IoT Solution Approach for Energy Consumption Reduction in Buildings

Part 4. Mathematical Model and Experiments for Cooling Energy Consumption

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***Abstract*— Nowadays it is possible to obtain almost real-time measurement data using various IoT solutions, which can be used in order to control building management systems like heating, ventilation, cooling equipment (chiller), lighting. Nevertheless there are limited number of solutions allowing to control it by using hourly data (like electrical power consumption, room temperatures, humidity, CO2 levels, heat energy, ventilation system pressures, outdoor climate data). This paper deals with 6R2C mathematical model development, that uses real-time data obtained from IoT sensors, practical measurements and experimental testing results achieved during summer period, when the cooling energy is needed. Measurements and experiments were conducted for certain building zone, which is PN4 ventilation zone for the most electrical energy consuming HVAC system of the building, located also in the south side and having most impact by the sun radiation. Using simplified modeling and input data approach, CV(RMSE) estimation of the model for daily consumption for the period from 8 August to 8 September resulted in a value of 28.62%. In monthly period average energy consumption error (single month) is 0.14%.**

Keywords*— *energy efficiency, energy consumption, Internet of Things, 6R2C, building simulation, building cooling load prediction.

I. Introduction

Energy efficiency, energy consumption and greenhouse gas (GHG) emission reduction, as well as need to decrease the building exploitation costs are the driving force for technology innovation all across the world. Nowadays various IoT based sensor systems (powered from AC mains or from battery) for measurement data collection are available on the market like Siemens Mindsphere, Aranet, Circutor, Adeunis, LoRa WAN and many more, where development and number of such systems and applications is growing each year.

Also smart control, optimization of Building Energy Management Systems (BEMS) is a complex socio-technic system [1], which includes knowledge from heating engineers, electrical engineers and ICT engineers, in order to solve the demands for energy, comfort and business needs.

Nevertheless also new methods are being developed by universities, where for electrical consumption some uses wired solutions [2], or by wireless solutions [3], and by such approach it is easy to connect any other sensor type to get also temperature, CO2, humidity, heat energy readings, air pressure data one in online data base system, like [4], that can help analyze building energy consumption and determine if it is normal or bad regime. This approach is very topical in various applications, where also large research projects can be found, like ADREAM building with 6500 integrated sensors and embedded systems, making it as one of the smart buildings of France [5]. Such model uses very large data input and calculation power, also obtains very high accuracy, reaching Normalized Mean Bias Error of 0.48% and Coefficient of Variation of Root Mean Square Error of 2.84%. Also IoT based sensor and actuator control concept can be used as a tool for retrofitting heat, ventilation and air conditioning (HVAC) systems reaching energy savings up to 59% [6].

Previous research already described in [7]-[9], focuses more on heating energy consumption and forecast modeling (winter period), with main goal to create a simplified modelling tool, that can be embedded in a modern industrial controller that is used for existing Building Management Systems (BMS). By embedding this model into BMS with the use of IoT sensors (online feedback data), we can reach the possibility to automatically adjust the mathematical model's input data to match the real-life setting and influencing factors (e.g. occupant count into the building or zone). When using a mathematical model for the control of the building system, IoT based data is a vital component to monitor the exact values of the influencing parameters that are used as the input data into the model and to make the correct decision for efficient and energy-saving building control. Moreover, the data gathered from the sensors is necessary in order to analyze and simulate the behavior of existing air handling units that have a great impact on indoor climate and energy consumption.

To determine the amount of input sensor data, energy consumption and forecast data calculation precision, a MatLab model is created and verified with real time heat and electrical energy data obtained by sensor network consisting of LoRa temperature and humidity sensors (30 pcs), CO2 sensors (10 pcs), Dynasonics TFX Ultra heat pipe flow meters (3 pcs), Circutor 3-phase electrical energy meters (13 pcs), Produal

IML-M air flow sensor (4 pcs) and real time heat energy consumption data from existing Danfoss Sonometer 1100 equipment (obtained through M-Bus).

