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Energy Reports 7 (2021) 216–224
www.elsevier.com/locate/egyr

6th International Conference on Advances on Clean Energy Research, ICACER 2021 April 15–17, 2021, Barcelona, Spain

Controlled adjustments of indoor microclimate parameters for building's energy demand management

Arseniy Sleptsov[a,*], Alexander Ryzhov[a], Ilia Luchnikov[a], Ashkan Haji Hosseinloo[b], Henni Ouerdane[a], Aldo Bischi[a]

[a] Center for Energy Science and Technology, Skolkovo Institute of Science and Technology, 3 Nobel Street, 121205 Moscow, Russia
[b] Department of Mechanical Engineering, Massachusetts Institute of Technology, USA

Received 21 May 2021; accepted 9 June 2021

Abstract

Indoor air quality and thermal comfort are regulated by heating, ventilation, and air-conditioning (HVAC) system modules, which play an increasing role in integrating buildings into future energy networks as active nodes permitting flexible consumption management. A building's HVAC devices are controlled by automation and control systems consisting of basic and supervisory control layers. Local discrete-mode controllers of HVAC system devices, which receive control signals proposed by a supervisory control method, cause a performance gap between these control layers. Here, we study the performance gap of discrete-mode controllers and examine how such controllers can maintain set-points, using simulation studies developed in the TRNSYS software environment. Considering a set of different devices operating within one room to manage its indoor air temperature and quality, we show that coordination of their discrete-mode controllers may yield a sizeable, larger than 10%, reduction of the heat use and average thermal load. However, such coordination may also entail indoor comfort violation, meaning that there should be a trade-off between comfort and energy performance. We propose controlled adjustments of indoor microclimate parameters to manage heat use (kWh) and thermal load (kW) within demand-side management programs. According to our simulation studies for discrete-mode controllers, the heat use and average thermal load may be reduced by up to 14.1%, ceding the indoor temperature set-point profile by 1 °C and the proportion of fresh air in the room by 50%. Hence, the controlled adjustments of various indoor microclimate parameters would be an excellent approach for integrating HVAC system field devices with discrete-mode controllers, and thereby buildings, into future energy networks providing them extra flexibility.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Advances on Clean Energy Research, ICACER, 2021.

Keywords: HVAC system control; Building energy performance; Discrete-mode controller; Thermal comfort; Indoor air quality; Demand-side management

* Corresponding author.
E-mail address: arseniy.sleptsov@skoltech.ru (A. Sleptsov).

https://doi.org/10.1016/j.egyr.2021.06.037

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1. Introduction

A building automation and control system (BACS), also known as a building management system, intelligent building, smart buildings, or in some cases, smart city [1], is a combination of centralized systems that monitor, control, and record the functions of building facilities. An adequately designed BACS maintains the requested indoor microclimate comfort and provides the demand-driven energy performance of a building's heating, ventilation, and air-conditioning (HVAC) systems. Analyzing these systems' energy performance, one can explicitly distinguish energy consumption trends such as peaks, bottoms, and plateau, to name a few. For instance, energy consumption peaks occurring during a short period may be shaved by shifting the HVAC system's loads [2]. Such activities result in a reduction of installed capacity and an increase in its effective utilization. Also, demand-driven energy consumption may not be economically feasible due to alternating tariffs. During high tariffs, one can reduce energy consumption by reducing the load leveraging upon load flexibility. The load flexibility is possible, thanks to the adjustability of HVAC systems [3]. One of the HVAC system's scheduling techniques is varying set-point profiles of controlled parameters [4]. Thus, one can manage HVAC systems by setting the set-point profiles of indoor microclimate parameters that correspond to the optimized environmental and economic objectives [5].

There is considerable literature on how to find optimal set-point profiles of controlled variables. Set-points may be derived from direct and predicted energy demand analysis, analog and predicted sensory data on occupancy [6], and various indoor air contaminants. There are many works on measuring such data, e.g., [7]. Modeling and predicting these data using different methods [8] and recently trending machine learning methods [9] are also well investigated. Another way to find environmentally and economically optimal set-point profiles is to consider thermal inertia by utilizing a building model and its systems modeling [10]. The development of models for these methods is a specific topic within such a broad research field. Many works also study how to use these models and integrate the models' predicted input variables [11].

