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Improvement of Building Performance through Optimization of HVAC Control Strategy

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Abstract-Energy management of heating, ventilating and air-conditioning (HVAC) systems is the biggest single energy consumer among all building services, installations and electrical appliances. Numerous evidences suggest that many buildings do not perform as intended by their designers. Their actual energy performance is often significantly higher than theoretical. The reasons for this include faulty construction, malfunctioning equipment, incorrectly configured control systems, system ageing, purpose or demand changing and inappropriate operating procedures. Therefore, it is necessary to identify opportunities for building performance improvement. Building management system (BMS) provides many data about building energy effectiveness that can be used by operators and managers in comprehending what really happens in a building. Efficient HVAC control and tuning control loops is often the most cost effective option to improve the energy efficiency of a building. This paper presents a possible approach of solving described problem using existing installed equipment, only, without additional investments.

Keywords- *Optimization, Energy Efficiency, Building Performance, Control Strategy*

I. INTRODUCTION

The building sector in the European Union is the largest end-use energy consumer, with a total share of approximately 40%. Besides, it is responsible for more than one third of overall GHG emission and it is growing. It is estimated that by the 2050 the building stock will increase with 25% [1]. Therefore, energy efficiency is one of the key objectives of the European policies to address the challenges of energy security and climate change [2].

In this respect, the Directive on Energy Performances of Buildings (EPBD) was published in 2002. This Directive underpins the majority of policies and regulations adopted by the EU Member States to improve energy performance of buildings in the first decade of 21st century [3]. The EPBD recast published in 2010 made one step forward by reducing area thresholds that make the EPBD requirements applicable to new and existing buildings and introducing "nearly Zero Energy Buildings" (nZEB) principle as a future requirement. It also mandates the Member States to set minimum cost-optimal requirements for energy performance of buildings to ensure there is a right balance between the investments involved and the energy costs saved throughout the life cycle of a building [3].

Moreover, the EU's Energy Efficiency Plan from 2011 states that "the sectors that deserves the highest attention are residential, tertiary and transport" among which, the residential sector has the biggest technical potential for increasing the energy efficiency, estimated at 30% [1].

Directive on Energy Efficiency (2012/27/EU) also reinforced recast EPBD version emphasizing exemplary role of public bodies' buildings. With article 5 EU Member States are obliged to renovate 3% of buildings owned by its central government each year in order to meet at least the minimum energy performance requirements that it has set in application of Article 4 of Directive 2010/31/EU. Implementing this concept for new and retrofit buildings it is expected to reach a main energy savings of 27% for residential sector by the year 2020 [1], with only one assumption: buildings' energy performance should be in line with predicted thermal model or calculation.

II. PROBLEM DEFINITION

Thermal modeling is a very useful and wide accepted method to calculate energy performance of buildings. It should comprise related physical properties of the building as well as operating conditions including adjacent climatic conditions. This is helpful tool to assess energy efficiency of facility under standard conditions, but because of many unknown factors and other uncertainties actual performance very often differ from predicted. Even with a correct model applied by a well-trained analyst, all predictions remain subject to fundamental uncertainties, especially regarding variation in aspects such as actual weather conditions, occupancy schedule, internal heat gains, and plug loads [4]. Moreover, there is extensive evidence suggesting that buildings usually do not perform as well as predicted [5]. This can seriously compromise energy efficiency of building stock in the EU.

Additionally, researches on the energy performance gap identified different causes for the discrepancy between prediction and measurements. They are related to the design, construction or operational stage and in practice they usually appear in combination specific for each building. Possible solution is prescribed in Directive on Energy Efficiency by introducing obligatory periodical cost-effective audits carried out by in-house experts or certified energy auditors.

Another approach is to accept optimization of HVAC systems as a constant task for energy managers as well as all employees. In line with this, a cautious estimate in German business management (based on EN 15232) indicates that 20 % of primary energy use in non-residential buildings can be saved by building automation and control. This finding certainly applies to a similar extend for other countries, so that the intelligent use of building automation and control can make a significant contribution to EU savings targets of 20 % in 2020 [6]. But, automation by itself does not imply optimal consumption. Only well adjust systems with its current needs can provide it. This paper will align itself to in-house achievement in increasing energy efficiency with general focus on readjusting control strategy according to current needs.

III. Case Study

A. Methodology

Taking a case study approach, this paper analyses the energy performance of described building. It is focused solely on oil and electricity consumption for air conditioning, ventilation, water heating and circulation of media on both: cold and hot side. Annual oil and electricity consumption presented reference point for comparison after redefining control strategy. Both readings were done on monthly bases. Oil consumption was accepted in complete amount whilst electricity consumption was calculated according to set time schedule and nominal electrical power. Additional sub-meters are not installed.