This paper shows the experiments carried out to develop a mathematical model for summer period, when cooling energy is needed. There are not much research data available for RC modeling and obtained data comparison with real building measurement data, as building is influenced by various dynamic parameter changes during the daytime (sun radiation, amount of persons in building, equipment usage and load, etc). Therefore it is important to analyze the mathematical model taking into account also such data that can be provided by real-time data from IoT sensors.

II. Materials and Methods

A. *Selected Building Zones for Experiments*

In previous paper it is described that a whole Riga Technical University faculty building (Power and Electrical Engineering) is selected for the experiments. Also in this research this building is used and from 13 HVAC ventilation systems – the PN4 zone (HVAC system PN4) is selected, due to fact that this zone is located to the south (most impact from the sunlight) and it has automated window blinds placed outside the windows, controlled by BMS system. The PN4 zone covers HVAC zone for corridor and offices in 2nd floor till 6th floor of the building, and it is also the largest electrical energy consumer of all HVAC systems.

Fig. 1. Faculty building south facade and PN4 zone.

B. *Used Measurement Equipment and Infrasturcture*

To measure electrical consumption from the electrical equipment, like computers, lighting systems, automated window blinds, located in the PN4 zone offices (in all floors), in total 8 Circutor CIR-E3 network analyzers were installed, and one CIR-E3 was used for consumption measurement of the building cooling system (chiller).

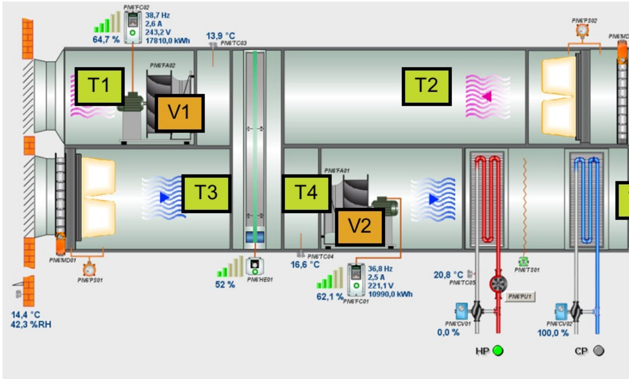

Fig. 2. Sensor placement in ventilation system of PN4 zone.

To obtain energy flowing through PN4 zone, it is needed to measure air flow of outside air (inlet V2) and room air (outlet V1), and also five temperature sensors (T1-T5), where placement is shown in Fig.2. Furthermore also temperature sensors (T1, T2) were placed on whole buildings cooling system (see Fig.3.) and existing cooler flowmeter (V1) digital outputs were used to obtain flow data with 10 second interval.

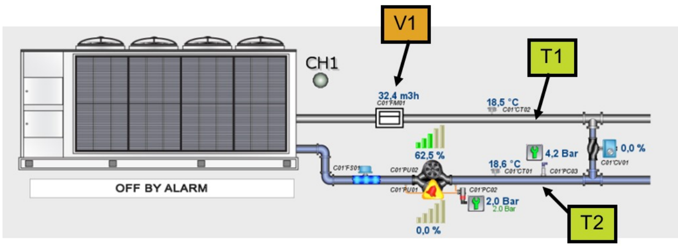

Fig. 3. Sensor placement at cooling system (whole building).

In order to monitor room temperature, 8 rooms were monitored using LoRa temperature sensors installed previously, covering all floors of the PN4 zone. Each PN4 zone floor office is equipped with 2x28W, 4x14W or 2x49W T5 fluorescent type luminaries, with total installed power of 9.408 kW (not taking into account ballast losses).

C. *Calculation Method for Real Energy Cosnumption of PN4 Zone*

PN4 zone is using one ventilation equipment, in order to calculate energy consumption of this zone, consumed cooling energy is measured indirectly. Energy consumption therefore is calculated using such measured data:

1. Temperature behind the recuperator, as in summer time it cools down outside air temperature if room air temperature is lower.
2. Outdoor air temperature at cooling heat-exchanger. If this temperature is lower than temperature behind recuperator, then cooling has happened and it is necessary to calculate the consumed energy.
3. Volume of incoming air flow. It is measured by diferenetial pressure flow meter at ventilator infeed measurement spots.

