GENETIC OPTIMISATION OF INDOOR ENVIRONMENTAL PARAMETERS FOR ENERGY USE AND COMFORT - A CASE STUDY FOR COOL-HUMID CLIMATE

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ABSTRACT

An office building was designed and built according to state-of-the-art design and energy management principles in 2008. Despite the expectations of high building performance, the owner was facing high utility bills and low user comfort in his building which is located in Budapest, Hungary. The objective of the project presented in this paper was to determine the optimal indoor environmental parameters and HVAC control scheme both from the energy use and the indoor thermal comfort point of view taking into consideration occupant behaviour patterns experienced in the building. Four different types of office rooms were investigated with different orientation and façade type. Simulation-based optimisation assisted the process and helped consultant engineers to undertake building management system fine-tuning tasks. The method applied includes the use of dynamic multizonal (nodal) energy simulation software, with optimisation plugin using NSGA-II genetic algorithm method. As a result, the pareto front of optimal indoor environmental conditions (setpoints), control schedules and principles could be determined for each office type ensuring highly energy-efficient operation and high comfort levels. At the end, results were compared with European comfort standard recommendations as well.

INTRODUCTION

The owner of a large office building was facing high utility bills and low user comfort in his building which is located in Budapest, Hungary and was built in 2008. The office building was designed and built according to state-of-the-art design and energy management principles. Therefore, the causes of the poor operation were not quite clear. The objective of the project was to evaluate the energy performance and comfort indices of the building, to identify the causes of malfunction and to elaborate a comprehensive energy concept. (Belafi, Zs., Reith, A., 2014)

In the first phase of the project, building conditions and operation parameters were evaluated with special regard to building management systems, occupant control behaviour and user comfort. The evaluation tools were:

- collecting and analysing available data related to building operation and energy use,
- online questionnaire on indoor comfort problems - with 212 of the 450 employees answering the questions,
- survey and on-site walk-through investigating building usage in offices and meeting rooms,
- thermal comfort measurement in the offices receiving the most negative feedback based on the results of the questionnaire and survey,
- thermographic survey of the building envelope,
- an analysis of the secondary HVAC equipment operation and indoor climatic conditions recorded by BMS system.

The current HVAC system of the building consist of a gas-fired boiler and a compact chiller supplying the fan-coil units of the offices. The air handling units supply only fresh air to the rooms. As an outcome of the preliminary analyses, our investigation found that the state-of-the-art building management system is in a good condition but it is operated by building operators and occupants who are practically not aware of the building management processes. (Belafi et al., 2015)

Therefore, it was assumed that the operational conditions could be improved. At first the owner was thinking of retrofitting his building. However, according to our investigations it was found that it is more cost-effective to fine-tune the HVAC operation parameters of the building. As an outcome, it was expected to decrease the energy use and increase indoor thermal comfort of occupants at the same time.

As an answer for such problems, the architectural design community has started to use building energy modelling and optimisation tools as decision support tools in the last decade. (Machairas et al., 2014) However, the applications of building optimisation in real-world design challenges are still in the early stage of development (Nguyen et al., 2014) and it is not commonly used at operational phase building improvement projects.

According to recent review studies, the most commonly used approach by designers is coupling building energy modelling tools (e.g.: EnergyPlus, TRNSYS, IDA ICE, Dymola, DOE-2) with optimisation toolboxes. (e.g.: MATLAB, GenOpt, GENE-Arch, modeFRONTIER). (Machairas et al., 2014; Nguyen et al., 2014; Amaran et al., 2014) Optimisation algorithms can be categorised according to the following pattern: genetic algorithms (GA), derivative-free search methods and also hybrid algorithms. (Machairas et al., 2014). The most commonly used optimisation algorithms in decision support problems are NSGA II and Back-propagation Network (Yu et al., 2015)

Most currently available studies investigate the optimisation possibilities of only one indoor environmental or operational parameter of a given building. For example either a proposed HVAC system parameter (Parameshwaran et al., 2009) or AHU inlet air temperature schedule (Candanedo et al., 2015) or heating and cooling setpoints (Hussain et al., 2014; West et al., 2014) or exchange rate of a given room (Pantelic et al., 2012). There is a gap currently in the literature of research studies where several indoor environmental parameters are optimised at the same time in case of existing, operating buildings.

