Assessment of Demand-Side Management on the Performance of a Single-Dwelling Mechanical Ventilation Plus Radiant Floor System

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Abstract

This paper focuses on the profitability of demand-side management strategies developed for a single-dwelling mechanical ventilation plus radiant floor system. Energy savings and comfort indicators are quantified for a number of control options, including demand-controlled ventilation and temperature setbacks. The assessment is based on numerical energy simulations conducted in TRNSYS for the climate of Bolzano (Italy). To perform the simulations, numerical models of the energy system and the reference dwelling were developed. Based on the analysed climate and building, it was found that demand-side management strategies can have a significant impact on the energy consumption and time distribution of energy loads: demand control ventilation allows the achievement of consistent energy savings in the electrical consumption of the fans (up to 37 %), whereas the use of an adaptive dehumidification setpoint can lead to savings within the range of 10 % in summer electrical consumption. The use of non-occupancy temperature setbacks does not show a significant impact on the annual thermal demand, although the time pattern of the loads is considerably affected, with a cascade effect on the performance of the air-to-water heat pump. The use of the climatic curve parameters at the generator allows an improvement of the electrical performance of the heat pump, increasing the SCOP of more than 20 %.

1. Introduction

The smart management of heating, ventilation and air conditioning systems is an active area of research, as new controls are developed to reduce energy consumption and improve occupant hygro-thermal comfort. Innovative solutions are moving on from simple strategies, providing an excess of ventilation to deal with poor or no information available on occupation, to providing just enough ventilation to fulfil comfort needs, thus avoiding waste of thermal and electric energy. This trend is favored by the availability of incrementally cheaper sensors and control hardware (Araújo et al., 2020), allowing for a detailed monitoring of the operation conditions and control of system components.

This paper investigates the impact of different control strategies on the performance of a single-dwelling mechanical ventilation and radiant floor system in the context of multi-family houses in Bolzano (Italy). Although a vast literature already exists on the topic of optimization of HVAC operational parameters (Gholamzadehmir et al., 2020; Selmat et al., 2020), this paper aims to contribute by providing a fresh perspective, since:

- it focuses on management strategies that could be easily adopted by using sensors and control hardware already on the market;
- it focuses on the growing sector of renovated buildings, where the use of mechanical ventilation and heat pumps is becoming a wide-spread solution;
- the impact of single-control choices are analysed considering not only the energy domain, but also IAQ and thermal comfort;
- the performances of a real ventilation unit are measured in the laboratory and used to calibrate the numerical model to provide more reliable results.

Part of
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This study was performed as part of the FESR project NewAir, which hosted the development of an innovative mechanical ventilation unit with dehumidification.

2. Methodology

To assess the energy and comfort signatures of the controls presented in the following, annual energy numerical simulations were performed with dynamic energy simulation software (TRNSYS (Klein et al., 1979)), coupled with a plug-in (TRNFLOW) modeling airflows and pollutant transport. Numerical models are elaborated accordingly after the following steps:

- Development of the thermal model of a renovated flat including a heat-pump-based energy system and radiant floors;
- Development and calibration of the numerical model of a ventilation based on the performance of a prototype tested in the laboratory.

Concerning Key Performance Indicators, the impact of single control strategies is assessed based on a set of indicators, which are (I) heat pump thermal energy generation, (II) heat pump electricity consumption, (III) electricity consumption of fans and refrigerant cycle in the ventilation unit, (IV) overheating / undercooling for thermal comfort and (V) occupancy hours distribution by CO_2 concentration classes according to (EN 16798-1, 2019).

Table 1 – CO_2 concentration thresholds for IAQ (EN 16798-1, 2019)

Class	Living room [ppm]	Bedroom [ppm]
1	< 950	< 780
2	950 < CO_2 < 1200	780 < CO_2 < 950
3	1200 < CO_2 <1750	950 < CO_2 < 1250
4	> 1750	> 1250

2.1 Reference Thermal Zone

The dwelling studied in this work is located in a multi-family house in Bolzano (Italy) and has a heated floor area equal to about 68 m². The apartment is divided into a living room, two bedrooms, a kitchen, a bathroom and a corridor.