4. Outdoor temperature. Obtained from local Meteostation data.
5. Outdoor relative humidity. Obtained from meteostation. Ventilation system is measured with 10 sec interval, but meteostation measures with 1min interval, thus measurements are synchronized using linearized Matlab synchronization function.

Energy consumption calculation of these data is calculated with 60 sec interval, using such average value calculation sequence: otdoor temperature (4), then temperature behind recuperator (1), infeed temperature (2), volume of air flow (3) and outdoor humidity (5). From these data calculation algorithm in each time interval is carrying out various parameter recalculation. Consumed heat energy for cooling is calculated as:

$$Q = m \times (h_2 - h_1) \text{, where} \quad (1)$$

Q – Cosnumed energy for air cooling [kJ],
m – Air mass [kg],
h2 – Entalpy of air infeed [kJ/kg],
h1 – Entalpy of air behind recuperator [kJ/kg].

Calculation is done each 60 seconds, thus getting energy consumption each minute. Energy consumption is calculated by multiplying change of air enthalpy with flowing air mass in 60 seconds.

D. *Creation of 6R2C Mathematical Model*

created in MatLab environment consists of two sub-models: 6R2C model and AHU model.

AHU (Air Handling Unit) model is very important in order to simulate real AHU equipment, which parameters change dynamically due to changes in outdoor and indoor parameters. This model is developed as close as possible to real PN4 zone AHU unit used in building. Operation principle of AHU unit:

1. Depending from outdoor temperature determines needed room temperature set point.
2. It compares room temperature set point with measured room temperature value at AHU extract and with PID regulator adjusts the downstream flow temperature, to achieve the set point value of the room temperature. Min and Max values are limited, in this case from 14 to 26ºC.
3. The AHU model checks whether it is possible to raise or lower the supply temperature value using the recuperator. The efficiency of the recuperator is based on measurements taken, and it is 61%. The efficiency of the recuperator temperature transfer is calculated according to the formula:

$$\mu_t = (t_2 - t_1)/(t_3 - t_1) \text{, where} \quad (2)$$

μ_t – efficiency of temperature transfer, t_1 – outdoor air temperature before heat exchanger, t_2 – infeed air temperature after heat exchanger, t_3 – exaust air temperature before heat exchanger. Here the temperatures are obtained from IoT sensors, that give real time data feedback.

4. The AHU model assumes that in summer mode, the supply temperature can be at a minimum of 14 °C, which can be provided by cooling, but no higher than the outdoor temperature or possible temperature behind the recuperator, whichever is the highest.
5. The AHU model also calculates the required amount of energy to heat the air using the temperature behind the recuperator to the desired supply air temperature, determined by the PID controller.

III. Experiments and Results

A. *Description of Performed Experiments*

To test the mathematical model of the cooling regime, two experiments were carried out. Goal of the first experiment is to determine impact of the PN4 zone window automated blinds on obtained heat energy in the building. Starting experiment in 10.08.18., all blinds were raised at 12:00, and electrical power was disconnected, thus 100% sun energy landed in building rooms, and BMS system was not affecting them. Experiment was finished in 14.08.2018. at 12:15, allowing BMS to control the blind system. According to Meteodata, it is possible to find similar days of experimental and normal operation mode days, thus comparing the energy data of them, and getting the impact value of blinds system. This would allow to calculate payback time for such system versus saved energy of any new building. Real data will enable to analyze and compare the model simulation data precision. Goal of the second experiment is to determine energy consumption of the system when blinds are lowered (blades turned at 75ºC), thus sunlight don't comes into the rooms and artificial lighting is turned ON in each room. Experiment was carried out in 23.08.2018., starting at 8:30 lowering the blinds and finishing at 17:30 – raising the blinds. All measurements are done in parallel, allowing to calculate precise energy consumption data and compare it with mathematical model results.

B. *Inputs for Cooling Energy Model*

As operation mode of automated building window blinds will make an impact on energy consumption, the model takes into account this effect, by means of automatic correction of optimal light and temperature levels in the rooms. Data on building construction envelope parameters were obtained from EEF building project documentation and the most important parameters are summarized in the Table I.