BACS sends these set-point profiles as control signals to the HVAC system modules, i.e., field devices. The modules may work independently: room air-conditioning unit, air handling unit of a ventilation system, fan-coil for cooling and heating. These field devices have local embedded controllers exerting a control action via actuators. Most of these devices' controllers are discrete-mode controllers because indoor parameters are allowed to fluctuate around set-point profiles. The response produced by discrete-mode controllers is conditionally stable thanks to the thermal inertia of the building structure, indoor content, and HVAC system modules. Hence, in most cases, the actual indoor microclimate parameters profiles and other economic, environmental, and energy-related metrics (objectives) do not match the theoretically calculated ones [12]. This makes it challenging to use all these advanced methods in practice [13], so one needs to consider the field side aspects of HVAC systems modules for simulation studies. In [5], the authors distinguish basic and supervisory control layers in the BACS scheme: discrete-mode local controllers are at the basic control layer, set-points profiles are at the supervisory control layer.

Here, we study the performance gap between basic and supervisory control layers of BACS, assuming that we have controllers set-point profiles as control signals for the basic control layer. These set-point profiles correspond to the objective function defined by an advanced HVAC system control method. Moreover, we highlight that the HVAC system is a group of field devices with local discrete-mode controllers. Since the local controllers are discrete, they are also assigned with dead bands. Therefore, control signals for the local controllers define the lower and upper limits of controlled variables. Local controllers provide the controlled parameter within these boundaries utilizing discrete positions of the actuators.

When the HVAC system has several discrete-mode controllers, there can be a situation when the actuators of all the discrete-mode controllers are at their high rate position, thereby causing an increase in heat consumption and thermal load. Thus, we discover the potential of controllers' discrete position coordination, although it may reduce indoor microclimate comfort. However, new trends of actively involving people in energy systems result in various programs such as DSM and personal thermal comfort [14]. Consequently, we suggest controlled adjustments of the indoor microclimate comfort: by adjusting indoor microclimate parameters, energy providers can also develop new billing models, i.e., they could sell comfort instead of kWh of energy [15]. In the present work, we unravel the impact of adjustments of indoor microclimate parameters of both thermal comfort and indoor air quality. For this purpose, we introduce a simplified characterization for the indoor thermal comfort and indoor air quality as indoor air temperature and the proportion of fresh (outdoor) air in the room air volume, respectively (See Section 2.2 for details.)

2. Case study development

We conduct a simulation analysis for the illustrative case of a single-story one-zone building model with heating and ventilation modules in the TRNSYS software environment.

2.1. Development of the model of a building and its systems

We develop a single-story one-zone building model with heating and ventilation modules in the TRNSYS software environment for dynamic simulation. TRNSYS software is primarily an equation solving program based on standard numerical techniques widely used to simulate transient systems. Notably, the software is used to simulate renewable energy systems, HVAC systems, building energy, etc. [16]. The schematic of the model is presented in Fig. 1.