The thermal model of the dwelling is divided into six different thermal zones (one per room), each containing an air node. Table 2 lists the main parameters of such a model. The occupancy profile is developed based on a three-state model: a person can be "away" or "at home and sleeping" or "at home and active". Depending on the occupancy status, different generation rates for internal gains (metabolism, use of appliances and lighting) and CO_2 emission are considered.

Table 2 – Thermal model parameters

Properties of building assemblies		
Glass, g-value	0.63	-
Glass, U-value	0.81	W/(m²K)
Window frame, U-value	0.93	W/(m²K)
External walls, U-value	0.35	W/(m²K)
Ventilation and infiltrations		
Design ventilation rate	0.75	ach
Infiltration rate at 50 Pa	1.5	ach
Internal gains and occupancy rate		
Occupants "home and active" (1.2 met (SIA, 2015)), latent gains	0.0153	g/s/pers
Occupants "home and active" (1.2 met (SIA, 2015)), sensible gains	76	W/pers
Appliances installed power (standby consumption: 10 %) (SIA, 2015)	10	W/m²
Lighting installed power (SIA, 2015)	2.7	W/m²
Crowding index	0.044	pers/m²
Full occupancy	3	pers
Thermostat settings		
Air temperature - Space heating	21	°C
Air temperature - Space cooling	25	°C
CO_2 transport model		
CO_2 generation, occupants "home and active" (based on (Persily & De Jonge, 2017))	0.009039	g/s/pers
CO_2 generation, occupants "home and sleeping" (based on (Persily & De Jonge, 2017))	0.007123	g/s/pers
Outdoor CO_2 concentration	400	ppm
Radiant floors		
Winter performance (room at 20 °C, water inlet at 30 °C, DT = 5 K)	36	W/m²
Summer performance (room at 26 °C, water inlet at 16 °C, DT = 5 K)	30	W/m²
Air-to-water heat pump		
COP (A7/W35)	4.17	-
EER (A35/W7)	3.02	-

The energy system is based on a 3 kW air-to-water reversible heat pump, which is able to work at partial loads in the range of 40-100 % compressor speed. For the sake of simplicity, it is assumed that domestic hot water is prepared with an additional heat generator. The heat pump numerical model is based on the performance map of a commercial product, including multiple air temperatures, water temperatures and compressor speeds. The space heating and cooling network is composed of the heat pump, a small thermal buffer and a radiant floor system. It is assumed that the thermal plant is activated without any restriction on the time of the day, and that the heating season spans the 1st of October to the 15th of April. It is assumed that sensors are installed in all rooms, except for the corridor and bathroom, to monitor temperature, humidity and CO_2 level. The radiant floor works both in heating and cooling working modes. The water loops in living room and bedrooms are managed based on the local temperature measures, whereas the ones in the kitchen and bathroom are controlled based on the living room temperature reading and can provide only heating. The supply temperature to the radiant floors is regulated based on the climatic curves shown in Fig. 1, whereas the water flow rate is governed in each loop by on-off valves activated when the air temperature thresholds are exceeded.

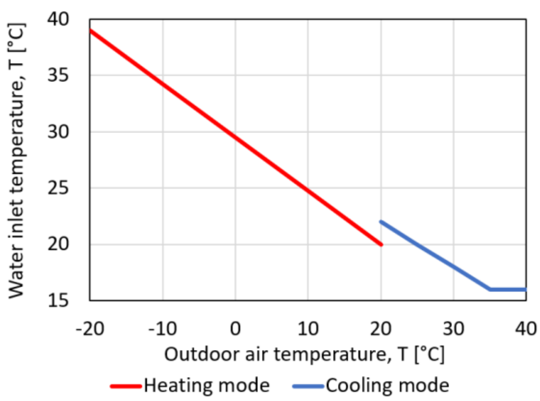

Fig. 1 – Climatic curves applied to the radiant floor system

An annual dataset of climate data was generated from the Meteonorm database for the locality of Bolzano (Italy). This dataset contains hourly values of climatic variables, such as convective air temperature and humidity, solar irradiation and intensity of wind for a typical meteorological year.