TABLE I. CONSTRUCTIVE PARAMETERS OF THE EEF BUILDING

Parameter	***Description***	***Value***	***Dimension***
A_{grid}	Conditioned space area	1358	m²
A_{kop}	Construction area covering the building	1102	m²
$H_{tr,op}$	Heat transfer loss through opaque enclosing structures	153.1	W/K
$H_{tr,log}$	Heat transfer loss through transparent enclosing structures (windows, glazing, doors)	204.9	W/K
$H_{tr,iv}$	Connecting conductivity between room temperature point T_{iek} and the point of the boundary structure surface T_{virsm}	21083	W/K
$H_{tr,im}$	Connecting conductivity between the point of the boundary structure surface T_{virsm} and termal mass point T_m.	43252.3	W/K
$H_{tr,am}$	Connecting conductivity between the termal mass point T_m and outdoor air temperature T_{arg}.	153.5	W/K
C_{m1}	Termial mass of the zone outdoor walls	29.2	MJ/K
C_{m2}	Termal mass of the zone indoor	407.9	MJ/K
A_m	Effective termal mass surface	4753.0	m²

Matlab model simulation had such inputs:

- Constructive parameters of the building,
- Meteostation temperature and solar radiation data located on the building roof,
- Graphs of human presence and the resulting internal heat gain,
- Effect on curtains and lighting system from experiments carried out.

C. Obtained Experimental Data

Simulation results of 6R2C model for the period of 08.08.2018. – 08.09.2018. show that 3595kWh of cooling energy is needed, and the real measurements shows that 3590 kWh were consumed in that period. Thus we can see, that in monthly period, the deviation in the result has minor impact. But if we look at the daily period, the deviation has much larger value. The results can be seen in Fig.4., where solid fill corresponds to measured and dashed to simulated values.

Monthly cumulative energy consumption can be seen in Fig.5., where solid line is measured values and dashed – simulated values. It can be observed, that in some days there are some deviations, also we can see that some days have with large difference in energy consumption. Days with low energy consumption value also can have the largest error, as small changes in some factors, can have large impact on the modeling result, like presence of people (was not measured in experiment) in building could be larger than it is foreseen in the model. This is justified by September, when studies started and the number of people has larger deviations during daytime.

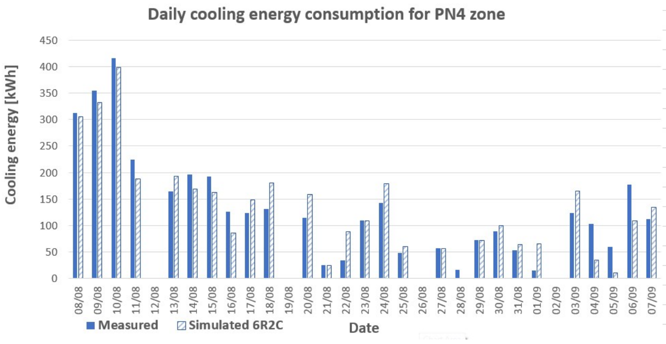

Fig. 4. Daily cooling energy for PN4 zone.

By analyzing PN4 zone simulation results, we must take into account, that this zone is connected with the rest of the building and ventilation systems, as one part of corridor is cooled by PN4 ventilation system and other part by another system. This also affects the PN4 zone consumed energy, and to obtain more precise result, the interaction with other zones also should be calculated. This complicates the mathematical model and also simulation itself, as all parameters of other ventilation systems should be known. If we look at Fig.5., it can be observed, that measured and modeled cumulative energy value at the end of each day, has deviation of 3.26% of average and maximum deviation is 7.62% (at 17.08.2018.). From the graph it can be seen, that both plots clearly correlate each other.

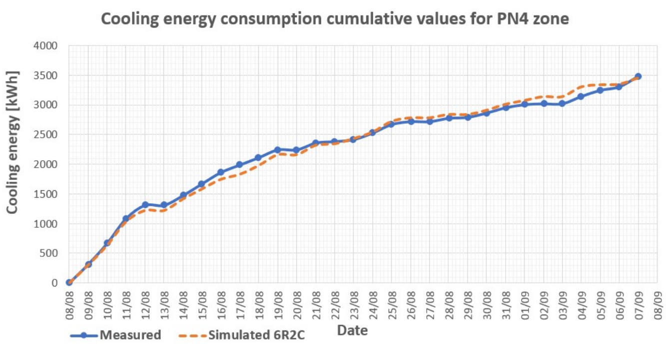

Fig. 5. Cumulative monthly cooling energy consumption for PN4 zone.