HVAC equipment consumes energy for basic heat exchange processes such as heating, cooling, drying and humidifying or most often combination of those. Energy is also consumed for ventilation and transport of media on both hot and cold side. According Todorovic [7], individual shares of total HVAC system energy consumption in the continental climate conditions are:

- Heating elements (air and hot media) - 40 %,
- Fans and pumps - 38 %,
- Cooling and drying elements - 20 % and
- Humidification equipment 2 %.

Presented case study is focused on the first three areas that present the biggest share of consumption without special attention to humidification process. System analysis began with users' feedback as a start point for identifications of faults and issues in building performance. After that, relevant data were collected from BMS and compared with valid standards of thermal comfort. Control strategy for selected HVAC elements has been considered and adjusted in four basic areas: daily/weekly time schedule, control points, comfort zone limits and operational modes. Faults diagnostic as well as validation of improvements were done by tracking equipment behavior through trend viewer charts. Occupancy patterns were also monitored by tracking the number of occupants within the office on working days as well as during the weekends.

The comfort surveys on satisfactory level were carried out periodically before and during the implementation of new control strategy while thermal comfort values were scanned constantly.

B. Building & HVAC description

Case study building is an educational facility built-up nearby Sarajevo, Bosnia and Herzegovina, in 2005. It is two stores, rectangular shaped building, positioned in South-North direction with approximately fifteen hundred square meters of useful space.

Its first floor provides offices for about 40 staff members, in both academic and administrative roles, while the ground floor contains a lecture theatre with adjacent interpreter's boots, as well as 5 smaller classroom spaces, library, server room and other necessary common areas (figure 1).

It is divided in three independent control zones and fully air-conditioned. Main lobby, classrooms, library and other common areas at the ground floor belong to zone one, main lecture hall with interpreters' boots represent zone two and zone three covers staff offices and meeting rooms on upper floor. Three related air handling units (AHUs) provide necessary heating/cooling, as well as fresh air to all teaching and office spaces. They provide fresh air into the working space by mechanical ventilation with constant air volume without mixing chambers (figure 2).

Run-around heat recovery system is installed in each of them. Two oil-burned boilers provide heating medium as well as hot domestic water while s medium for cold side is provided by one liquid chiller. A building management system (BMS) with five slaves and one master programmable logical controller (PLC) monitors and controls mechanical and electrical elements within the HVAC system.

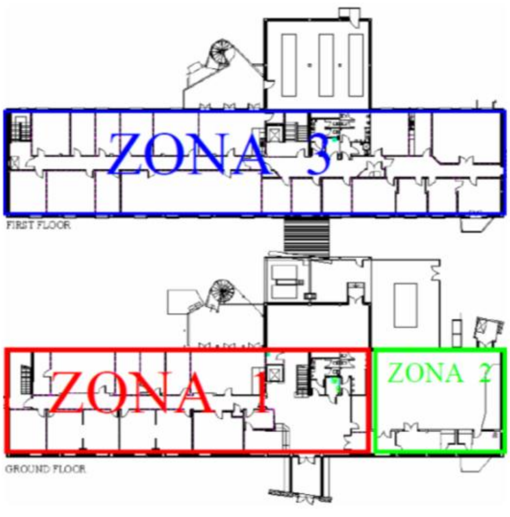

Figure 1. Building scheme with zones

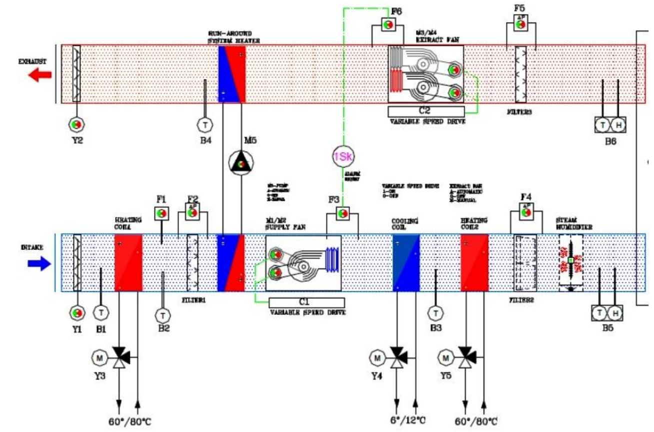

Figure 2. Air-handling unit scheme

IV. Analysis of Control Strategy

Before Control variables for all three AHUs are temperature and humidity but measured at different control points. Relative humidity dead band was set from 45% to 55% while variable temperature set point is positioned in range from 21 to 24 °C depending of outside air temperature from 6 to 24°C. Control point for auditorium was an active temperature/humidity sensor at exhaust branch (B6). Humidity and temperature values of supply air (B5) represented control point for other two units.

