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POSSIBILITIES TO MINIMIZE GREENHOUSE GASES EMISSION AND MAINTAIN THERMAL COMFORT IN OFFICE BUILDINGS WITH CO-SIMULATION ASSISTED OPERATION OF AIR HANDLING UNITS

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Abstract. *Energy efficiency measures in existing buildings include improvements in heating, ventilation and air conditioning systems but from the perspective of system renovation and components upgrade. These measures target the building energy consumption and resulting greenhouse gases emissions, with thermal comfort of occupants being seen only by one or two parameters. Improvements in the existing system operation can lead to minimum greenhouse gases emission, while thermal comfort maintained at the desired level. This paper evaluates the possibility to minimize greenhouse gases emission while maintaining occupant thermal comfort within prescribed class, by optimizing the existing air conditioning system operation with five-weekday-planning horizon. Particle swarm optimization method is used. The paper shifts the focus from minimal emissions to minimal emissions for desired thermal comfort range, without system renovation or upgrade. The results show that maintaining thermal comfort results in higher greenhouse gases emission compared to usual system operation where emissions are lower but thermal comfort is outside the desired range almost all the time.*

Key words: *building energy simulation, thermal comfort, operation optimization, greenhouse gases emission, EnergyPlus*

1. INTRODUCTION

Significant increase of energy consumption in buildings has led to prioritizing energy conservation in buildings as part of energy policies in many countries. Building energy consumption in EU was in the range of 37% of the final energy consumption in 2004 [1]. In USA, building energy consumption participated with more than 40% of primary energy consumption in 2010 [2]. About 50% of building energy consumption is related to heating, ventilation and air conditioning (HVAC) systems [3]. The situation in Serbia is similar, where

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building sector participates with more than 50% of consumed energy [4]. Dominant energy source in Serbia is fossil fuels for both electricity production (needed for space cooling) and for space heating in non-residential buildings (natural gas or other fossil fuels are mainly used), making buildings one of the main emitters of greenhouse gases (GHG). This is why reducing energy consumption in buildings is important for reducing overall GHG emissions.

The energy consumption in buildings and resulting GHG emissions can be reduced in many ways: improving building envelope thermal characteristics, using energy efficient HVAC equipment and using renewable energy sources (RES) [5]. In the last several years, there has been a tendency to reduce building energy consumption without major renovations of the building or its systems, but just by improving HVAC [6-9] systems operation. This means to minimize the energy consumption of HVAC system as is, while maintaining occupants' thermal comfort in the desired range. Thermal comfort in buildings is mainly evaluated using the air temperature and in some occasions with the mean radiant temperature, although thermal comfort is far more complex parameter.

In accordance with ISO 7730 [10] international standard, thermal comfort can be defined as: *"that condition of mind which expresses satisfaction with the thermal environment"*. Many researchers have shown that thermal comfort is influenced by physical, physiological and even psychological processes. Also, it has been shown by different studies that despite different climate, living conditions and culture, the temperature that people choose as comfortable under similar conditions of clothing, activity, relative humidity and air velocity is very similar.

Numerous research studies have been conducted to calculate thermal comfort conditions. The most widely used thermal comfort index is Predicted Mean Vote (PMV) index developed by Fanger. The PMV index predicts the mean response of large group of people according to thermal sensation scale given in Table 1. PMV index encompasses four environmental parameters (ambient air temperature, mean radiant temperature, relative air velocity and relative humidity) and two personal parameters (clothing insulation and metabolic rate). In addition to PMV index, predicted percentage of dissatisfied (PPD; statistical comfort accessibility rate) can be directly calculated from the equation:

$$\mathrm{PPD} = 100 - 95e^{-0.03353\mathrm{PMV}^4 - 0.2179\mathrm{PMV}^2} \tag{1}$$

Table 1 Seven point thermal sensation scale in [10]

Thermal sensation	PMV
Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

Based on PMV/PPD model, three classes of comfort have been defined in [10]:

- Class "A" is very restrictive and defines the comfort range of PMV $\in$[-0.2; 0.2] and PPD < 6%
- Class "B" is generally recommended and defines the comfort range of PMV $\in$ [-0.5; 0.5] and PPD < 10%
- Class "C" is less restrictive with PMV $\in$[-0.7; 0.7] and PPD < 15%

This paper evaluates the possibility to minimize GHG emissions while maintaining occupants' thermal comfort within prescribed class, by optimizing the air conditioning system operation with five working days (weekdays) planning horizon, assuming weather forecasts for the planning horizon to be ideal.