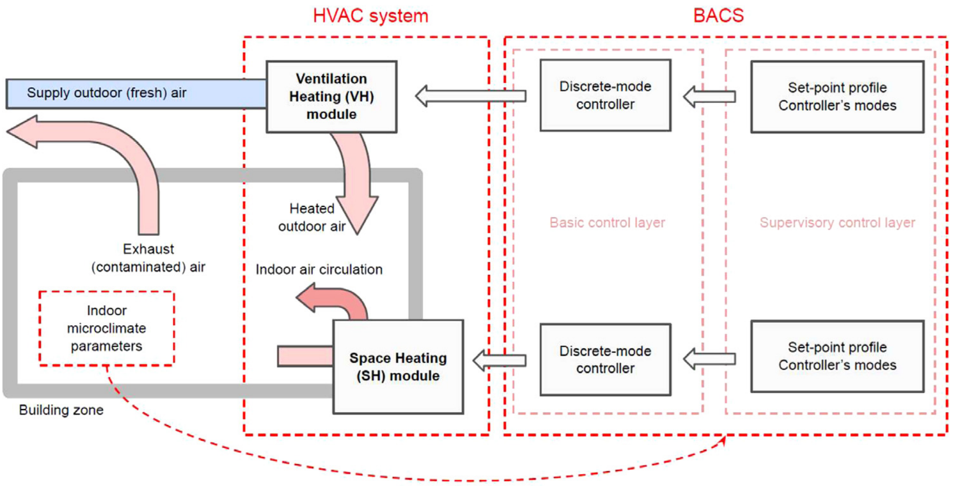

Fig. 1. Schematic of the model: a single-story one-zone building with heating and ventilation modules.

The test case building zone has a roof, a floor adjacent to the ground surface, and four external walls fitted with windows. The building model is developed using the TRNSYS component referred to as Type 56, which takes as inputs the building parameters on geometry and materials of the envelope (enclosure). The component enables to simulate a specific thermal behavior, i.e., heat dissipation through the building envelope, under given weather conditions. The envelope characteristics, the area (m^2), and u-value ($W\ m^{-2}\ K^{-1}$), are as follows: 30 and 0.339 for external walls, 6 and 1.4 for windows, 100 and 0.233 for the roof, and 100 and 0.313 for the ground floor.

The air node's thermal capacity consisting of indoor air and indoor content such as furnishing depends on the building's precise details. Johra and Heisenberg [17] proposed to consider a planar element with equivalent indoor content material to quantify the indoor thermal inertia of the building zone (air node). The following parameters for 1 m^2 the zone floor area are assumed here: planar element thickness of 4 cm, the material-specific heat capacity of 1400 $J\ kg^{-1}\ K^{-1}$, the material thermal conductivity of 0.3 $W\ m^{-1}\ K^{-1}$, the material density of 600 $kg^{-1}\ m^3$.

The outside temperature is assumed to be fluctuating within −5 and +5 °C according to the profile depicted in Fig. 2. We also provide an assumed number of occupants and fresh air demand during the simulation period. We assume no solar gains in this work as we are mostly interested in winter weather conditions, but we acknowledge that these gains may contribute to the building zone's thermal balance.

Our test case building's HVAC system consists of two sub-systems: heating and ventilation modules (Fig. 1). Their local discrete-mode controllers operate these two sub-systems. The local controllers are at the basic layer of the BACS. These devices' control signals are set-point profiles and a set of available discrete modes (regimes) sent from the BACS' supervisory layer. The heating processes of the zone air in the space heating (SH) module and the supply airflow in the ventilation heating (VH) module are done via forced airflow through the coils. In the coils, there is a circulating heat-carrier fluid (water). The speed of fans moving air through the coils is regulated by the

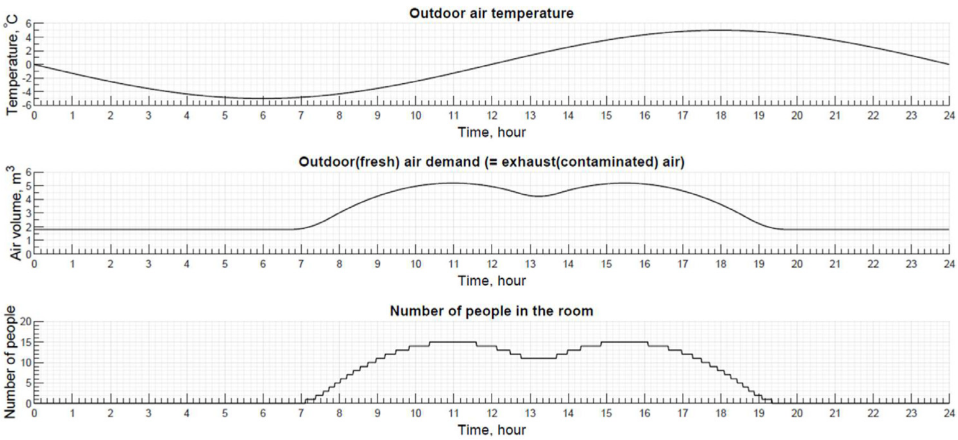

Fig. 2. Input parameters for simulation studies.