2.2 Mechanical Ventilation Unit

In the FESR project "NewAir", a single-dwelling mechanical ventilation unit was developed to supply fresh air, provide dehumidification during summertime and support the distribution of space heating/cooling thermal power. This unit is double flow and integrates a high-efficiency heat recovery unit, a water-to-air heat exchanger, as well as a refrigerant cycle that is used for dehumidification. In more detail, the condenser and the evaporator of the refrigerant cycle are crossed by the supply airflow and a pre-cooling coil is also activated whenever dehumidification is required. Two dampers regulate the heat recovery bypass and the amount of indoor air that is circulated.

The numerical model of the ventilation unit consists of multiple TRNSYS Types, each simulating an energy component of the ventilation unit. Selected parameters were tuned to replicate the performance of the ventilation unit developed in the NewAir project as closely as possible. More specifically, the data sources for the calibration process were:

- Laboratory measures for (1) external pressure - airflow rate - electrical consumption curves, (2) thermal efficiency of the bypass to the heat recovery and (3) dehumidification capacity;
- Online calculators and datasheets from manufacturers for the thermal performances of heat recovery and water coil.

Table 3 lists the maximum airflow rates and the fan consumption in different working modes, derived assuming external pressure losses equal to 100 Pa at 200 m³/h.

Table 3 – Working modes of the ventilation unit

Working mode	Fresh air [m³/h]	Circulated air [m³/h]	Supply air [m³/h]	Fan cons. [W]
Renewal	140	-	140	110
Circulation	-	200	200	75
Renewal and circulation	100	100	200	124

The ventilation unit is connected to the different indoor spaces by three separate aeraulic networks (supply air, return air and air circulation air), as shown in Fig. 2. The airflow is split among living room and bedrooms based on the floor area.

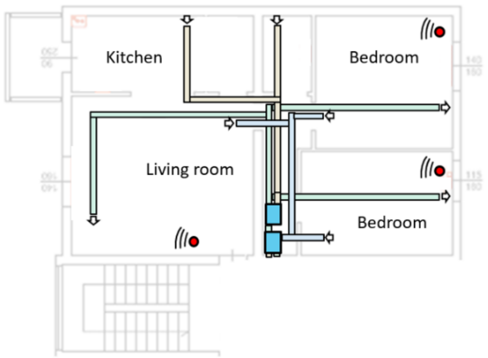

Fig. 2 – Schematic of the aeraulic networks in the apartment. Return air in orange, supply air in green, air circulation in blue

2.3 Demand-Side Management

The demand-side management of energy systems aims at optimizing the use of energy by acting on the consumption picture, that is, on energy use, energy quality or load time-patterns. In the context of a single-dwelling mechanical ventilation plus radiant floor system, this study quantifies the effects of the following control management strategies designed to reduce energy waste:

