compare baseline vs. control 1 strategy results for a variety of combinations of plenum temperature setpoints (PCC ranges 23-27ºC, RHC ranges 13-14ºC).

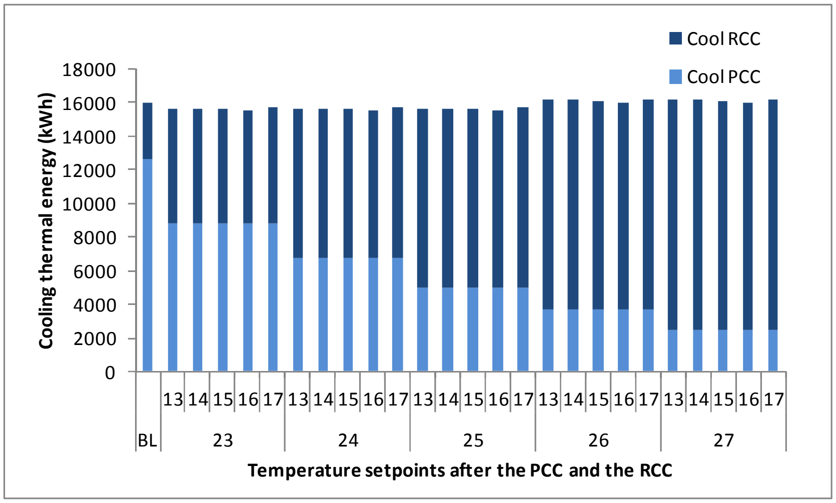

Figure 9 – Control logic 1 results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Unlike in heating mode, overall cooling energy use does not see a substantial reduction with control 1 strategy, and even slightly increases in high PCC setpoints. This result suggests that the "not controlled" waterflow rates better match the cooling loads that they do the heating loads.

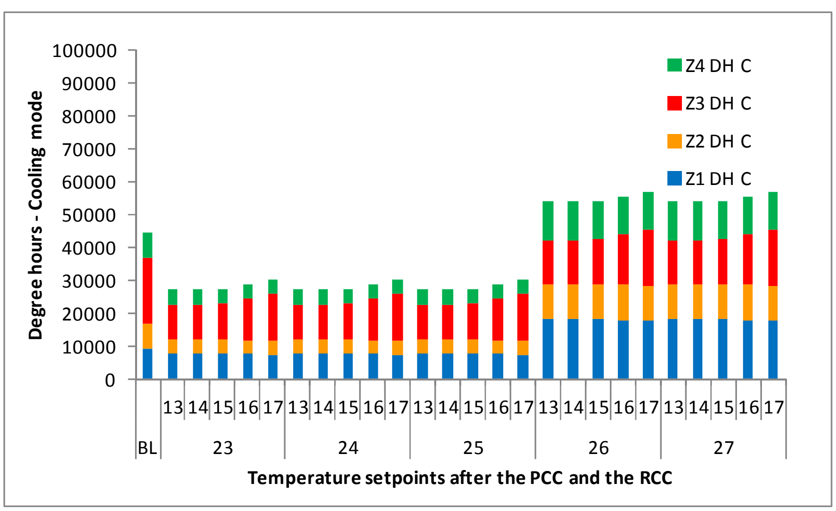

Figure 10 – Control logic 1 results. Degree hours in cooling mode

Similarly, degree-hours in cooling mode with control logic 1 do not see the consistent drop that was found in heating mode. It must be noted that with high PCC temperature setpoints degree hours with control logic 1 increase above the baseline. The sharp increase of degree-hours at the 25-26ºC boundary is the result of the internal control logic of supply air temperature as a function of room air temperature difference with its setpoint (see "baseline model") and the constant 1ºC deadband. Nevertheless, results suggest that control logic 1 provides more benefits in heating mode than it does in cooling mode.

Although it cannot be seen in the above results, it must be noted that, unlike the baseline case, control logic 1 guarantees minimum supply air temperature equal to or above PCC setpoint (13-17ºC depending on the case), which avoids local thermal discomfort (draught). This is an additional comfort benefit of control strategy 1.

Control logic 2 Results

The controller is being tested connected to the developed TRNSYS model. The new supply air temperature set-points are provided every 15 min to the TRNSYS model based on temperature readings of this time step. Figure 11 and Figure 12 show monthly profiles of heating and cooling thermal energy use, respectively. Both figures show the relative contributions of the 2 conditioning stages.