discrete-mode controllers mentioned above. The Type 753e describes both SH and VH modules in the TRNSYS environment. For both SH and VH modules, the fluid (water) temperature is assumed to be 45 °C. The fluid flow rates are considered to be 900 kg h^{-1} in the SH module and 100 kg h^{-1} in the VH module. The maximum airflow rates are 1200 kg h^{-1} in the SH module and 900 kg h^{-1} in the VH module. The airflow rate variations are subjected to the discrete-mode controllers' actions, i.e., the controllers change the airflow rate through the coils to provide a set-point temperature. Our test case mimics public premises such, e.g., as offices, museums, large classrooms.

2.2. Indoor microclimate parameters

Indoor thermal comfort is a subjective state perceived by a person, depending on physical, physiological, and psychological factors. A comprehensive discussion on thermal comfort is available in [18], where the authors also discuss Fanger's thermal comfort approach [19]. Fanger proposed a predicted mean vote (PMV) model to evaluate the building's occupants' comfort perception [20]. The PMV primarily depends on the indoor air temperature [21]. Moreover, the indoor air temperature is a comprehensive communication metric with the occupants who set its level in the ad-hoc interface. Thus, we use this parameter as a simplified thermal comfort index. In our test-case building model, the indoor air temperature related to the air node (building zone) is Type 56 in the TRNSYS building model. We explore the impact of the indoor air temperature variations and controlled adjustments on the heating devices' energy performance.

Indoor air quality (IAQ) is also comprehensively discussed in [18]. Although it is complex to measure IAQ, the authors highlight that the ventilation system requirements proposed by standards may support an acceptable IAQ. Thus, we assess the indoor air quality through the proportion of outdoor (fresh) air in the room air volume. We assume that the IAQ in a fully-ventilated room is at the desired level of air quality. The standards suggest upper levels for acceptable indoor contaminants' concentrations. In Fig. 3, we explain our assumptions: the proportion of outdoor (fresh) air in the room vs. an indoor air contaminant concentration. The indoor air contaminant stands for any pollutant in the room, including humidity, CO_2, (volatile organic compounds) VOCs, (particulate matter) $PM_{2.5}$. Although we do not know what proportion of outdoor air corresponds to the maximum level of these contaminants, we assume the following:

- A fully-ventilated room has an acceptable IAQ: the proportion of outdoor air in the room is 100%;
- A contaminated air volume is a volume of air mixed with various room pollutants and human exhaled breath;
- Occupants may remain in a fully-ventilated room as long as people, necessarily breathing out CO_2 and humid air, as well as sources of pollutants, do not contaminate a significant proportion of air in the room;
- In a fully-ventilated room with a temporarily not functioning ventilation system, a contaminated air volume in the breathing zone is replaced by an existing "pure" air volume from another part of the room;
- A contaminated air surrounding a person is moved by convection to the upper part of the room because of human physiologically generated heat, and hence first fills the upper part of the room volume;

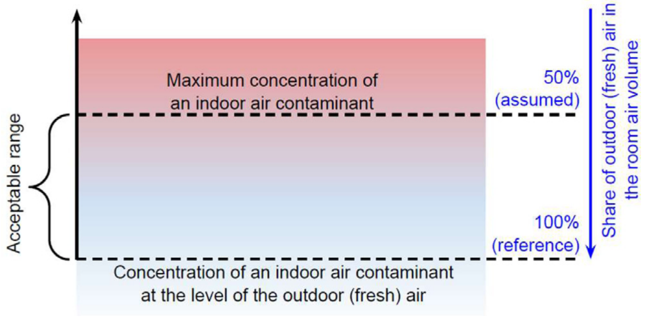

Fig. 3. Methodology for indoor air quality assessment.