Another important parameter of the optimisation process is the selection of the appropriate number and kind of objective functions. In order to keep an investigation study applicable to real-world situations the number of objective functions should be minimised but at the same time it should be ensured that the optimal HVAC operation comfort parameters provide indoor conditions that are comfortable for users and are reached in the most energy efficient way. In case of a low-energy building optimisation process the most commonly used objective functions are the energy use, indoor comfort, room HVAC equipment size and investment cost of an intervention. (Hamdy et al., 2011; Asadi et al., 2014; Pantelic et al., 2012) Usually in the studies referenced above, two or three objective functions were used.

Based on the above identified findings of current literature available in this topic and answering the needs of the case study building owner, the following research question was addressed in case of the case study introduced above:

- To what extent can the energy use and the uncomfortable hours be decreased by optimisation of 3 indoor thermal control parameters (namely fresh air supply temperature, heating and cooling setpoints) in case of an existing, operating building?

METHODOLOGY

As the first phase of the project, a comprehensive energy audit was completed as described above. The results of the audit were used to model the building as is (baseline case), the energy model was created in software IDA ICE v4.6. (IDA ICE) This model was calibrated based on 4-year historical building energy use data and the behaviour and presence of the building occupants was modelled based on the survey results and occupancy signals of the office sensors. (OB15)

As part of the analysis of the applicable building operation improvement measures, the key HVAC control parameters were optimised: setpoints of the Air Handling Unit (AHU) for the supply air temperature and the daily setpoints of the minimum and maximum temperature in the offices of the building. The parameters optimised can be seen on figures 1-2-3 and each variable is defined in the nomenclature. It should be noted that in this case, ventilation is used only for fresh air supply. Therefore, the supply air temperature follows the indoor air temperature. (i.e. it is warmer in summer)

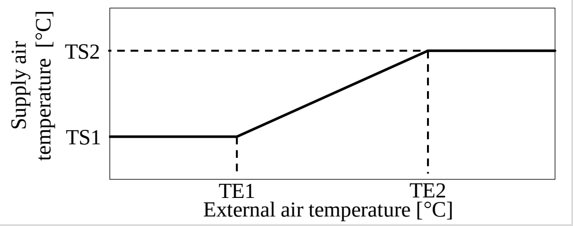

Figure 1 – Variables of AHU setpoints

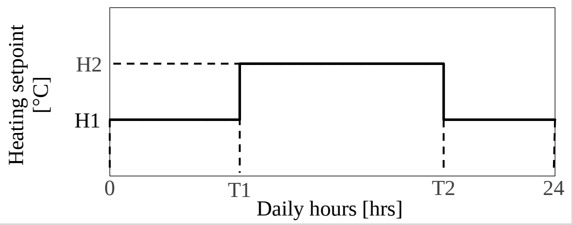

Figure 2- Variables of the daily heating setpoints

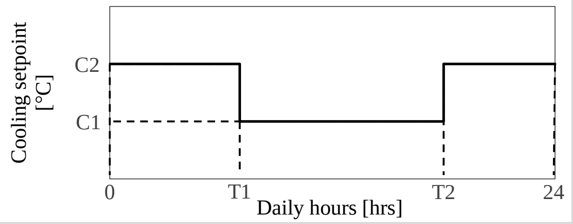

Figure 3- Variables of the daily cooling setpoints

The optimisation was carried out in case of four characteristic sample offices that are representing the main office types (size, façade type and orientation) of the building under investigation.

1. SW: south-facing office with windows,
2. N: north-facing office, inner yard with windows,
3. E: east-facing office, inner yard with windows,
4. SC: south-facing office with curtain wall façade.

The optimisation simulations were run for two whole months: July and January. This way run-time of the models was adequate and at the same time it was possible to model average summer and winter environmental conditions. The algorithm NSGA-II was used to find the optimal solutions (Pareto front) with the minimization of two objective function: monthly energy usage in kWh (including heating, cooling, lighting, equipment and HVAC_aux, using system efficiencies of the actual building) and predicted number of people dissatisfied hours (PDH).