2. CASE STUDY

For this paper, one part (offices) of Feniks BB company building was chosen (Figures 1 and 2). This building represents the combination of office and manufacturing type of buildings which are very common in Serbia.

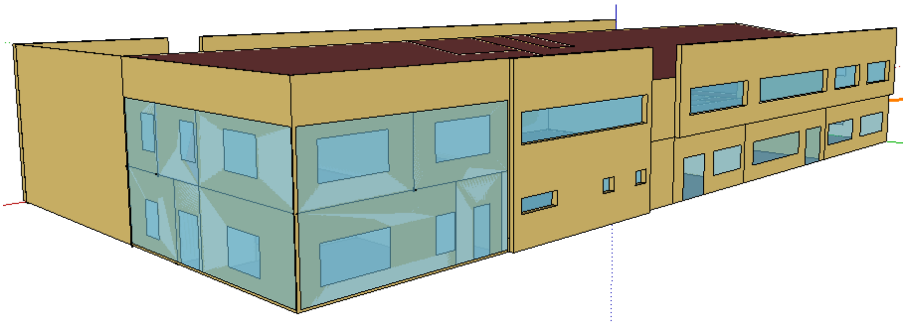


Fig. 1 Building model created with Open Studio Plug-in for Google SketchUp

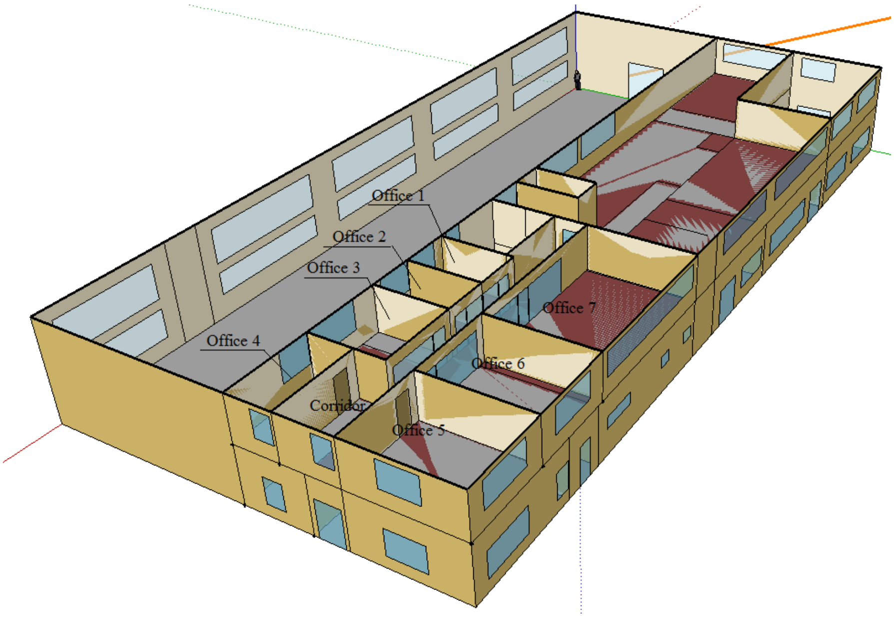


Fig. 2 Office part of the building

The building is located on the outskirts of City of Niš, Serbia. The building has 1630m^2 of useful floor area. One part of the building, approximately half in volume, is a manufacturing hall while the other part is divided in two stories where light manufacturing, servicing facilities and offices are located. Most of the outside windows and doors are double glazed with low emission glass. Windows and doors account for 35% of the building façade. In one part, north-east and south-east façade of the building are realized with semi-structural glass façade. All glass fields are double glazed 6-15-4 with green stopsol outside glass layer. Outside walls are masonry with insulation and aluminum panels (except north-west wall).

On a zone level, heating system consists of baseboard heaters (radiators) which heat most of the building premises, air heaters (for heavy manufacturing premises), and ducted fan-coil unit (serving the dining room). For the office part of the building, the cooling is provided with central air conditioning system (central air handling unit-AHU) which can be used also as alternative heating system in transitional periods or as an additional heating system during winter period in order to provide the fresh air to the occupants. AHU consists of the following sections: air-to-air plate heat exchanger (for heat recovery) which can act also as mixing box, coil section (cooling or heating), supply and exhaust fans and sound attenuators. The air conditioning system is designed in traditional manner to meet the design indoor temperature for summer design day (thermal comfort is perceived only with indoor air temperature) and its operation for the same period is used as baseline. The AHU operation is controlled by PLC.