- A maximum volume of contaminated air is considered to be half of the room air volume, occupying an upper half of the room volume because the height of the breathing zone is in the middle of the room, i.e., the proportion of outdoor (fresh) air in the room is expected to be between 50% and 100%;
- The controller is given a set-point profile for the proportion of outdoor air.

According to ASHRAE standard [22], the ventilation demands for a particular space based on people and floor area are then added together to determine the total ventilation demand for a given room:

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \tag{1}$$

where V_{bz} is the demanded breathing zone outdoor airflow, L s^{-1}; R_p is the outdoor airflow rate required per person, L s^{-1} · person; P_z is the zone population: the largest number of people expected to occupy the zone during typical usage; R_a is the outdoor airflow rate required per unit area, L s^{-1} m^2; A_z is the zone floor area: the net occupiable floor area of the zone, m^2.

Further, to consider an uneven distribution of the air in a room, the standard introduces the outdoor airflow that must be provided to the zone by the air supply system:

$$V_{oz} = \frac{V_{bz}}{E_z} \tag{2}$$

where V_{oz} is the outdoor airflow that must be provided to the zone by the air supply system, L s^{-1}; E_z is the zone air distribution effectiveness which depends on the configuration of a distribution system [23].

For single-zone systems, the outdoor air intake flow is equal to the zone outdoor airflow V_{oz} [22]. The standard provides R_p, R_a, and E_z depending on the functionality of a premise (see Table 1).

Table 1. Parameters for ventilation requirements calculation assumed in the test case [22].

Parameter	Value	Comments
R_p, L s^{-1} person	3.8	Occupancy category examples: classrooms, museums, lobbies, mall
R_a, L s^{-1} m^2	0.3	common areas, supermarket, transportation waiting, lecture hall
E_z	0.8	Ceiling supply of warm air at least 8 °C above space temperature and ceiling return.

We assume that the demanded outdoor airflow (V_{oz}) maintains an acceptable IAQ considered in the standard of ASHRAE [22], and the fresh outdoor airflow(V_{oz}) replaces the same amount of contaminated indoor air (V_{ea}).

3. Simulation results and discussion

We carry out simulation studies for a three-position controller to evaluate the impact of the dead bands' width on the energy performance gap caused by the discrete-mode controllers. In Fig. 4, we show the performance of the controller in five plots describing (1) the instantaneous value of the indoor air temperature (solid lines) and its dead bands (dashed lines), i.e., lower and upper limits; (2) the instantaneous value of the outdoor (fresh) air proportion