PDH is defined as the hours of people dissatisfied, i.e. the integral of the PPD measure multiplied by the total number of present occupants.

The software IDA ICE was connected to a new multi-objective optimisation plugin called MOBO (Multi Objective Building Optimisation).

Parameters used for the NSGA II optimisation were:

- population size: 16,
- generations: 126,
- mutation probability: 0.0166 (July), 0.025 (January) – this value is the reciprocal of the number of the variables,
- crossover probability: 0.9.

At the end, two ideal solutions were chosen from the Pareto front to be proposed to the owner of the office building:

- One where the energy use can be minimised by same indoor comfort values as experienced currently in the building. (Case A) In this case, the proposed solution was selected by projecting the current case (marked with Δ) vertically onto the Pareto front. On Figures 4-11, these solutions are marked with symbol ◊.
- Secondly, one where the possible maximal indoor comfort values can be reached by the current energy use. (Case B) In this case, the proposed solution was selected by projecting the current case (marked with Δ) horizontally onto the Pareto front. On Figures 4-11, these solutions are marked with symbol O.

Between the two cases selected on the Pareto front, each case is better (either from energy use or comfort perspective) than the current case. It is up to the owner which aspect is more important to him in case of the given building. In this paper we introduce the two extreme cases.

At the same time, it was also determined in which cases the indoor parameters fall in comfort category I of standard EN 15251. (or category A of standard EN 7730)

Simulation data of baseline case are shown in tables 1 - 3 below.

Table 1
Simulation data of baseline case

ZONE NAME	**FLOOR AREA**	**OCCUPANTS**		**WORKING HRS**	**PDH HEATING**	**AV. PPD HEATING**	**DEL. ENERGY HEATING**		**PDH COOLING**	**AV. PPD COOLING**	**DEL. ENERGY COOLING**	
	m^2	**no/m^2**	**no**	**hrs/month**	**hrs**	**%**	**kWh**	**kWh/m^2**	**hrs**	**%**	**kWh**	**kWh/m^2**
South - windows (SW)	34.56	0.10	3.49	453.60	32.72	7%	642	18.58	24.34	5%	380.00	11.00
North (N)	37.55	0.10	3.79	492.84	33.79	7%	678	18.06	25.75	5%	395.00	10.52
East (E)	19.70	0.10	1.99	258.56	17.7	7%	338	17.16	13.50	5%	199.00	10.10
South - curtain wall (SC)	36.53	0.10	3.69	479.45	42.01	9%	869	23.79	27.72	6%	423.00	11.58

Table 2
Operation parameters of baseline case in January investigations

ZONE NAME	**H1**	**H2**	**T1**	**T2**	**TS1**	**TS2**	**TE1**	**TE2**
	°C	**°C**	**hr**	**hr**	**°C**	**°C**	**°C**	**°C**
South - windows (SW)	20.00	22.50	7:00	17:00	22.00	26.00	26.00	32.00
North (N)	20.00	22.50	7:00	17:00	22.00	26.00	26.00	32.00
East (E)	20.00	22.50	7:00	17:00	22.00	26.00	26.00	32.00
South - curtain wall (SC)	20.00	22.50	7:00	17:00	22.00	26.00	26.00	32.00

Table 3
Operation parameters of baseline case in July investigations

ZONE NAME	**C1**	**C2**	**T1**	**T2**	**TS1**	**TS2**	**TE1**	**TE2**
	°C	**°C**	**hr**	**hr**	**°C**	**°C**	**°C**	**°C**
South - windows (SW)	24	40	7:00	17:00	22	26	26	32
North (N)	24	40	7:00	17:00	22	26	26	32
East (E)	24	40	7:00	17:00	22	26	26	32
South - curtain wall (SC)	24	40	7:00	17:00	22	26	26	32

In tables 1-3, those parameters are highlighted with grey that were fixed during the optimisation process. These parameters were fixed to optimise the number of variables in the study and at the same time there was no point in changing them due to fixed working hours in the building or modelling constraints.