As primary systems, gas-fired condensing boilers and air-to-water heat pump are being used.

Whole building energy simulation program *EnergyPlus* was used to model the building with its systems. Building geometry was created using *Open Studio Plug-in for Google SketchUp*, as shown in Figures 1 and 2. All rooms in the building are treated as separate thermal zones.

In order to run the simulations, weather file containing all boundary conditions necessary to run the EnergyPlus equations is needed. Custom weather file in required format for July 2015 was made from the data provided by hydro-meteorological station Niš.

The offices are assumed to be occupied during weekdays from 08:00 until 18:00 (the last occupied hour is from 16:01 to 17:00) and have number of occupants as given in Table 2. For the occupied period the goal is to maintain thermal comfort within the prescribed range by optimizing AHU operation for every day. Predicted mean vote (PMV) is used as the indicator for thermal comfort and can be generated as output from the simulations on hourly basis for every modeled zone. Though the outputs for PMV have a discrete scale (–3 to +3), the calculations in EnergyPlus are carried out on a continuous scale which is not an error [11] and one can treat particular value of PMV only as within desired range or outside this range (for instance PMV output can be 0.23784 and if desired comfort is class "B" this value meets the criteria)

Table 2 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	2
Office 6	2
Office 7	4
Corridor/lobby	2

3. METHODOLOGY

The methodology is based on the combination of detailed hourly simulations of building modeled in EnergyPlus and 5-day-planning air-handling unit operation optimization developed in C#. For this paper, one summer week from July 20th to July 24th was selected.

3.1. Decision variables

In order to perform the optimization task and calculate the objective function, decision variables should be defined first. Since the goal is to achieve the minimum GHG emissions while maintaining thermal comfort of occupants in defined range for 5 weekdays, and having the simulation tool limitations in mind (for instance there are variables that cannot be varied hourly or daily), variables are classified in two groups: the ones which can be modified hourly/daily and the others which can be modified once per simulation. Some of the variables which can be modified hourly are for every day of planning horizon subdivided into three periods of day: unoccupied before occupants arrive (from midnight until 08:00); occupied period (from 08:00 until 18:00); unoccupied after occupants leave (from 18:00 until midnight). In order to reduce total number of decision variables only one decision variable for each of the unoccupied periods is allowed. Also, some decision variables are constrained by the fact that the system is already installed and there are limitations especially in air flow rates.

Total of 207 decision variables were selected for the research:

- Chilled water supply temperature (hourly for each day of planning horizon with distinction between occupied and unoccupied periods) - 65 variables;
- Minimum outside air fraction (hourly for each day of planning horizon) - 120 variables;
- Heat Recovery runtime (daily) - 5 variables;
- Heat Recovery finish time (daily) - 5 variables;
- Cooling Coil runtime (daily) - 5 variables;
- Cooling Coil finish time (daily) - 5 variables;
- System air flow rate (once per simulation) - 1 variable;
- Heat Recovery bypass maximum limit temperature (once per simulation) - 1 variable.

3.2. Objective function

The objective function of the optimization problem is minimum operation-related GHG emissions subject to the thermal comfort related constraints. Other boundary conditions are taken into account as a part of EnergyPlus simulations. The objective function can be defined as:

$$\min GHG[\mathrm{kg\ CO_2e}] = \left(\frac{E_{cc}}{3} + E_{SF} + E_{RF}\right) * 0.74 \tag{2}$$

where *GHG* represents greenhouse gases emissions due to primary energy consumption from three AHU sections: cooling coil, supply fan and return fan*; ECC* - cooling coil cooling energy consumption; *3* - COP for heat pump (assumed constant); *ESF* - supply fan electricity consumption; *ERF* - return fan electricity consumption*; 0.74* - specific emission for electricity in $\mathrm{kgCO_{2e}/kWh}$ [12]. The values of *ECC*, *ESF* and *ERF* are the outputs from EnergyPlus simulations.

Thermal comfort related constraints are given in the following form:

$$-\varepsilon \leq TCF \leq \varepsilon \tag{3}$$

where ε is non-dimensional nonnegative variable that is parametrically varied in the range 0.2–0.7. and considered as a constant in the optimization problem, while *TCF* is a thermal comfort-related function, defined either as the average or minimal PMV index value for all occupied hours in all offices during planning horizon. The values of PMV index are obtained as the outputs from EnergyPlus simulations.

