Articles

Optimization of HVAC system operation based on a dynamic simulation tool

MARKO G. IGNJATOVIĆ
University in Niš,
Faculty of Mechanical Engineering in Niš
marko.ignjatovic@masfak.ni.ac.rs

BRATISLAV D. BLAGOJEVIĆ
University in Niš,
Faculty of Mechanical Engineering in Niš
bbata@feniksbb.com

MIRKO M. STOJILJKOVIĆ
University in Niš,
Faculty of Mechanical Engineering in Niš
mirko.stojiljkovic@masfak.ni.ac.rs

DEJAN M. MITROVIĆ
University in Niš,
Faculty of Mechanical Engineering in Niš
mitrod@masfak.ni.ac.rs

ALEKSANDAR S. ANĐELKOVIĆ
University of Novi Sad,
Faculty of Technical Science Novi Sad
aleksa@uns.ac.rs

Energy efficiency measures in existing buildings include improvements in heating, ventilation and air conditioning systems through systems renovation and components upgrade. These measures target building energy consumption through improving the overall system efficiency, with the thermal comfort of occupants being observed through only one or two parameters. Improvements in the existing system operation can lead to better energy efficiency as well, but with a possibility of maintaining the occupant thermal comfort in the desired range. This paper implements the parallel particle swarm optimization to determine the operation parameters of an existing HVAC system that corresponds to the minimal primary energy use while maintaining the desired occupant thermal comfort. The existing HVAC system is modeled in the simulation software EnergyPlus. The moving horizon approach in near-real time was adopted. The focus in this paper is shifted from the minimal energy consumption to the minimal energy consumption for a desired thermal comfort level, without any renovation or upgrade of the system.

Keywords: building energy simulation; primary energy; thermal comfort; operation optimization; EnergyPlus.

Energy consumption in buildings is one of the top priorities in official energy policies of many countries. The main reason behind this lies in the significant increase in energy consumption in the building sector. According to Perez-Lombard [1], buildings accounted for more than 37% of the final energy consumption in EU during 2004, with a similar situation present in the USA where in 2010 buildings participated with more than 40% of primary energy consumption [2]. Gruber [3] points out that 50% of the energy consumed in buildings in industrialized countries is used for heating, ventilation and air-conditioning. The situation is almost identical in Serbia, where the building sector participates with more than 50% of the consumed energy [4].

Energy consumption in buildings can be reduced by a number of energy efficiency measures, with the most frequent being: improving the building envelope thermal characteristics, using energy efficient HVAC equipment, and employing renewable energy sources. What is common for all these measures is that they are implemented during the refurbishment of existing buildings or the construction of new buildings, and that in the majority of cases it is legally regulated [5]. Recently, strong research efforts have been put in to improve building energy performance without major renovations of buildings/systems, but just by improving the existing systems and incorporating new automatic regulation concepts [6–8]. This primarily relates to the minimization of energy consumption/energy cost/GHG emissions in buildings while maintaining the thermal comfort of occupants within the desired range. The basis for this kind of research are the mathematicsl models of buildings and related systems. Modeling and prediction of performance focus on three categories [9]: long-term load forecasts for system selection and planning; medium-term forecasts for system maintenance and fault detection and diagnosis; and short-term forecasts for daily operation, scheduling and load-shifting plans.

Models of buildings and their accompanying systems for short-term forecasts are as follows: white-box models, black-box models, and gray-box models. White-box models include physical characteristics and relations of buildings and their systems, and are incorporated in the best-known building dynamic simulation programs such as: EnergyPlus [10], TRNSYS [11] etc., and are of special interest for this research.

The optimization process can be repeated time after time, resulting in the moving horizon optimization implemented in numerous studies on the topic of model predictive control [12–16].

This paper presents the possibility to minimize building energy consumption by optimizing the existing HVAC system operation modeled in EnergyPlus, while maintaining the occupant thermal comfort at the same time. The planning horizon is set to one day assuming a perfect weather forecast, and the optimization process is repeated day-by-day in the observed period.

Optimization process

The optimization process is based on the combination of detailed hourly simulations of the building performed in EnergyPlus and the operation optimization of selected HVAC systems developed in the C# programming language.

The optimization process follows a relatively simple iterative procedure described in [9].

The optimization problem is solved by using the parallel particle swarm optimization (PSO) [17].