January:

- T2: end of the workday in each zone and each case
- TS2, TE1, TE2: The external temperature is always below TE1, therefore the results do not affect these parameters, only TS1

July:

- T2: end of the workday in each zone and each case
- C2: cooling is switched off besides occupied hours, in the model a constant high temperature – that internal temperatures do not exceed anytime - needs to be specified

Therefore, they were not moving during the iterations and this way the population size of the investigation could remain in a manageable order of magnitude.

RESULTS

In the framework of the optimisation tool, MOBO, 2016 variations were run for heating (January) and cooling (July) seasons each, using the genetic optimisation algorithm, NSGA II. Results of the optimisation runs can be seen on figures 4-11 for each office type and season. The results of the run with current operating conditions are marked on the charts as well as the two selected optimal solutions from the Pareto front: case A with minimum energy use and case B with minimum PDH values.

Tables 4-5 shows the parameters of the selected, optimised solutions in both seasons in cases A and B.

On figures 4-11 the border between comfort categories I, II and III of standard EN 15251 is marked with a vertical line in. These categories are separated by average PPD values (6% and 10% respectively). As the PPD value depends on the total working hours of each occupant in a zone, the border lines are assigned to different PDH values in different zones. (See equation 1.) By achieving <6% PPD value, the comfort category can be increased to I (or ‘A’ regarding the standard of EN ISO 7730).

$$PDH / \Sigma working\ hours = PPD \qquad (1)$$

Table 4
Results of January investigations

ZONE NAME	H1	H2	T1	TS1	PDH	AVERAGE PPD	DELIVERED ENERGY	
	°C	°C	hr	°C	hrs	%	kWh	kWh/m^2
Optimised - Case A -Minimum Delivered Energy								
South - windows (SW)	18.95	23.1	4:15	17.03	32.72	7.2%	609.96	17.65
North (N)	19.18	23.47	4:03	17.22	33.79	6.9%	654.28	17.42
East (E)	19.51	23.51	5:30	17.68	17.70	6.8%	328.42	16.67
South - curtain wall (SC)	17.02	22.46	4:02	17.03	42.01	8.8%	818.43	22.40
Optimised - Case B - Minimum PDH								
South - windows (SW)	19.44	24.29	4:05	17	25.30	5.6%	642.00	18.58
North (N)	19.47	24.27	4:10	17.28	27.82	5.6%	678.00	18.06
East (E)	20.92	24.09	4:04	17.55	15.03	5.8%	338.00	17.16
South - curtain wall (SC)	17.02	24.28	5:35	17.14	28.89	6.0%	869.00	23.79

Table 5
Results of July investigations

ZONE NAME	C1	T1	TS1	TS2	TE1	TE2	PDH	AVERAGE PPD	DELIVERED ENERGY	
	°C	hr	°C	°C	°C	°C	hrs	%	kWh	kWh/m^2
Optimised - Case A - Minimum Delivered Energy										
South - windows (SW)	24.03	4:21	23.53	27.5	25.55	30.8	24.34	5.4%	369.92	10.70
North (N)	24.02	4:03	23.74	27.72	27.62	30.34	25.75	5.2%	384.69	10.24
East (E)	23.99	5:06	23.59	27.88	24	30.22	13.50	5.2%	193.06	9.80
South - curtain wall (SC)	24.03	4:08	22.49	27.88	24.15	30.01	27.72	5.8%	413.10	11.31
Optimised - Case B - Minimum PDH										
South - windows (SW)	23.22	4:13	20.45	27.58	26.04	30.46	23.00	5.1%	380.00	11.00
North (N)	23.31	4:54	20.63	27.16	25.9	33.8	24.97	5.1%	395.00	10.52
East (E)	23.26	5:10	20.6	27.91	24	30.21	13.14	5.1%	199.00	10.10
South - curtain wall (SC)	23.34	4:07	20.98	26.75	24.12	30.01	25.07	5.2%	423.00	11.58