The optimization problem is solved using particle swarm optimization (PSO) method [13]. The population is set to 400 and the maximal number of generations was constrained to 200. The termination criteria for optimization is to run at least 100 generations and that in 50 consecutive generations there is no more than 0.1% difference in best objective value.

4. SIMULATIONS AND DISCUSSION

In order to test the methodology presented, several different TCFs were created and the results are compared to baseline operation:

- TCF is average PMV for planning horizon:
  – PMV conforms class "A" - case 1
  – PMV conforms class "B" - case 2
  – PMV conforms class "C" - case 3
- TCF is minimum PMV for planning horizon:
  – PMV conforms class "A" - case 4
  – PMV conforms class "B" - case 5
  – PMV conforms class "C" - case 6

The baseline operation has GHG emissions of 323.8 $kgCO_{2e}$ with an average PMV of 0.66. PMV varies within zones from -0.38 to 1.24 as shown in Figure 3. Only in 2 offices PMV conforms to class "B" thermal comfort, while in other zones it is outside desired range. For total of 296 hours (out of possible 400 hours) the PMV was outside desired range for the planning horizon.

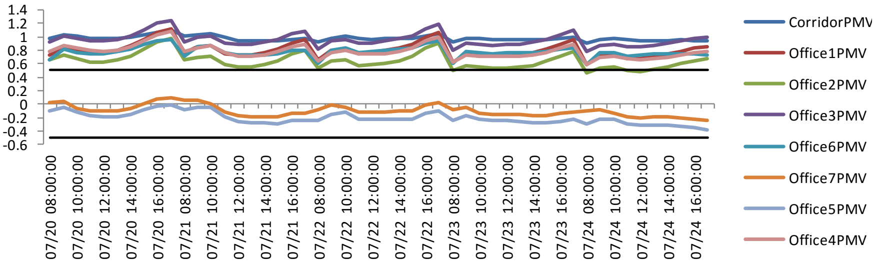


Fig. 3 PMV variation in all zones for baseline operation

GHG emissions for cases 1-3 are, compared to baseline case, higher for 93%, 20% and 2% respectively, as shown in figure 4. It is clear that stricter the comfort, more GHG emissions occur; however, thermal comfort is far better as shown in Figure 5. Although average comfort has been satisfied, which was the constraint of optimization problem, there are strong deviations from threshold values in all three cases.

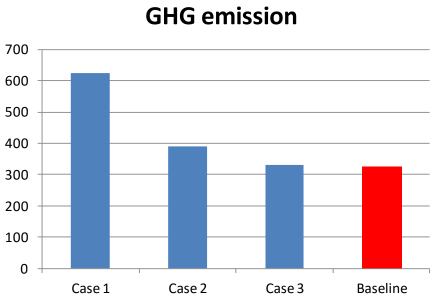
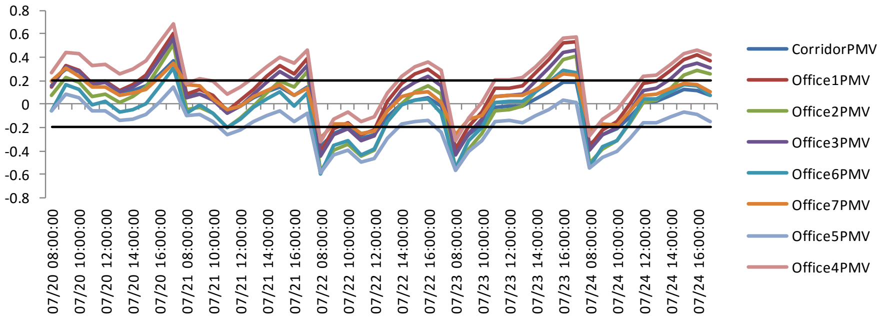
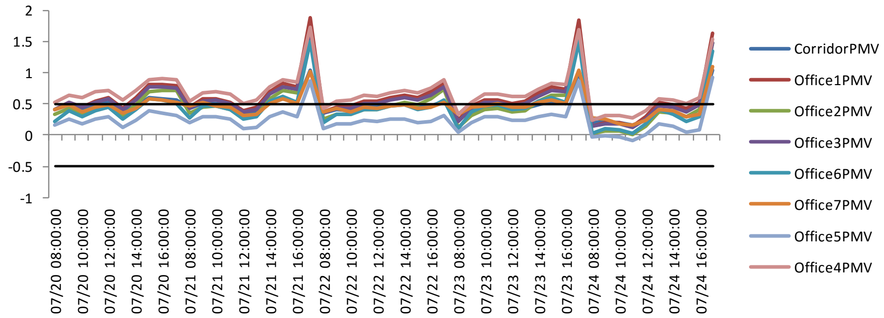