- Implementation of demand-controlled ventilation (DCV) (Emmerich & Persily, 2001), that is, the modulation of the fresh air intake to meet the ventilation demand of the zone. In this work, multiple options are compared: (1) occupancy-based DCV strategy, where the control hardware is reactive to human presence through, for example, PIR sensors or geofencing, and triggers air renewal at nominal airflow rate when the apartment is occupied; (2) CO_2-based DCV strategy, where the fresh air intake is modulated based on the CO_2 concentration. In this case, the system can work in on-off mode based on a single hysteresis, but could also implement a multi-step or a proportional control. In the case of multiple CO_2 sensors, the most critical reading is considered for the fresh airflow calculations. Fig. 4 shows the selected CO_2-based DCV strategies and the related CO_2 thresholds, which were identified based on (EN 16798-1, 2019) limits for IAQ Category I.
- Use of moving thresholds to trigger the dehumidification function of the ventilation unit during the cooling season. A constant relative humidity threshold is a common way of managing dehumidification units, but an alternative solution could be dividing the goals of guaranteeing comfort conditions to occupants and avoiding condensation over the radiant floors. To assess such a strategy, a comparison is performed between a baseline scenario (constant setpoint equal to 55 % relative humidity) and an advanced scenario where multiple movable thresholds are implemented: (1) a limit of 60 % relative humidity and 12 g/kg absolute humidity is applied when the dwelling is occupied to guarantee acceptable comfort (Class II comfort according to (EN 16798-1, 2019); (2) a limit in absolute humidity is applied to avoid condensation based on the working conditions of the radiant floors (i.e., temperature at the inlet of the radiant system). When multiple criteria apply at the same time, the strictest threshold is considered.

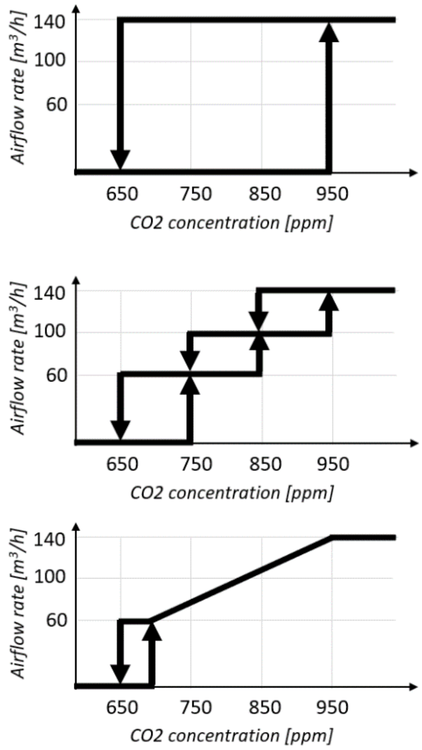

Fig. 3 – CO_2-based DCV with on-off hysteresis (top), multistep modulation (middle) and proportional modulation (bottom)

- Use of moving thermostat temperature setpoints. A 2 K setback is applied to the air temperature thresholds in two separate circumstances, that is, when the apartment is not occupied (non-occupancy setback) or between 23:00 and 06:00 (night setback). To demonstrate, Fig. 4 shows the air temperature setpoints for a single day.

Fig. 4 – Temperature setpoints with non-occupancy setbacks (top) and night setbacks (bottom)

- The implementation of the climatic curve parameters directly to the heat pump rather than to the radiant collectors during wintertime is to produce heat at the required temperature and to avoid a pointless reduction in the heat quality with thermostatic valves. The efficiency of heat pumps is indeed correlated to the temperature level of the water in the condenser, with higher Coefficients of Performance (COPs) at lower water temperatures.

3. Results and Discussion

This section presents the numerical results of the energy simulations divided by analyzed strategy.

3.1 Demand-Controlled Ventilation

Several DCV strategies are compared with a baseline where air renewal is always active. Table 4 reports the numerical results for different scenarios. The air quality is medium-high in all simulated cases. Slightly worse results are found for DCV strategies based on CO_2 concentration, but also in this case, C1 and C2 categories are vastly more populated than C3 and C4. Space heating and cooling thermal demands show limited variations, with higher heating demand and lower cooling demand at higher air change rates. During wintertime, the effect of the additional heat losses due to overventilation is indeed limited by the high-efficiency heat recovery unit. During summertime, higher air change rate may provide at times some benefit in removing the excess heat from indoor spaces, thus reducing the active cooling load. A more evident impact is registered on dehumidification, since the removal of indoor-generated humidity is also influenced by the hygienic air change. DCV strategies are indeed linked to an increase in the consumption of the refrigerant cycle in the range of 11 % to 20 % with respect to the baseline. The electrical consumption of the fans is reduced in the range of -17 % to -38 % in the DCV scenarios, as a result of the lower air volumes exchanged throughout the year. The best- performing DCV strategies are the ones based on CO_2 concentration, since CO_2 generation is dependent on the number and the activity of occupants and thus the air change can be more sharply adapted to the effective demand for air change. Among CO_2-based strategies, no significant difference is found between multistep and proportional control, whereas the on-off strategy is outperformed, as it cannot modulate the airflow and thus is less flexible than the others.
Neither overheating nor undercooling issues are found in any of the tested scenarios. The annual HVAC electrical consumption is reduced by DCV between -6 % and -13 % compared with the baseline, but it has to be noted that the advantages of such strategies may vary significantly depending on the occupancy patterns of spaces (IEA, 1997).