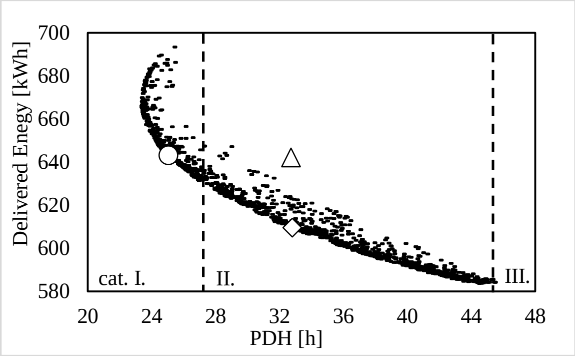

Figure 4 - Results of Zone SW (January)

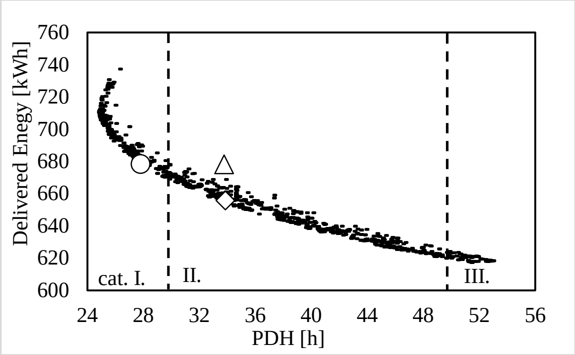

Figure 5 - Results of Zone N (January)

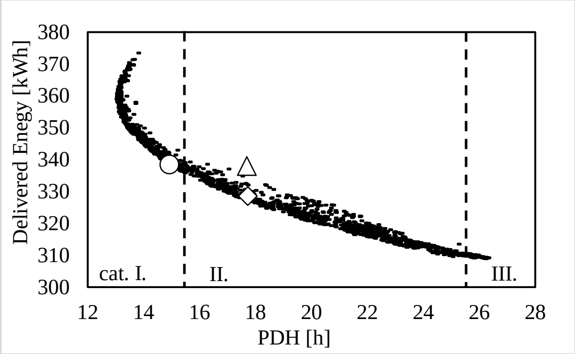

Figure 6- Results of Zone E (January)

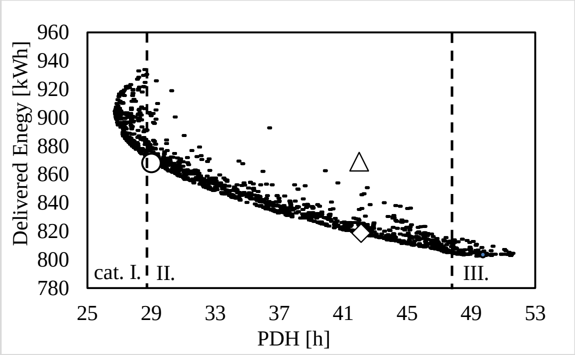

Figure 7- Results of Zone SC (January)

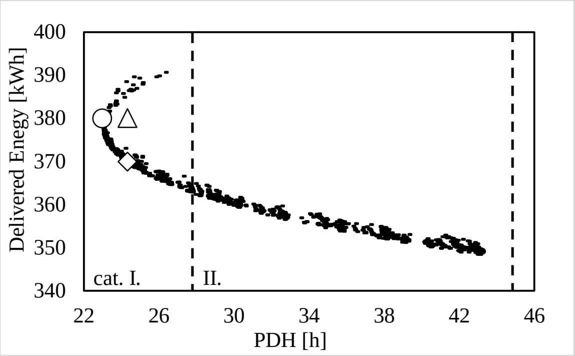

Figure 8 - Results of Zone SW (July)

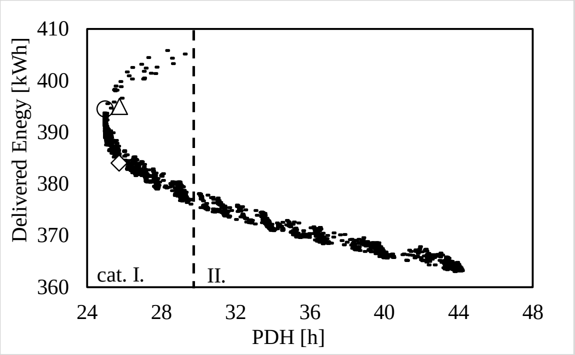

Figure 9 - Results of Zone N (July)