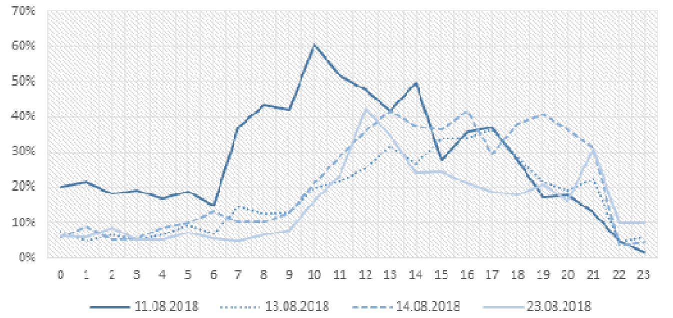

Fig. 6. Electricity consumption of the cooling unit (chiller) in relation to the total daily consumption of the building (hourly measurement).

If we look at the graph (see Fig.6.), it can be seen that chiller, during the daytime, consumes 20-40% of the total buildings electrical energy consumption, reaching even 50% in holidays. If we use only average daily consumption value, it gives less information, but if we use hourly values, we can determine electrical energy consumption in maximum hours, when the prices are the highest on energy markets (NordPool, etc), also enabling new control strategies of such equipment.

If we look at the lighting system consumption (see Fig.7), we can identify people presence in the rooms (real business load data), which can be used for improved (or individual) AHU unit or ventilation vale control, in order to decrease energy consumption.

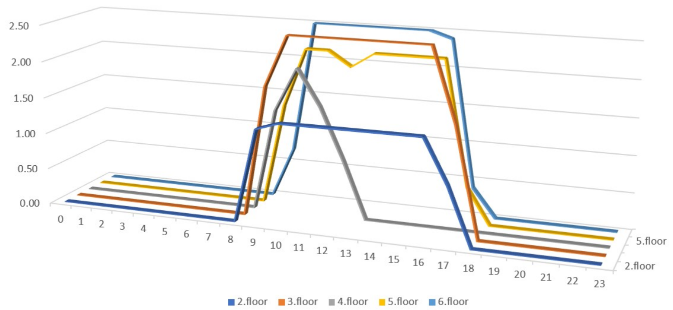

Fig. 7. Electricity consumption of the lighting system in floors 2 to 6.

During the experiment day, blinds were lowered and rooms were using artificial lighting during whole day. As PN4 zone is in south side of the building, by lowering the blinds we also decrease sun radiation impact (also increase comfort of persons working in the room) and decrease also the chiller unit electrical consumption. During the morning period when solar radiation has the highest impact on building windows (8:00 till 12:00), lighting system consumed 38.2 kWh (100% rooms occupied). Chiller total consumption (24h) during this experimental day (23.08.2018.) was 323.1 kWh. If we compare obtained chiller consumption results to other meteorologically "similar" days (solar radiation, air temperature and wind speed), we can see that, in other days it consumes additionally 12 kWh in 14.08.2018.; 50 kWh in 15.08.2018.; 34 kWh in 16.08.2018.; 46 kWh in 17.08.2018.; 36 kWh in 18.08.2018. Same tendency can be observed also with "non-similar" days, where chiller system consumes additionally 98 kWh in 19.08.2018.; 82 kWh in 21.08.2018.; 87 kWh in 22.08.2018. It clearly shows that it is feasible to lower the blinds and use the artificial lighting, as energy balance will be positive, as chiller will use more energy to cool down the heat energy gains from sunlight. Still to prove this statement full year should be analyzed, by carrying out such experiments once per each month.