Table 4 – Numerical results for scenarios (1) baseline, (2) DCV based on occupancy, (3) DCV CO_2 based with on-off hysteresis, (4) multistep modulation and (5) proportional modulation

	Annual energy demand						CO_2 classes			
	Q_{heat}	Q_{cool}	W_{fan}	W_{rf}	W_{hp}	W_{tot}	C1	C2	C3	C4
	kWh	kWh	kWh	kWh	kWh	kWh	%	%	%	%
1	3333	1515	942	186	1425	2553	44	40	16	0
2	3333	1519	778	207	1423	2408	44	40	17	0
3	3320	1547	674	233	1424	2331	40	42	18	0
4	3316	1535	587	229	1417	2232	38	42	20	0
5	3318	1529	591	224	1416	2231	38	43	19	0

3.2 Moving Thresholds for Dehumidification

Fig. 5 shows the numerical results of the energy simulations for the cooling season: the use of mobile thresholds is compared with a baseline with a constant humidity setpoint equal to 55 % relative humidity. As may be seen, the use of moving thresholds allows the achievement of significant energy savings (about -13 % total electrical consumption). The impact is not limited to the refrigerant cycle consumption (-40 %), but extends to fan consumption (-4 %) and active cooling demand (-9 %).

The active dehumidification triggers the “renewal and circulation” mode of the ventilation unit, which provides higher airflow rates to maximise the dehumidification effect, but also increases the fan consumption. Dehumidification is also linked to the active cooling load, since before entering the refrigerant cycle, the supply airflow is pre-cooled by a water coil as described above, thus generating a thermal load for the heat pump. The lower electrical consumption of refrigerant cycle, fan and heat pump points to a less frequent use of active dehumidification. No significant difference is found in terms of air quality and thermal comfort. It has to be noted that the working conditions of the radiant floor, and thus the humidity threshold for active dehumidification, will depend on the intensity of the cooling load. In this sense, more challenging conditions for the radiant floor during summertime will represent a smaller possibility of achieving savings by using a movable setpoint.

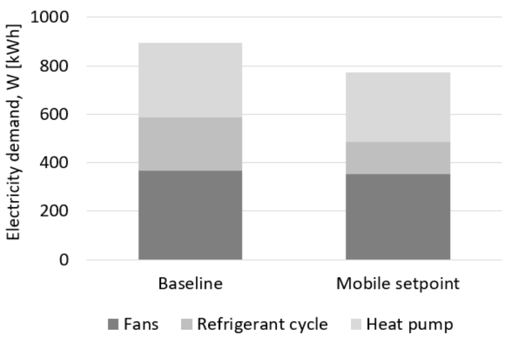

Fig. 5 – Electrical consumption during the cooling season

3.3 Non-Occupancy and Night Temperature Setback

The use of temperature setbacks is assessed by comparing a baseline scenario where the setpoints remain unvaried to the use of a 2 K setback during non-occupancy periods or during night-time. In the non-occupancy scenario, the setback is applied every time the dwelling is empty, which is equal to about 19 % percent of the year, or 1680 hours/year, divided into events that are mostly 1 to 4 hours long for the studied occupancy schedule. The night setback is applied for about 29 % of the year, or 2555 hours/year, in events that are each 7 hours long.