Total heating and total cooling energy monthly profiles are similar than in the baseline scenario. However, total heating demand with control strategy 2 is reduced, while total cooling demand is slightly higher. The share of heating energy supply by the reheat coil is much larger with control strategy 2 than it was in the baseline scenario.

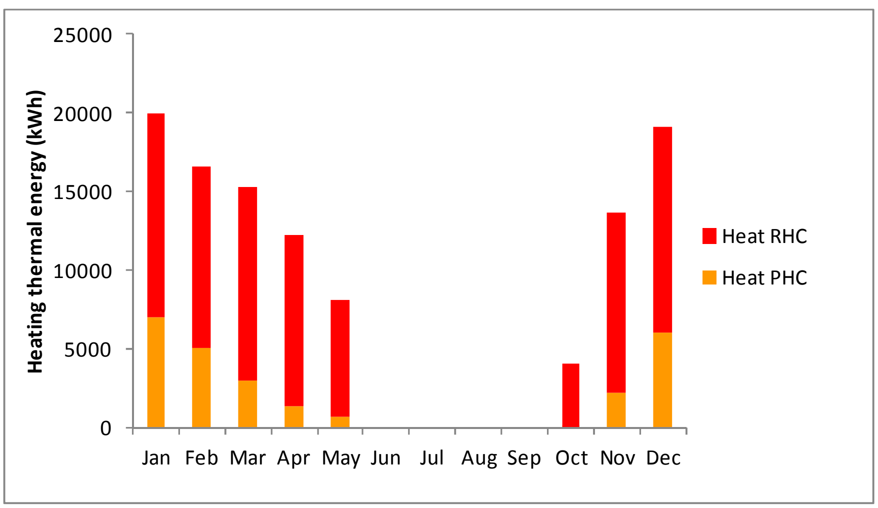

Figure 11 – Control logic 2 results. Heating thermal energy use. PHC is energy use in the preheating coil (1st stage of conditioning), RHC is energy use in the reheating coil (2nd stage of conditioning)

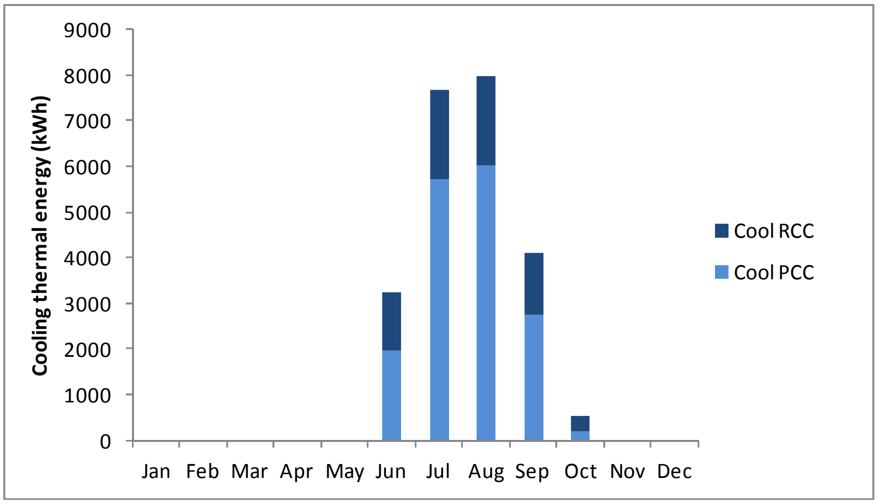

Figure 12 – Control logic 2 results. Cooling thermal energy use. PCC is energy use in the precooling coil (1st stage of conditioning), RCC is energy use in the recooling coil (2nd stage of conditioning)

Figure 13 and Figure 14 show monthly profiles of degree-hours (cumulative deviation between air temperature and room temperature setpoint) in heating and cooling season, respectively. Both figures show the degree-hours break-down by zone.

Both figures show similar profiles than the baseline scenario equivalents (with outstanding discomfort peaks close to the season-change dates), however, control strategy 2 provides much lower absolute values of degree-hours both in heating and cooling modes.