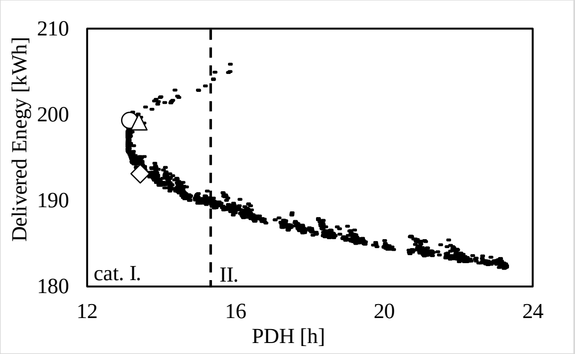

Figure 10 - Results of Zone E (July)

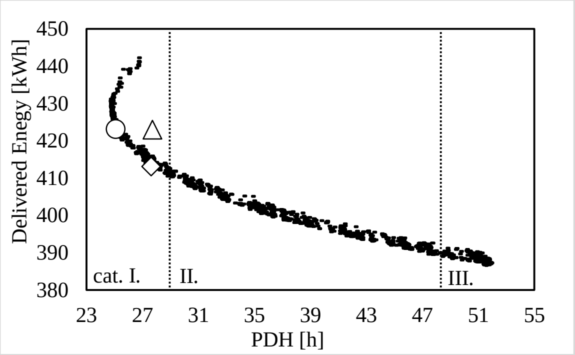

Figure 11 - Results of Zone SC (July)

Legend:

Δ:	current operating conditions
◊:	case A - minimum energy use, with current PDH values
O:	case B - with minimum PDH values, with current energy use value

On Figures 12-19 the optimised setpoint and inlet fresh air temperature control schedules can be seen.

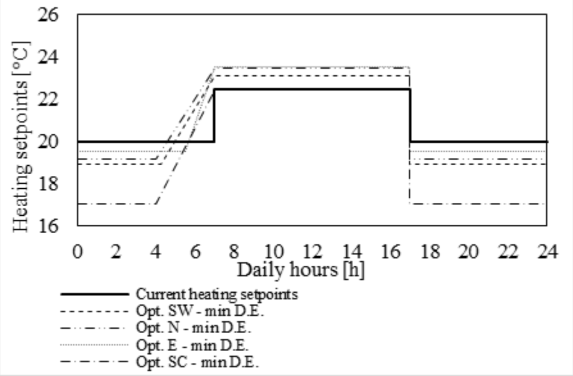

Figure 12 – Heating setpoints (Case A – min D.E.)

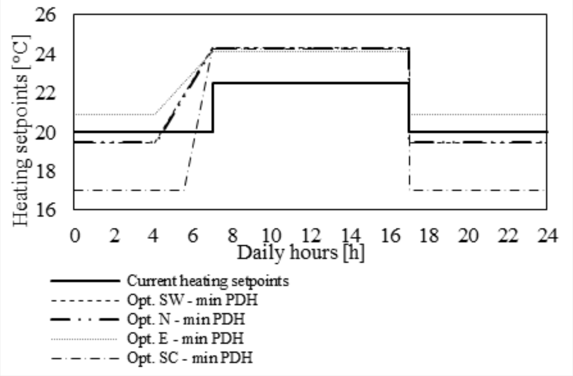

Figure 13 – Heating setpoints (Case B – min PDH)

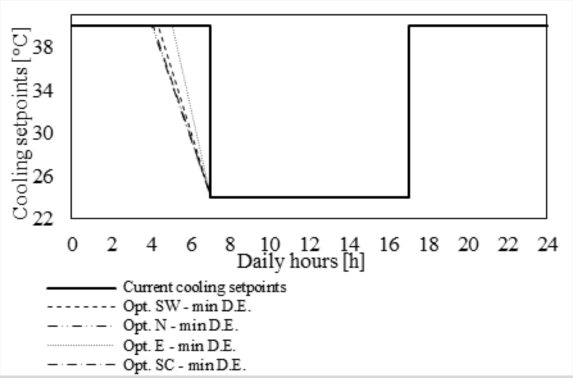

Figure 14 – Cooling setpoints (Case A – min D.E.)