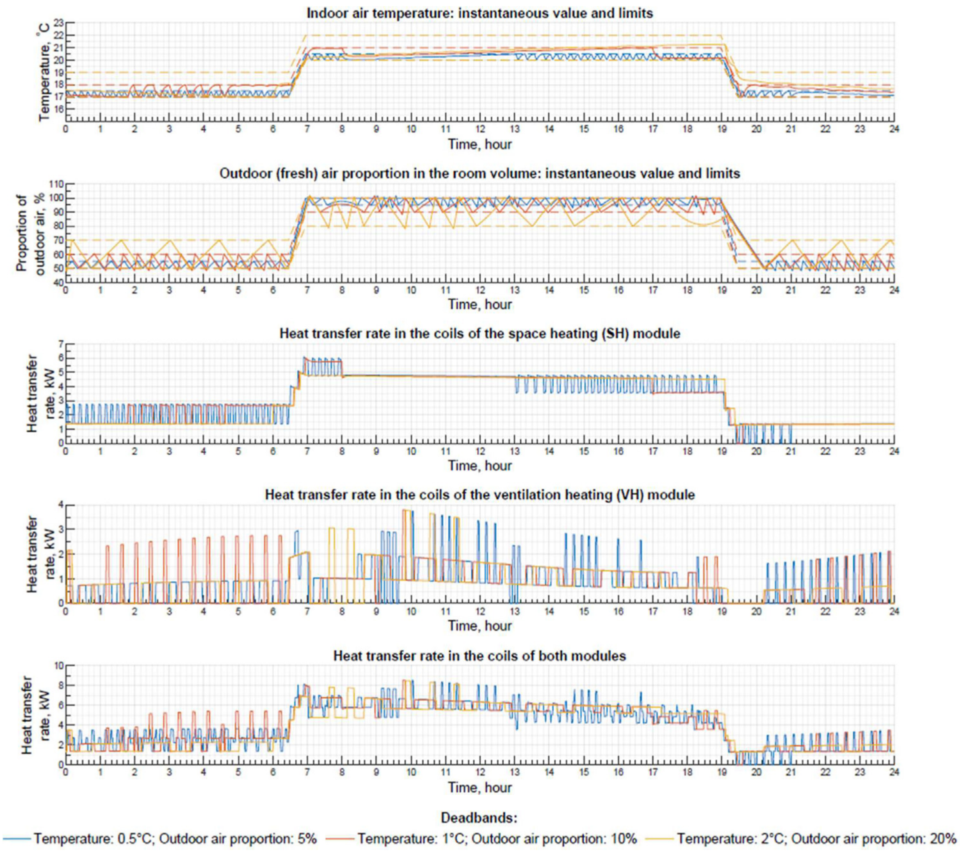

Fig. 4. Three-position controller: different acceptable dead bands for set-points of the indoor temperature and outdoor air proportion in the room are assessed.

in the room (solid lines) and its limits (dashed lines); (3) heat transfer rate in the coils of the space heating (SH) module; (4) heat transfer rate in the coils of the ventilation heating (VH) module; and (5) heat transfer rate in the coils of both modules (total). We see that the narrower the dead band's width, the higher the number of the system's switching on–off. Many switching on–off may damage the hardware and cause numerous fluctuations of the indoor microclimate parameters and heat transfer rate. For three-position controllers, the following dead bands are sufficient: 1 °C for the temperature and 10% for the room's outdoor air proportion. The largest dead bands we evaluate for the controllers – 2 °C for the temperature and 50% for the proportion of outdoor air in the room — increase the cumulative heat transfer by 8.5% compared to the one resulted from the reference dead bands (0.5 °C for the temperature and 5% for the fresh air proportion). Thus, we recommend the dead bands 1 °C for the temperature and 10% for the proportion of outdoor air in the room for discrete-mode controllers. These dead bands cause a sufficient number of discrete positions' switching and the increase of the energy performance gap by no more than 4%.

We further study the coordination of discrete-mode controller positions of the HVAC system modules as they may work simultaneously at high rates, causing saturation of larger loads. The impact of discrete-mode controllers' coordination is most notably expressed for the less discrete controllers such as two-position (On/Off) controllers. In Fig. 5, we see the coordination of two independent On/Off controllers of the SH and VH modules. In this case, we assume that the proportion of fresh air is a higher priority than the indoor air temperature. Therefore, the VH module's controller follows the set-point profile with a given dead band. The SH module's controller follows the indoor temperature set-point profile when the VH module's controller is not active. The analysis of this particular case, Fig. 5, shows that the coordination of these On/Off controllers may reduce heat consumption and average thermal load by 12.4%, the maximum thermal load by 40%. However, the indoor temperature may be violated uncontrollably: the indoor temperature is sometimes below the lower limit by up to 2 °C.