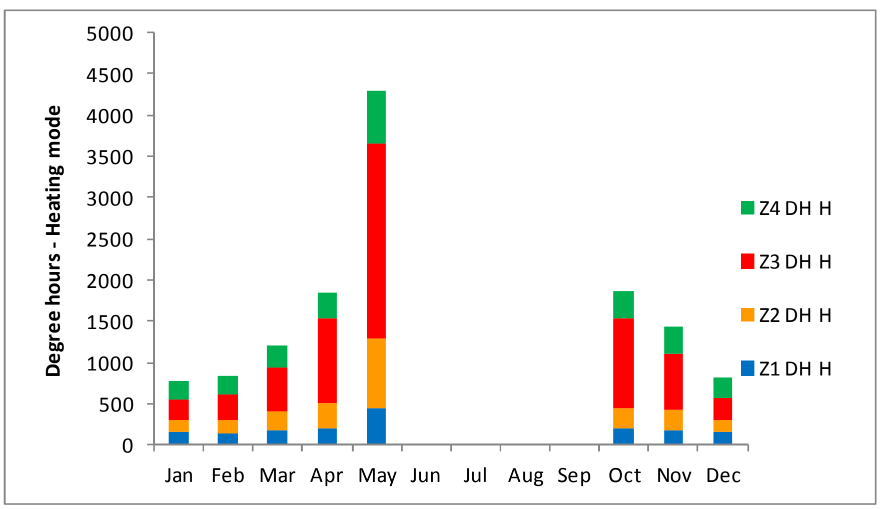

Figure 13 – Control logic 2 results. Degree hours in heating mode

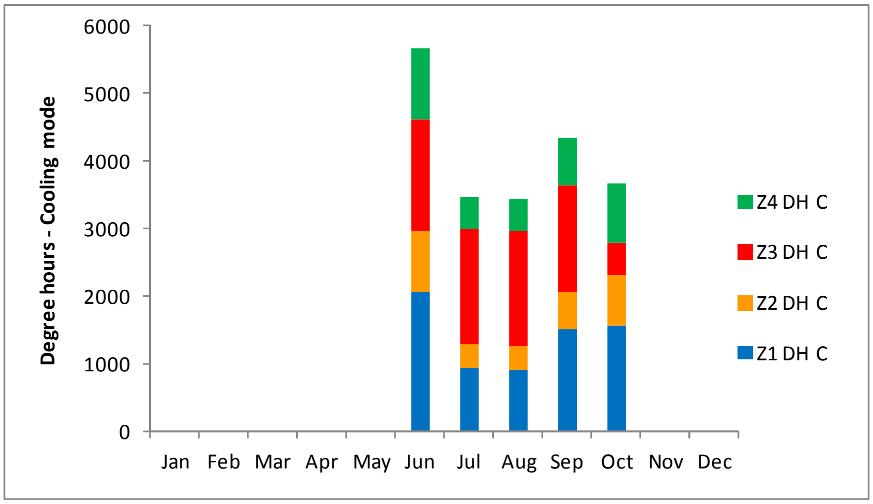

Figure 14 – Control logic 2 results. Degree hours in cooling mode

Table 6 summarizes the main energy and degree-hour results of the 2 control strategies, and compares them against the baseline case. Results of control 1 strategy correspond to the best performing case in the parametric analysis.

Table 6: Summary results. Energy use, degree hours, and relative improvement (%) vs. baseline

	Baseline	Control Strategy 1		Control Strategy 2	
Total heating energy (kWh)	143000	109000	24%	109000	24%
Total cooling energy (kWh)	15900	15500	3%	23500	-48%
Total heating DH	93000	40200	57%	13100	86%
Total cooling DH	44500	27100	39%	20600	53%

Control strategies 1 and 2 result in very similar energy savings in heating mode (24%), however, control strategy 2 achieves much larger comfort benefits, as it reduces degree hours in heating mode by 86%. In cooling mode, control strategy 1 performs slightly better than the baseline in terms of energy, while control strategy 2 uses more energy. However, control strategy 2 achieves much larger comfort benefits compared to the baseline.

5 Conclusions

Simulation results show that the AHU installed at Hospital Virgen de las Nieves currently performs poorly both in terms of energy use and thermal comfort (particularly in heating mode). Reliability of the baseline results is somewhat limited due to the lack of data of water-flow rate though the conditioning coils. Nevertheless, baseline results are a good illustration of the performance limitations of the currently implemented control system.

Control strategy 1 (fixed plenum setpoints) provides a better balance between the relative contributions of the 2 conditioning coils. Results show that in heating mode thermal energy use decreases by 24% and degree-hours decrease by 57%. Benefits in cooling mode are smaller.

Control strategy 2 (variable plenum setpoints) has a similar energy performance than control strategy 1 in heating mode, but achieves much better comfort results. In cooling mode this strategy uses more energy than control strategy 1 and even the baseline, however it does so in benefit of comfort.

Overall, both control strategies show large benefits compared to the baseline, both in terms of energy savings and thermal comfort. Control strategy 2 should be the choice to better satisfy comfort needs.

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