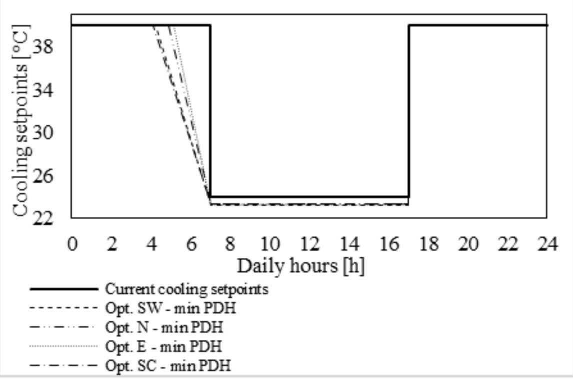

Figure 15 – Cooling setpoints (Case B – min PDH)

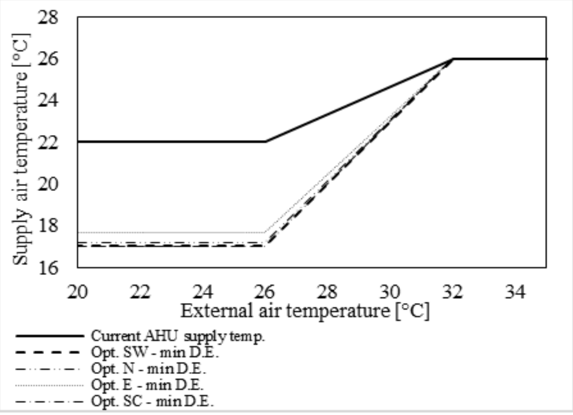

Figure 16 – AHU temperatures - January (case A - min D.E.)

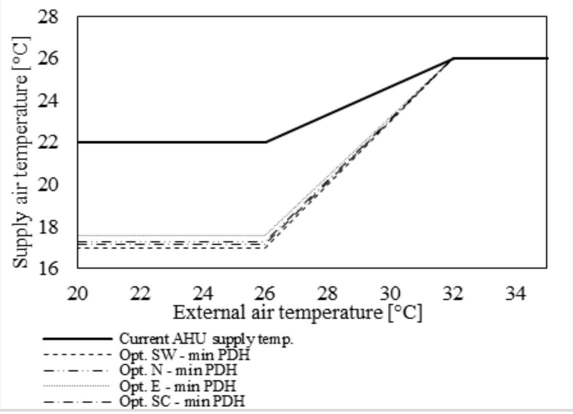

Figure 17 – AHU temperatures - January (case B - min PHD)

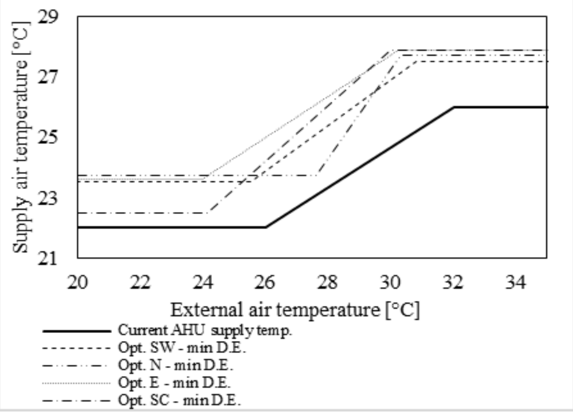

Figure 18 – AHU temperatures - July (case A - min D.E.)