The program starts by loading the building model and weather file. The building energy model created in EnergyPlus contains all the information on the analyzed building, and it is, basically, a text file with the values in particular lines which the optimization algorithm will replace with the values of selected decision variables. At the beginning of each iteration, the program randomly generates a population of decision vectors and creates as many text files as there are vectors. The program initiates the simulation of all files related to a current PSO iteration, and all simulations are carried out simultaneously. After all the simulations have finished, the program reads the resulting output files and extracts the values required to calculate the objective function value(s). The objective function can be easily defined according to a particular interest. The process is then repeated in a new iteration, with a new population of decision variable vectors randomly generated around an optimal vector of the last completed iteration. This process repeats until the exit criteria is fulfilled.

When the exit criteria is satisfied, the optimization process is repeated for the next optimization period (part of day, one day, several days, etc.).

Case study

Building description

The case studied in this paper is the office part of the Feniks BB Company building in Niš, Serbia (**Figure 1**). The building is a combination of the office and manufacturing type.

The building is located on the outskirts of Niš, the largest city in Southeast of Serbia. The useful floor area of the building is 1630 m². One part of the building, approximately a half, represents a manufacturing hall, while the other part is divided into two stories. The lower storey houses manufacturing premises and warehouses, while the upper storey is where offices and manufacturing of electronic components are located.

The building is mainly heated by radiators and air heaters (the manufacturing hall), while the office part of the building can also be heated by a ducted fan-coil unit with 100% of fresh air which at the same time presents the basic cooling system in the said space. The AHU consists of the following sections: air-to-air plate heat exchanger for heat recovery, coil section (cooling or heating as necessary), fan sections, and sound attenuators. The air conditioning system is designed in the classical manner to ensure the indoor temperature for a summer design day. The operation of all secondary systems is controlled by PLCs.

Gas-fired condensing boilers and air-to-water heat pump are used as the primary energy sources.

The simulation program EnergyPlus was used to create the building model and the mentioned HVAC systems. The building geometry was created using the *Open Studio Plug-in* for *Google SketchUp*. All rooms in the building were treated as separate thermal zones.

To simulate the building, an appropriate weather file containing all boundary conditions was also needed. A custom weather file in was formed from the data provided by the hydrometeorological station Niš.

The offices were assumed to be occupied during weekdays from 08:00 to 17:00 (the last occupied hour is from 16:01 to 17:00), with a number of occupants occupying them as defined in **Table 1**. The aim is to maintain thermal comfort within the prescribed range by optimizing the HVAC system operation day by day. As the indicator for thermal comfort the predicted mean vote (PMV) was used, and this value could be generated as the output from the simulations on an hourly basis for every modeled zone. Even though the outputs for PMV are expressed on a discrete scale from –3 to +3, the EnergyPlus algorithms carry out the calculations on a continuous scale which is not an error [18], and the value of PMV obtained through simulation can be treated as the one which meet or does not meet the desired value (e.g. PMV can have the value of 0.23784, so if the desired comfort value is 0.5, this means that the comfort is satisfied in the given hour).

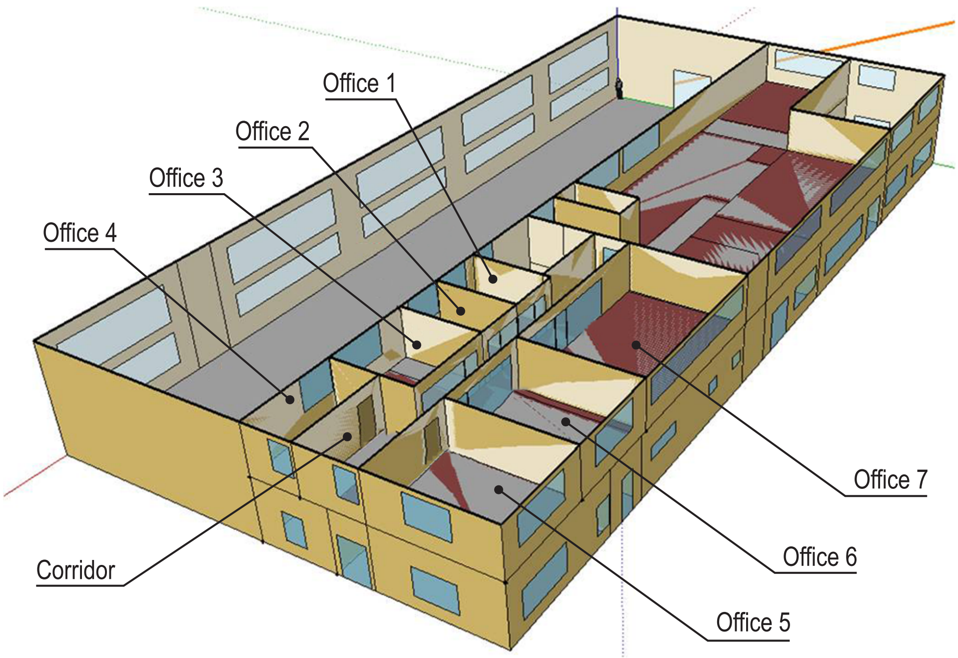

Figure 1. Office part of the building.