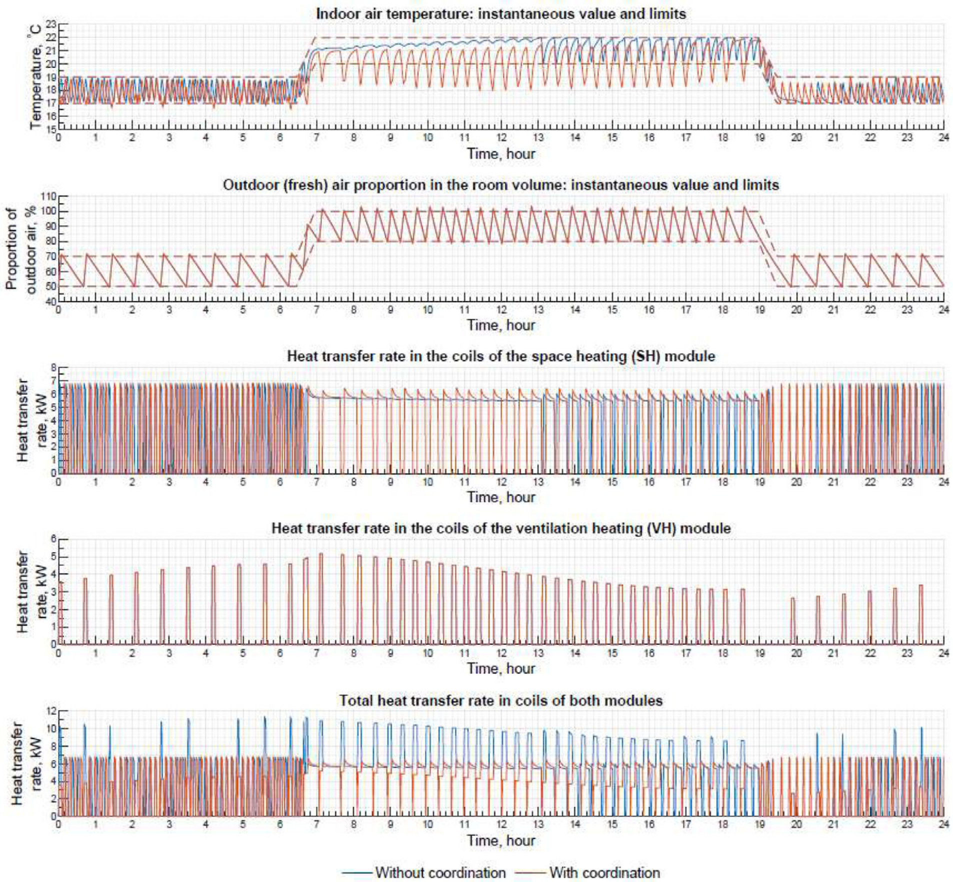

Fig. 5. Two-position (On/Off) controller: comparison of two modules controllers in coordinated and non-coordinated modes.

We consequently reveal controlled adjustments of the indoor air temperature and proportion of outdoor air in the room to guarantee the exact quantitative change of the indoor microclimate comfort indices in favor of systems' energy performance upon request. In Fig. 6, we present an example for the three-position controller: we decrease the temperature by 1 °C and the proportion of outdoor air in the room by 50% gradually during 9–12 h, as shown in the plots. We conclude that the softening of both microclimate parameters requirements according to predefined set-point profiles' adjustments may reduce the maximum thermal load (See the thermal load duration curve in Fig. 6). The average thermal load and cumulative heat transfer in both SH and VH modules (SH +VH) may reduce by 14.1%. Also, note the decrease of the heat transfer in both modules separately. For the developed test case, the space heating module possesses a larger heat consumption proportion than the one of the ventilation heating module — the reader can compare the heat transfer values in each module in the plots at the bottom of Fig. 6. That is why the impact of indoor temperature adjustments is considerable. For this particular case, indoor air temperature adjustments significantly affecting thermal comfort may be the primary strategy to impact energy performance.

4. Conclusion

The work reported in this article concerns discrete-mode controllers of HVAC system devices, which receive as control signals set-point profiles proposed by any supervisory control method. In our simulation studies, we showed that the controlled adjustments of indoor air temperature and the proportion of fresh air in the room could reduce the average thermal load by up to 14.1% during the period of demand-side management. Hence, controlled adjustments of the parameters affecting indoor microclimate comfort would be an excellent tool for the concept of "selling comfort".