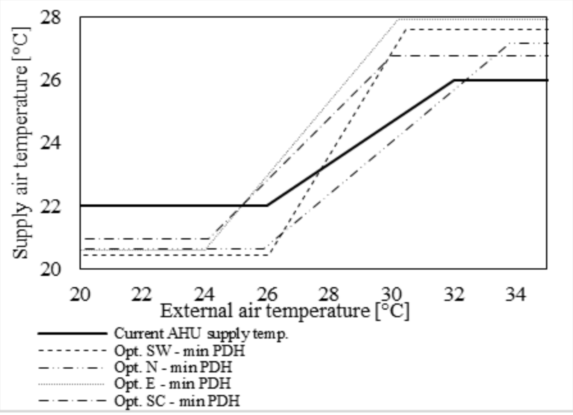

Figure 19 – AHU temperatures - July (case B - min PHD)

DISCUSSION

Winter month result analysis

Results showed that the heating system of the rooms should be switched on earlier in the morning. This way both energy use and discomfort could be minimised as the significant thermal mass of the office could balance the heat supplied to the rooms during the day.

Heating setpoints are higher and AHU inlet air temperatures are lower in case of both A and B cases as the investigation showed that it is more advantageous (both from energy and comfort point of view) to heat the room with the heating system instead of providing fresh air with higher temperature.

Night-time and weekend setback temperatures are lower in the optimised cases as during unoccupied periods heating is not necessary and the above mentioned optimised morning pre-heating period ensures the lowest energy use and maximal user comfort. In case of the eastern office, the optimal setback values were higher than in the other rooms 19.51°C (case A) and 20.92°C (case B) which is because the heat loss is relatively low in that room due to smaller glazed façade area this way night heating consumes less energy. At the same time, the morning preheat starts later in these rooms as morning sunshine has a significant heating effect during morning hours.

In the south facing room with curtain wall, the heating setpoint during the day is lower than in the other room types in case A as average PPD value originally was the highest here and in case A the goal is to decrease energy use by the same comfort level. This way the original comfort level could be maintained with lower heating setpoint value as well.

Summer month result analysis

In case A, where the energy use is minimised, results do not show major setpoint change necessary. In case of the application of morning precooling 2.7-3% energy can be saved.

According to the results of case B, PDH values can be decreased significantly (9.6-2.7%) with the optimised parameters. The cooling setpoint was decreased and morning precooling was implemented as well.

In both cases A and B, precooling should start later in the Eastern than in the other room types (5:06 and 5:10 respectively). This phenomena refers to the same low heat loss property of the Eastern room type mentioned above at the winter month result analysis.

AHU inlet air temperatures during the summer are higher than the current values in case A and lower in case B. in case A where the goal is the minimal energy use, the inlet air is cooled down only to that extent which fulfils current indoor comfort conditions. In case B, the inlet temperatures are lower to achieve better user comfort with the same energy use.

CONCLUSION

According to the occupant survey the highest discomfortwas reported from south-facing offices with curtain walls. By means of the optimisation user comfort can be increased by 31.2% and 9.5% in winter and summer conditions respectively in case B where discomfort was minimised by the current energy use.

Based on the results of the optimisation study, it can be stated that the inlet air temperature is different for each office type. In case of large office buildings, in most cases AHU-s are installed based on office orientation. Therefore, this solution could be applied as on average 2.7%-4.3% energy can be saved in cooling and heating seasons (in case A).

Our first research question was how much energy can be saved and the thermal comfort to what extent can be increased at the given case study by optimisiation. In case of the office building investigated the delivered energy use could be decreased by 2.7%-4.3% and the indoor comfort levels could be increased by 5.2%-21.7% on average in cooling and heating seasons respectively.

OUTLOOK

Future work should be done on further indoor operational parameter optimisation (e.g. fresh air supply amount, lighting levels). It would be also important to investigate how the BMS system of a whole storey of the building can handle different control setpoints for the different offices. After the implementation of our proposed, optimised indoor setpoints, it should be checked whether the expected energy saving and comfort improvement values were fulfilled.

Also, further research is required to determine the sensitivity of the starting values (population size, generations, crossover probability).

NOMENCLATURE

PDH = Hours of people dissatisfied, i.e. the integral of the PPD measure multiplied by the total number of present occupants. [hrs]
H1 = Setback heating setpoint [°C]
H2 = Heating setpoint [°C]
C1 = Cooling setpoint [°C]
C2 = Setback cooling setpoint [°C]
TSi = Supply air temperature [°C]
TEi = External temperature [°C]
Ti = Daily hours [hrs]

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