Table 1. Typical number of occupants in offices during weekdays.

Thermal Zone	Number of occupants
Office 1	2
Office 2	2
Office 3	2
Office 4	2
Office 5	1
Office 6	4
Office 7	4
Corridor/lobby	2

Application of the Optimization process

The period starting on January 27th 2014 and ending on February 6th 2014 was selected to meet the needs of this paper and check the methodology. A weather file in the appropriate format was created on the basis of the data provided by the Republic Hydrometeorological Service of Serbia – the hydro-meteorological station Niš. The optimization period of one day was adopted, and the optimization process itself was performed for each day of the stated period including weekends, which were treated as a single optimization period.

Decision variables

To perform the optimization task and calculate the objective function, decision variables should be defined first. Since the optimization goal is to achieve the minimum primary energy consumption while maintaining the thermal comfort for one day, having the simulation tool limitations in mind, variables were classified into two groups: the ones which can be modified hourly/daily and the others which can be modified once per simulation. Certain variables were further subdivided into three periods of day for each day in the observed period: unoccupied before occupants arrive (from midnight to 08:00); occupied period (from 08:00 to 17:00); unoccupied after occupants leave (from 17:00 to midnight). To reduce the total number of decision variables, only one decision variable for each of the unoccupied periods was allowed. Furthermore, some decision variables were constrained by the fact that the system was already installed and there were limitations especially in terms of capacity and maximum flow rates.

For the observed winter operation, the following variables were adopted:

- Hot water supply temperature (hourly with distinction between occupied and unoccupied periods) - 13 variables within range 40–70°C;
- Heating set-point for offices served by baseboard heaters (hourly with distinction between occupied and unoccupied periods) - 13 variables within range 18–24°C;
- System air flow rate (once per simulation) - 1 variable within range 0.5–1.2 m^3/s ;
- Minimum outside air fraction (hourly) - 24 variables within range 0.6–1;
- Baseboard heaters runtime (daily) - 1 variable;
- Baseboard heaters finish time (daily) - 1 variable;
- Heat Recovery runtime (daily) - 1 variable;
- Heat Recovery finish time (daily) - 1 variable;
- Heating Coil runtime (daily) - 1 variable;
- Heating Coil finish time (daily) - 1 variable;
- Heat Recovery bypass minimum limit temperature (once per simulation) - 1 variable.

Since two different HVAC systems (radiator heating and air-conditioning system) were served by the same heat source, using a built-in energy management system of EnergyPlus, a syntax was created according to which the heat source (boiler) was available whenever either of the two systems was required. A similar syntax was created for the AHU supply and exhaust fans, depending on whether the heating coil and/or heat recovery were needed.

Objective function

The objective function of the optimization problem is given in the form:

$$min\, E[kWh] = E_B \times 1.1 + (E_{SF} + E_{RF}) \times 2.5 \qquad (1)$$

subject to:

$$-0.5 < TCF < 0.5 \qquad (2)$$

where E represents the primary energy consumption from the systems; E_B [kWh] is the boiler energy consumption; E_{SF} [kWh] is the supply fan electricity consumption; E_{RF} [kWh] is the return fan electricity consumption; 1.1 is the primary energy conversion factor for natural gas; 2.5 is the primary energy conversion factor for electricity; 0.5 is the boundary value of PMV, and TCF is the thermal comfort related function in the form:

$$TCF = \sum_{i=1}^{i=8} (min\, PMV_i) \times \frac{N_i}{N_{tot}} \qquad (3)$$

In equation 3, *i represents the zone identifier;* minPMV_i is the minimal value of PMV in the i-th zone; N_i is the number of occupants in the i-th zone; N_{tot} is the total number of occupants.

The values of E_B, E_{SF}, E_{RF} and PMV are the outputs from EnergyPlus simulations.

For the PSO algorithm, the population size was set to 1000, while the number of generations was set to 50. The exit criteria were not defined, meaning that all 50,000 simulations were performed.