Thermal comfort control within the lecture hall was achieved by variation of air temperature/humidity. It is directly supplied with outside air, whilst hot ceiling supply approach with constant value is applied in the rest of the building. Besides, each office, meeting room and classroom is equipped with channel fan coil unit (FCU) with separate room control unit for additional heating/cooling.

Set points for all three units are the same, as well as control logic, but their practical routine is not equal. Office units more or less maintain constant temperature and humidity values of supply air. On the other hand control point at the beginning of exit channel caused more robust and agile response in auditorium unit that provides appropriate reaction for continuous fluctuation of occupants.

Although, direct outdoor reset was applied in both concepts control point diversity made a huge difference in actual performance. In the first one, applied for the main lecture hall, air temperature is indirectly controlled with more or less appropriate seasonal temperature compensation but not so well-adjusted temperature range. Its application has been estimated quite well by users. Minor complains indicated occasional dissatisfaction in short intervals up to fifteen minutes connected with increased system inertia. Deeper analysis showed that delay of control devices (in this case three-way valve at heating/cooling section) was a consequence of control point position. Much faster reaction has been achieved by taking average temperature of two temperature sensors within the main lecture hall as a control point.

On the other hand there were lot of complains regarding thermal comfort in offices and classrooms. Temperature overview showed significant discrepancy with amount and capability of installed equipment as well as control devices. Analysis of operational sequences within belonging air handling units and fan coil units indicated contradictions in control strategy. The biggest issue appeared during extremely high or low temperatures when system was not able to achieve standardized thermal comfort. Even during seasonal changes it hardly maintained desired temperature values though FCU worked at maximum level. According to design and applied control logic, AHU purpose should be treatment of outside air, according to assumed average needs in offices and classrooms. Additionally, supplied air might be handled through FCU, if necessary. It was obvious that variable temperature set point band is too narrow and does not fit with daily needs.

Consequently, problem solution was found analyzing behavior of air-handling unit responsible for zone 2. Trend viewer snapshot (figure 3) illustrates changes of control point in relation with control device and its effects on supply air temperature for main lecture hall. According to this diagram energy demand is closely connected with working hours or, to be more precise, with internal gains. Since building envelope is the same for both floors, intensity of internal gains per square meter has been calculated. Comparison of auditorium and the biggest office on the first floor showed approximately the same level of internal gains, so consequently value of supply air temperature for offices and classrooms should replicate variation applied in zone 2. It has been achieved by choosing reverse outdoor reset instead of direct one and adjusting temperature limits of both supply and outdoor air. Respecting higher solar gains for the first floor and chimney effect a bit lower values were set for ground floor. Revised variable temperature set point were extended from 15 °C to 24 °C (1st floor) and from 17 °C to 26 °C (ground floor) depending of outside air temperature from 24 °C to 0 °C.

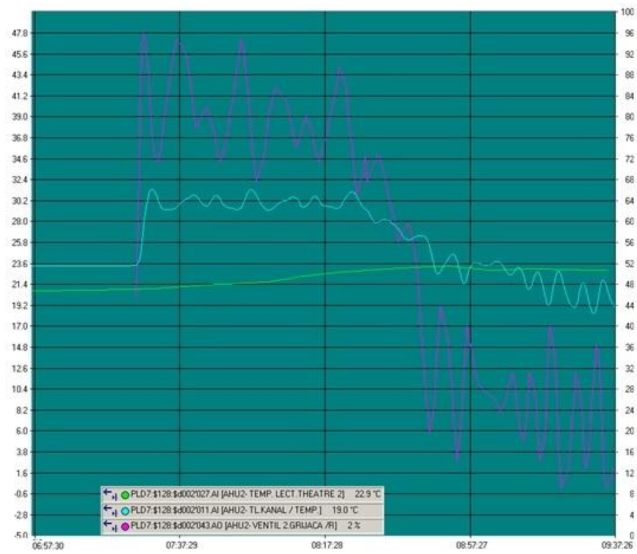

Figure 3. Trend viewer snapshoot (AHU-2)

After set point revision there was no any registered problem to achieve demanded values but the air handling process throughout air handling units was questionable from optimization aspect. Physical position of run-around heating unit after preheating section and its high setup temperature diminished ability of heat recovery unit to use a waste heat potential. Run-around coil efficiency ratio is approximately 45 % but its absolute possible heat transfer is directly dependent of exhaust and intake air temperature difference. Minimizing set point at preheating section from 12 °C to the frost protection value (3 °C) exhaust/intake temperature difference has been raised for nine degrees. As a result potential absolute heat gains within run-around system been enhanced for more than 4 °C.