Fig. 6 and Fig. 7 show the monthly thermal energy demand and the percentage variation of heat performance indicators SCOP and SEER with respect to the baseline. As may be seen, the use of the temperature setback leads only to a limited reduction of the thermal demand (in the range of -1 % to -5 % on an annual basis), likely due to the fact that the setback is applied only for limited periods (especially in the non-occupancy scenario) and the thermal losses of the building are minimized by fair envelope properties and low ventilation/infiltration heat losses. The annual electricity consumption of the heat pump is reduced by a factor of -3 % in the non-occupancy setback scenario, and -12 % in the night setback scenario. This is only partially connected to the reduction of the thermal load, since the performance of the heat pump is also affected by the setbacks, as shown in Fig. 6. More specifically, the use of non-occupancy setbacks leads to better SEER during summertime, whereas the use of the night setback leads to higher SCOPs in winter and lower SEERs in summer.

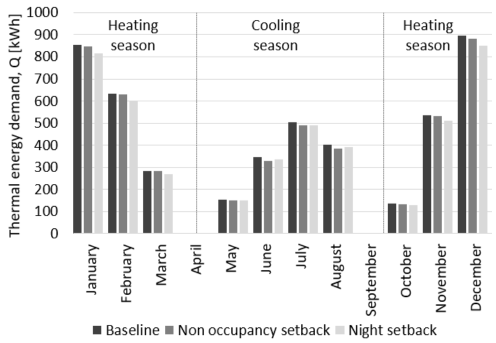

Fig. 6 – Monthly thermal energy demand

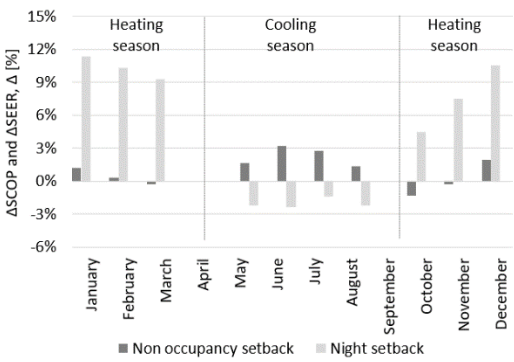

Fig. 7 – SCOP and SEER variation in setback scenarios

To better understand the underlying causes, the hourly daily averages of the thermal energy produced by the heat pump in heating and cooling are shown in Fig. 8 for the months of January and July. Even though the thermal loads do not significantly vary in absolute terms, as discussed above, the use of setbacks causes a massive impact on the time patterns of thermal energy generation. In the non-occupancy setback scenario, the load profile tends to differ from the baseline during the daytime when occupants are mostly away and a peak in energy demand is registered at around 18-20 h around the time when the dwelling is be occupied again.

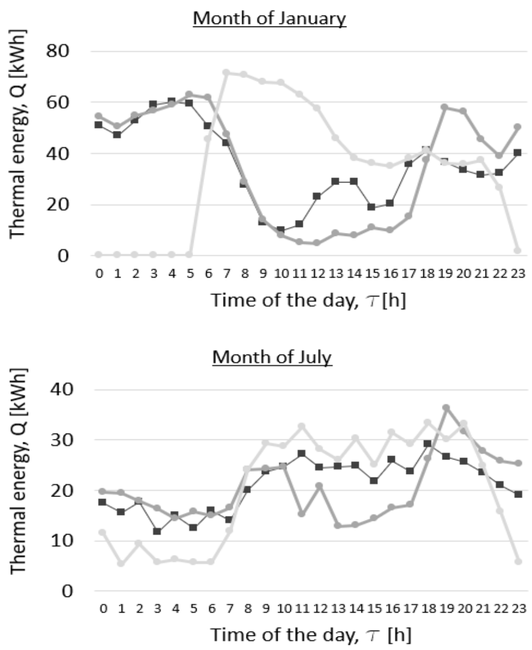

Fig. 8 – Hourly averages of heat pump energy generation

As expected, the use of night setback leads to lower thermal loads during the night, but most of the energy is then delivered during the daytime. The variation of the time patterns for energy generation has quite a significant effect on the air-to-water heat pump performances, since the external air temperature varies throughout the day, with generally higher temperatures during the day (better COPs and worse EERs) and lower temperatures during the night (lower COPs and higher EERs).