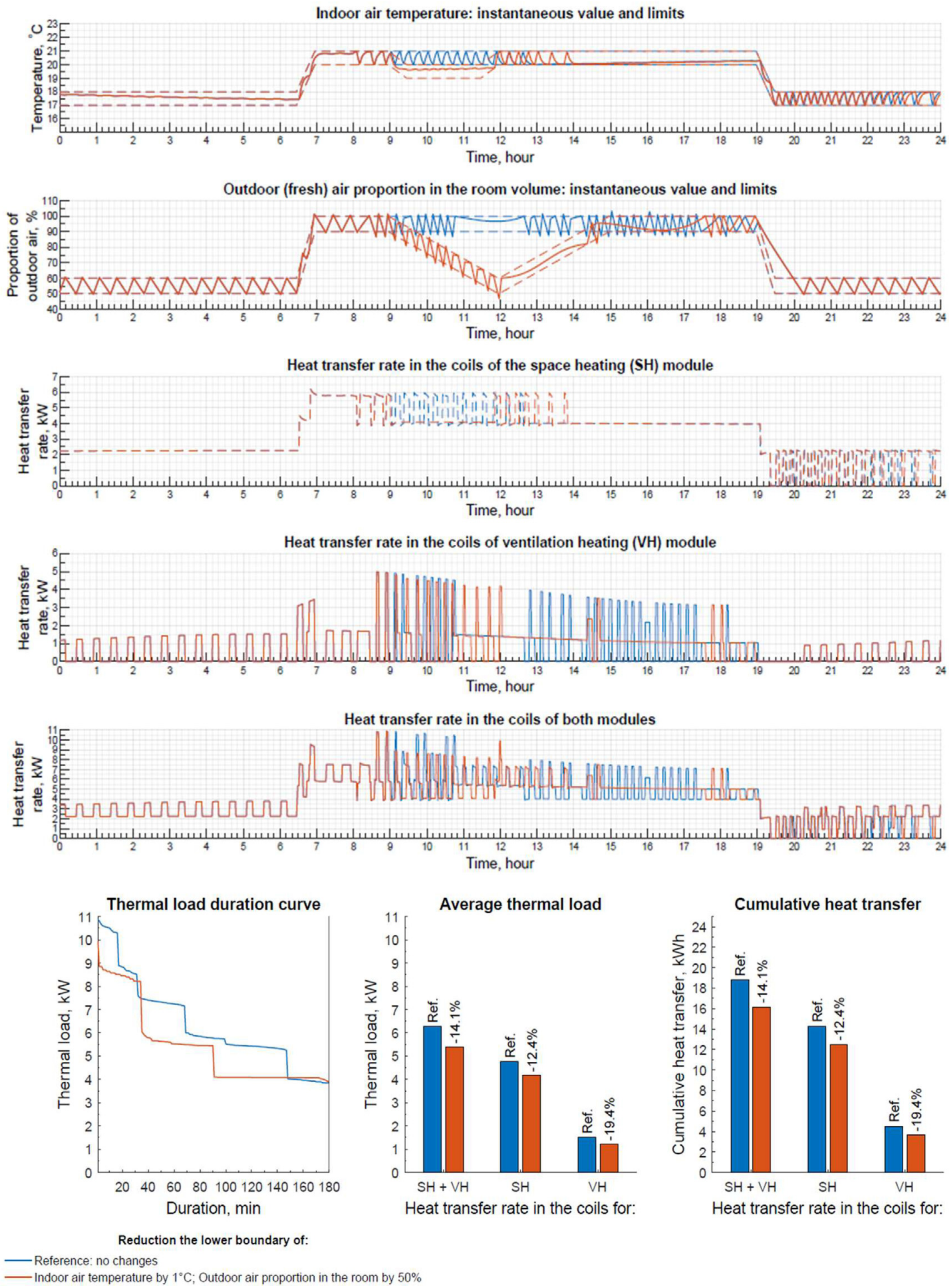

Fig. 6. Three-position controller. A response to the DSM event by ceding indoor temperature set-point value and reducing fresh air proportion in the room, consequently softening indoor air quality within acceptable ranges.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was partially supported by the Skoltech NGP Program (Skoltech-MIT joint project).

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