Results and discussion

The simulations were run on a 24-core Intel Xeon working station with 32GB of RAM memory. The optimization process was run for every weekday of the observed period and also for the weekend but with less strict criteria for TCF. The optimization lasted between 22 and 24 hours, meaning that there was enough time left to implement the optimal decision variables vector into the existing automatic regulation system, assuming that the weather forecast for that particular day was perfect.

To compare the results obtained in the optimization, a baseline case was adopted. This case represented the usual operation of the existing HVAC systems. The main differences between the baseline and the optimal model were:

- in the baseline case, the given thermostat values for all zones were predefined with constant value setpoints (18/20/22°C during the occupied period depending on the part of the building), while in the initial models, the thermostat values in the office part of the building were varied (in the remaining zones of the model the values are the same as in the baseline model),
- the systems were turned on in a predefined manner - 1 hour before the occupants arrive (AHU was turned on during the occupied period only), and remained on for the entire occupied period of day, while in the initial models these could be turned on any time if necessary,
- in the baseline case the heating supply temperature was dependent on the outdoor temperature, while there was no such dependency in the initial models,
- during the weekend there were no occupants, thus the systems remained turned off in the baseline model, while in the optimized model the systems might be run in order to provide good initial values for the first day following the weekend.

In the baseline case, the primary energy consumption had the value of 3451.2 kWh for the analyzed period, out of which 3232.6 kWh was for space heating (baseboards, unit ventilators and heating coil), and 218.6 kWh was for electricity for running the AHU fans. The PMV values in the offices are shown in **Figure 2.** As it can be seen, the PMV value in every zone was not even near the threshold value of –0.5. For the optimized case (the optimal