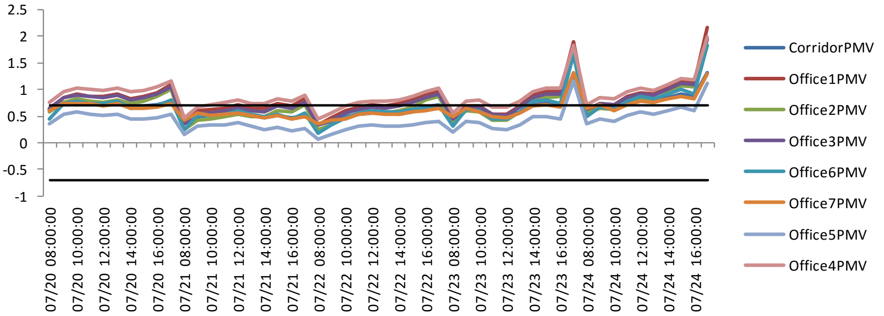
Fig. 4 GHG emissions for average PMV, in $kgCO_{2e}$



Case 1



Case 2



Case 3

Fig. 5 PMV variation in all zones for planning horizon for average PMV

From Figure 5 it is clear that in each case there are hours when PMV threshold are not satisfied within each zone. For case 1 there were total of 166 hours when PMV was outside the range (-0.2, 0.2). For case 2 there were total of 161 hours when PMV was outside the range (-0.5, 0.5). For case 3 there were total of 174 hours when PMV was outside the range (-0.7, 0.7).

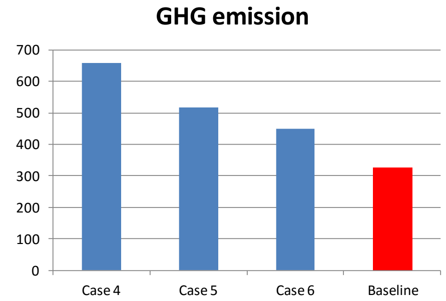
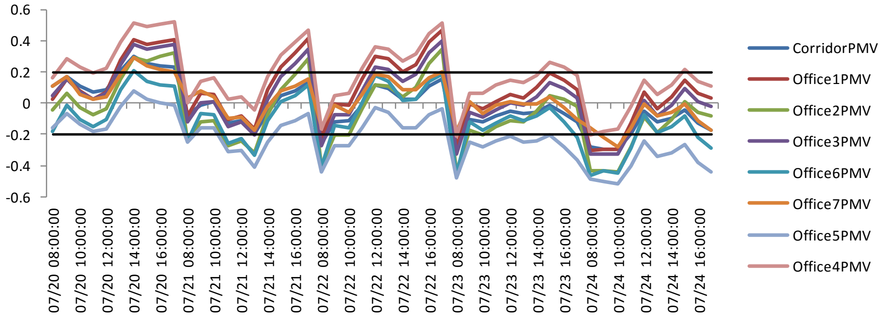
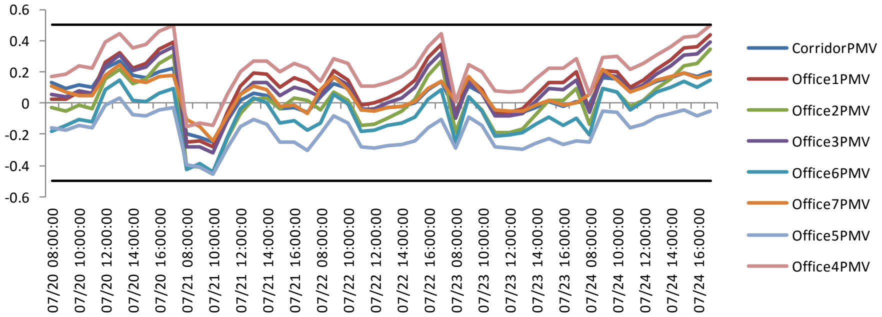