Thermal comfort is maintained at all times, although it is found that, when setbacks are applied, air heating/cooling is called on to support the radiant floor, which has a slower response to changing temperature setpoints due to the thermal capacity of the screed.

3.4 Implementation of Climatic Curve at the Generator

A baseline scenario, where the heat pump produces warm water at 40 °C and a thermostatic valve controls the inlet temperature to the radiant floors, is compared with an advanced scenario, where the climatic curve is implemented directly at the heat pump to avoid depreciation of the heat quality.

Table 5 – Performances in baseline and advanced scenarios

Description	Q_{heat}	W_{hp}	SCOP	
	kWh	kWh	-	Δ %
Baseline	3315	1150	2.88	-
Advanced	3226	863	3.74	23 %

As shown in Table 5, the thermal load in the baseline is higher, mostly due to the more intense thermal losses from the water distribution system (about +100 kWh/y). It is also found that applying the climatic curve at the generator leads to a significant improvement in the electrical performances of the heat pump, with a SCOP increasing from 2.9 to 3.7, about +23 % percentage improvement. This is due to the better working conditions of the heat pump, which is not required to produce water at 40 °C, but can profit from a lower-temperature energy demand. It is, however, remarked that state-of-the-art heat pumps can usually offer some form of climatic control. In this case, the simulation results simply reflect the importance of selecting the most appropriate climatic curve based on type of terminals and energy performance of the dwelling to avoid energy waste.

4. Conclusions

This paper presents a study on the performance of different demand-side management strategies applied to a ventilation system plus radiant floor system in the climate of Bolzano.

Based on the analyzed building and climate, the implementation of DCV strategies shows good potential for reducing the electrical consumption of fans (up to -38 %) without worsening the indoor air quality. Space heating and cooling thermal demand are not significantly affected, whereas a moderate impact is registered on dehumidification. It is found that the use of moving setpoints could be a valid strategy to adapt the operation of the dehumidification system to the dehumidification load and reduce the summer energy consumption (-10 % for the studied conditions). The use of non-occupancy or night setbacks does not lead to significantly different annual energy demands, but a considerable impact is found on the time distribution of the thermal loads, with a cascade effect on the performance of the heat pump. More specifically, night setbacks allow the thermal loads to be shifted to the daytime, with a positive effect on the winter performances of the heat pump and a negative effect in summer. Finally, the implementation of a climatic curve at heat pump level allows the achievement of lower heat losses from the distribution system and a significant improvement in the heat pump performance. Overall, it was found that air change, thermal load and dehumidification are interconnected: changes in the control strategies looking at one domain at the time may lead to suboptimal solutions. In addition, it was found that the performance of the heat pump is massively influenced by the controls of the heating/cooling emission system and that there are options for load shifting that could be synergically exploited by photovoltaics. Far-reaching integrated control logics that can better capture the overall impact of single-control choices to reach one or multiple goals are to be implemented to achieve significant energy savings, while preserving optimal comfort conditions. Future studies will focus on the use of Model Predictive Control (MPC) based on forecasted weather conditions and dwelling loads.

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Nomenclature

Symbols

HVAC	Heating, Ventilation and Conditioning
IAQ	Indoor Air Quality
Q	Thermal energy demand, [kWh]
SCOP	Seasonal Coefficient of Performance, [-]
SEER	Seasonal Energy Efficiency Ratio, [-]
W	Electricity consumption, [kWh]

Subscripts/Superscripts

cool	referred to cooling energy
fan	referred to the fans
heat	referred to heating energy
hp	referred to the heat pump system
rf	referred to refrigerant cycle

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