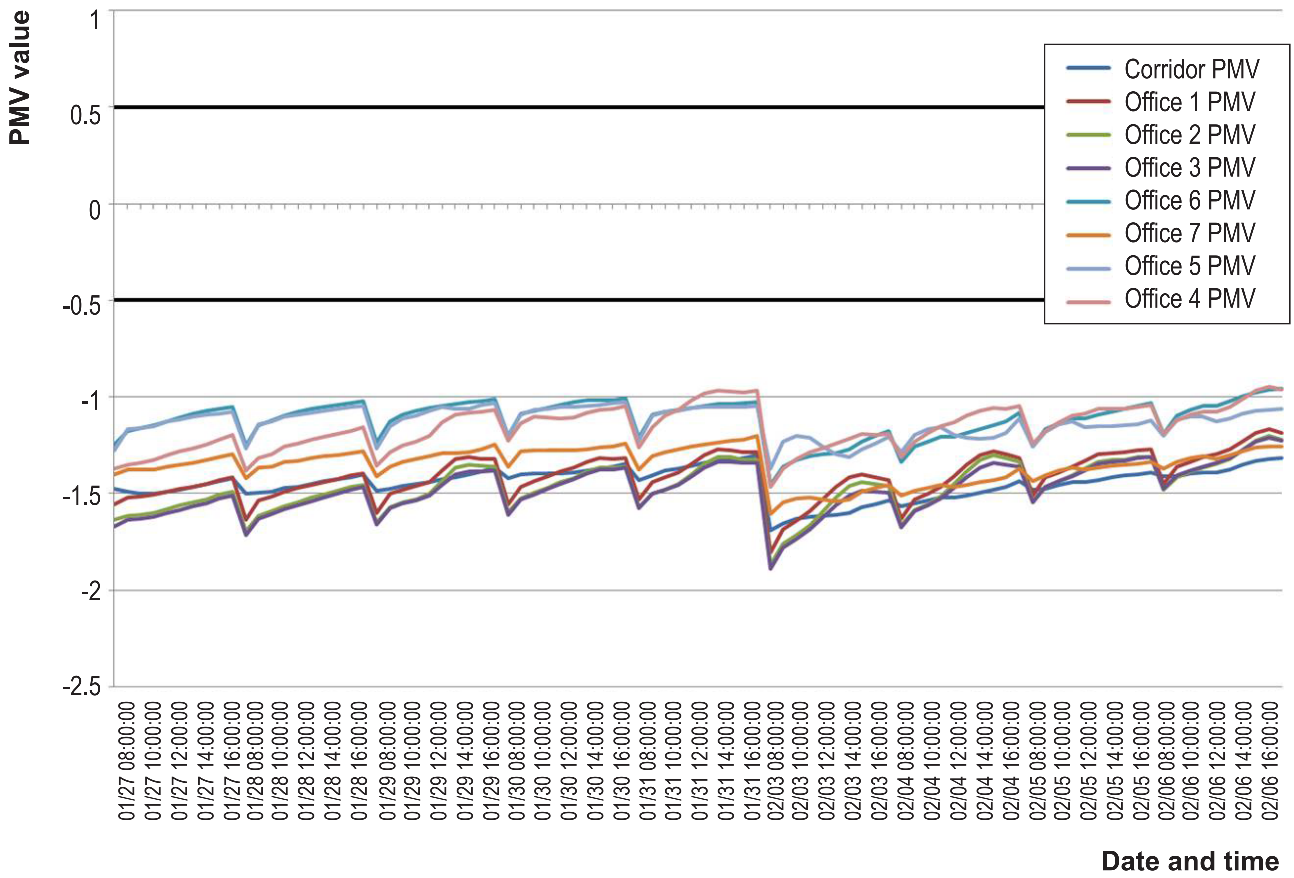

Figure 2. PMV variation in offices - baseline case.

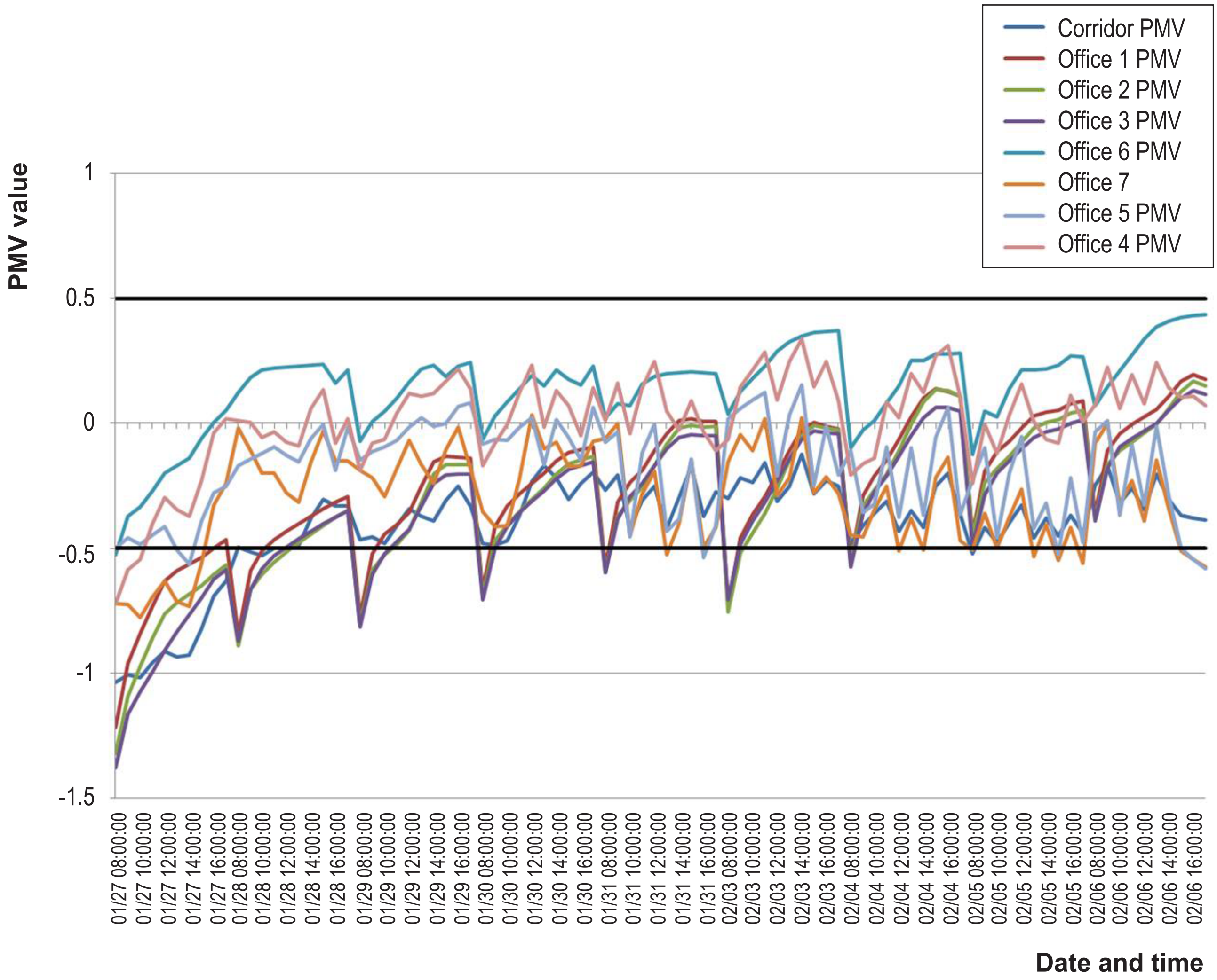

Figure 3. PMV variation in offices - optimized operation.