Besides, sometimes during the seasonal changes, heat recovery and cooling section work in opposite working mode. Heating/cooling mode was determined according to difference between control point temperature of intake (B5) and outside air (B1) more than 1° C (positive - heating; negative - cooling). Condition for circulation in run-around system was absolute difference between exhaust and outside air more than 2 ° C (∣B6 - B1∣> 2 ° C). As a consequence, heating and cooling of incoming air occurs at the same time often followed by short cycled mode switching and hunting set point temperature. Apparently narrow band of both preconditions led control device into short cycling mode and hunting desired value. Moreover, prevention of opposite working mode has been realized by introducing additional with additional prerequisite as follows: temperature difference between of intake air measured at B5 and B3 sensor has to be more than 1° C (B5 - B3> 1 ° C). This simple measure turns of water pump at run-around system and prevents rising air temperature value above set point.

Mechanical ventilation with constant air volume without mixing chambers is applied all three AHUs. Units responsible for zone one and three were set at maximum capacity while the zone two was set at 70 % on both exhaust and intake side. Air volume directly affects the energy consumption and operating costs, so it is desirable to assess appropriate amount of fresh air for all three AHUs in order to minimize rations. This quantity has been determined combining occupancy and air change rate methods. Calculation was done taking 50 m3/h per person and six air changes per hour. Those increased standardized comfortable values could be achievable with approximately 60 % of capacity for all three air-handling units.

Run time of all air-handling units has been established in accordance with educational activities, staff duties as well as their working habits. It was a typical academic regime used throughout the year, which sees use from early in the morning (06:00) to late (22:00), on workdays as well as weekends. After several years, time schedule remains the same although there were significant changes in the length of daily classes, staff members and their daily routine. Working load during system commissioning was from 08:00 to 16:00 on workdays. There were no regular activities during the weekend but a few staff members and students were using facility. All those facts indicated substantial waste of energy because AHUs are unnecessary turned on without occupants. Weekly run time has been decreased from 112 hours to 50 - 70 hours depending of building zone or season. Instead, FCU are programmed for pre-heating/cooling of office spaces as well as classrooms. With this simple measure electricity consumption of air-handling unit has been decreased from 37 to 55 percent and thermal comfort standard has not been violated.

Fan Coil Units take required air from the ceiling and push it into the working space according to customers' requirements chosen at room unit. Three different operational modes were available:

- Comfortable (temp. range: 21 °C - 24 °C; time schedule: 06:00 - 22:00)
- Reduce Comfortable (temp. range: 18 °C - 28 °C; time schedule: 22:00 - 06:00)
- Night time (temp. range: 15 °C - 35 °C; time schedule: not used)

Listed values for FCU operational modes have been adjusted in order to adjust temperature in working spaces with standard EN 15251 and prevent misuse or inappropriate setup. Temperature range in comfortable mode has been extended and daily run time shortened and synchronized with depending air-handling unit in accordance with daily needs (temp. range: 20.5 °C - 25 °C; time schedule: 07:00 - 17:00).

The main goal of listed adjustment was HVAC performance improvement during seasonal changes mainly, as it presents the main indicator of their energy efficiency [8].

V. Results

By described HVAC system adjusting and fine-tuning of its main elements the new control strategy has been established in order to eliminate identified problems and increase its energy efficiency. By cutting down run time of air-handling units as well as fan-coil units and extending dead bands out of working hours unnecessary heating/cooling of non-used spaces is avoided. Besides, amount of handled fresh air is significantly reduces as well as consumed energy during the hottest and coldest months but still within approved ventilation standards. On the other hand extending temperature range within outdoor reset dependencies together with maximized ventilation rate during seasonal changes resulted in less overall energy consumption because thermal comfort within the working space have been achieved by pure ventilation and heat recovery, only. There was no energy consumption for preparation of hot or cold media. The consumption data for both years are presented in table I.

TABLE I. HVAC Consumption Overview

	Year 1	Year 2	Difference	
Oil [l]	26610	18606	8004	30.1%
Electricity [kWh]	265440	206980	58460	22.0%

VI. DISCUSSION AND CONCLUSION

It is important for everyone who participates in the design, operation and maintenance of the building to realize that, however energy efficient the system is initially designed and installed, the energy efficiency will degrade unless it is operated correctly and deliberately maintained. Presenting methodology, experiment's steps and in particular the analysis of the HVAC elements, it is emphasized that control strategy modification, and success of defined measures for improving energy efficiency are directly related to understanding of mechanical as well as control segment. Key findings from this paper highlight the need for better understanding of occupancy patterns, behavior of building users and HVAC tuning according to their needs. Ignorance of any of those components generally leads to inadequate system performance, increased energy consumption, long repayment period and dissatisfied users. Finally, it appears that application of control strategy strongly relies on final users. If they are not familiar with a system, rebound effect is almost inevitable, but, with a few simple presentations and short instructions for new-comers energy efficiency of HVAC system will probably increase and even pre-bound effect is achievable.

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