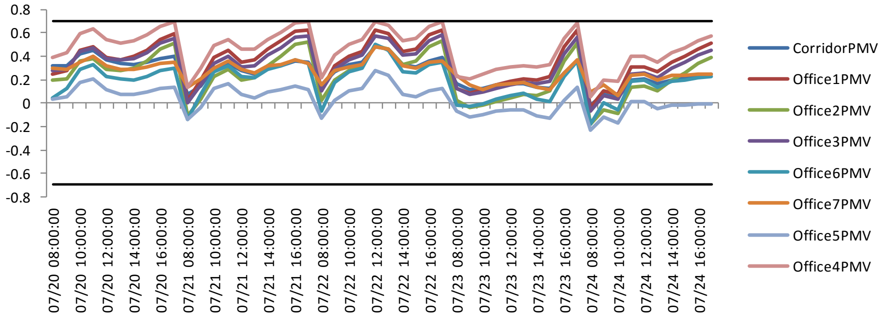
Fig. 6 GHG emissions for minimum PMV, in $kgCO_{2e}$



Case 4



Case 5



Case 6

Fig. 7 PMV variation in all zones for planning horizon for minimum PMV

GHG emissions for cases 4-6 are, compared to baseline case, higher for 104%, 60% and 39% respectively, as shown in figure 6. The emissions in all cases are higher compared to cases 1-3 as expected, since stricter thermal comfort function has been used. However, when looking closer at PMV variation in all zones, it is evident that in cases 5 and 6, PMV was within the specified range but in case 4 PMV was outside the range for 136 hours, as shown in Figure 7.

5. CONCLUSIONS

This paper examines the possibility to minimize GHG emissions in offices by implementing co-simulation assisted operation of central air handling unit, while maintaining occupants' thermal comfort within desired range. The main goal was to show that with the existing air conditioning system designed in traditional manner, users or system operators can define in advance the thermal comfort level which the system will try to meet and at the same time to minimize the GHG emissions while doing so. The methodology was applied for relatively warm period starting on July 20th 2015 and ending on July 24th 2015. The main advantage of the methodology is that neither refurbishments nor modifications of the air conditioning system itself are needed.

The results show that resulting GHG emissions are strongly dependent on the type of thermal comfort function being used. Although average PMV results in lesser emissions, thermal comfort is more often violated for the planning horizon. As a function of thermal comfort, minimum PMV gives higher emissions, but far better thermal comfort within all zones during the planning horizon. The tradeoffs between GHG emission and thermal comfort are possible on daily or weekly level, depending on priority.

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MOGUĆNOSTI SMANJENJA EMISIJE GASOVA SA EFEKTOM STAKLENE BAŠTE I ODRŽANJA TERMIČKOG KOMFORA U POSLOVNIM ZGRADAMA KO-SIMULACIJOM PODRŽANIM RADOM KLIMA KOMORA

Mere povećanja energetske efikasnosti postojećih objekata uključuju i mere koje se odnose na sisteme klimatizacije, grejanja i ventilacije ali iz perspektive rekonstrukcije tj. zamene sistema i njegovih komponenata. Ovim merama se utiče na smanjenje potrošnje energije i rezultujućih emisija gasova sa efektom staklene bašte, povećanjem efikasnosti sistema, pri čemu se termički komfor ljudi koje borave u prostorijama koje sistemi opslužuju tretira kroz jedan ili dva termička parametra. Unapređenjem u načinu rada sistema moguće je emisiju gasova sa efektomstaklene bašte držati na minimumu , pri čemu se termički komfor prisutnih može održavati u željenim granicama. U ovom radu istražena je mogućnost minimizacije emisije gasova sa efektom staklene bašte uz istovremeno održavanje termičkog komfora prisutnih unutar željene klase, optimizacijom rada postojećeg sistema klimatizacije za horizont paniranja od pet radnih dana. Paralelna optimizacija rojem čestica je implementirana u radu.

U radu se fokus pomera sa minimalne emisije na minimalnu emisiju za željeni nivo termičkog komfora bez renoviranja ili nadogradnje sistema. Rezultati su pokazali da se termički komfor može održavati u željenim granicama sa višom emisijom u poređenju sa uobičajenim načinom rada sistema kada su emisije gasova niže ali je termički komfor van željenog opsega gotovo čitav horizont planiranja.

Ključne reči: *Simulacija energetskog ponašanja zgrada, termički komfor, optimizacija radnog režima, emisije gasova sa efektom staklene bašte, EnergyPlus*