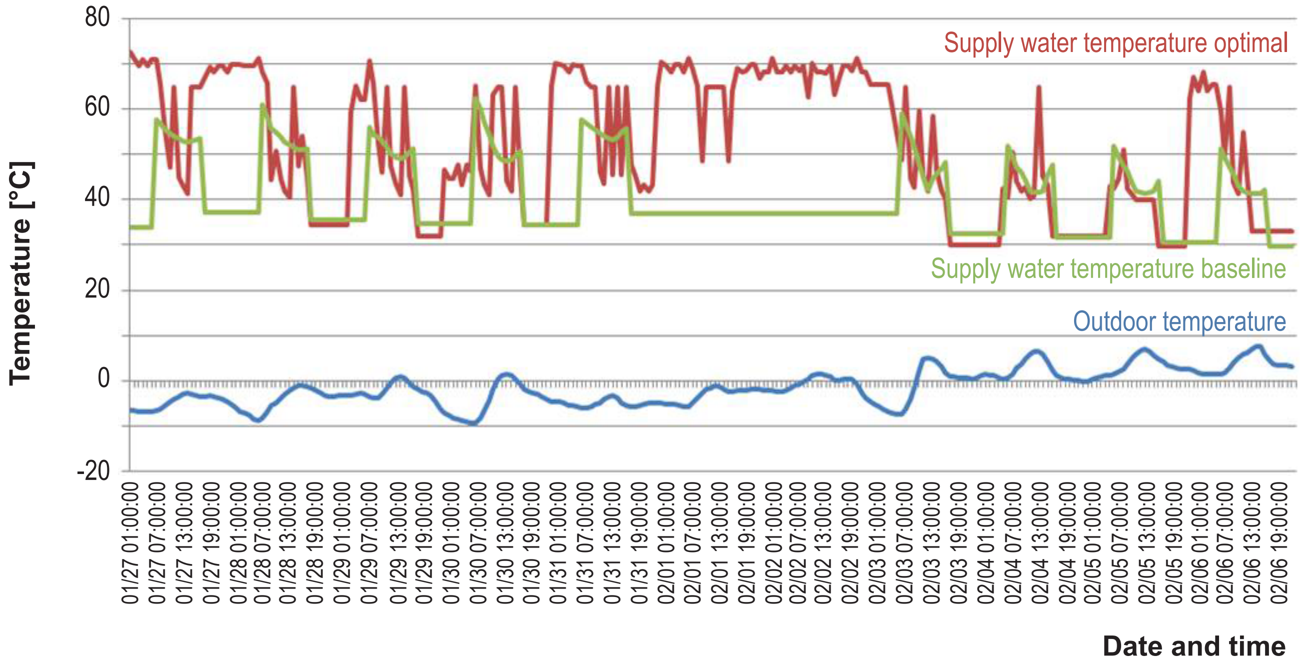

Figure 4. Heating supply temperature variation.

values from each day joined into a single simulation), the primary energy consumption had the value of 4024.9 kWh, and was used only for space heating, meaning that there was no need to turn on the AHU. The increased energy consumption was due to the weekend operation of the systems and resulted in 618.2 kWh of primary energy consumption. Thus increased energy consumption resulted in a much better occupant thermal comfort in all zones as shown in **Figure 3**.

It is interesting to note that for the optimal case no correlation could be made between the heating supply temperature and the outdoor temperature (**Figure 4**), which can potentially represent the material for future research with the aim of finding the heating curves with which system operators are familiar.

Conclusion

This paper presents the possibility to minimize primary energy consumption in offices by implementing the optimized operation of the existing HVAC systems, while simultaneously maintaining the thermal comfort of occupants within the desired range. The main goal of the paper was to show that with the existing HVAC system designed in the traditional manner, users or system operators can define in advance the thermal comfort level which the system will try to meet with minimal energy consumption. The main advantage of this methodology is that it can be applied with relatively small modifications of the existing HVAC system. Future research will be dedicated to the moving horizon approach and the implementation of the obtained optimal values into a real system, as well as their experimental verification. In addition, decision variables and objective function need to be checked in order to generalize the application of the presented process. ■

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