D. Data Analysis and Results

To evaluate results of the created model, ASHRAE CVRMSE (Coefficient of Variation of Root Mean Square Error) method was used [10]. The CV(RMSE) estimation of the model for daily consumption for the period from 8 August to 8 September resulted in a value of 28.62%. Such a deviation is considered to be a good result, as according to ASHRAE guidelines, this value should be less than <30% for the model to be used to determine the energy baseline. Nevertheless it shows also potential for precision improvement, which could be done if more precise data about heat energy gained from people, electrical equipment and zone itself would be available.

$$CV\left(RMSE\right)=\frac{\sqrt{\frac{\sum_{i=1}^{n}\left(E_{m,i}-E_{mod,i}\right)^{2}}{\left(n-1\right)}}}{E_m}, \text{ where} \tag{3}$$

CV (RMSE) Error value
E_m Measured energy value
E_{mod} Modeled energy value
n Number of measurements
$E_{m,i}$ Average measured energy at given period

From the mathematical model it is also possible to retrieve average PN4 zone room temperatures, which can be seen in Fig.8., thus we can compare them with measured values from LoRa sensors both in rooms and ventilation unit exhaust. Here we should take into account that ventilation unit is switched OFF during the night time. Differences between values can be explained due to fact that ventilation exhaust combines mixed 6R2C simulation model doesn't takes it into account, but in reality the energy transfer between walls and rooms still happens, main errors causing in Sunday and Monday.

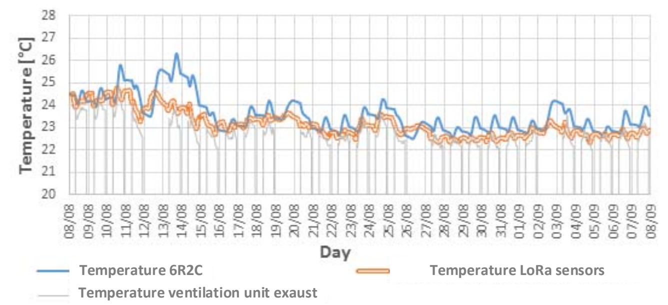

Fig. 8. Average PN4 zone temperature value comparison

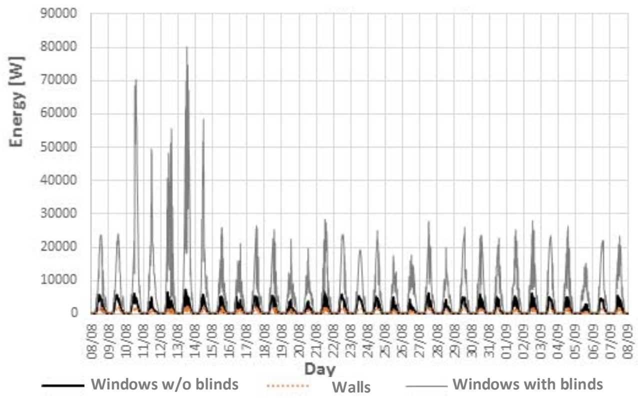

Fig. 9. Gained heat energy from sunlight.

The 6R2C based model can calculate also building heat energy gain from sunlight, coming from walls, windows with blinds and windows without blinds (see Fig.9.). It can be observed that main gains are coming from buildings south side windows, despite they use automatic window blinds, as in comparison energy gained from all walls and eastside windows (without blinds) are much lower.

A significant impact on energy consumption is the ability of the ventilation model to provide the required supply temperature just as the actual ventilation unit does. Since the energy consumption required in the simulation is calculated directly from the temperature difference between the temperature behind the recuperator and the required temperature (at the inlet), the control algorithm of the ventilation model has a very significant impact on its precision. During the optimization process of the AHU model, it was observed that Proportional (P) and Integrating (I) values of PI-type control algorithm had great impact on results. As these values are commercial secret of manufacturers, they are not available, but nevertheless the operational principles are well known, and the PI control can be tuned till the needed precision is obtained.

IV. Conclusions

By simulating the 6R2C model from August 8 to September 8, it was found that needed cooling energy for the PN4 zone requires 3595 kWh, and the measurements showed value of 3590 kWh, thus we can conclude that energy consumption error in the current month is less than 0.14%. Calculating the deviation of the cumulative value at the end of each day with respect to the measured value, we get an average deviation of 3.26% from the real building, but the maximum deviation in this period was 7.62% achieved on 17 August. As a result the energy curves of the model are similar to the measured curves, thus it is tangible to use this approach also in real control systems. The CV(RMSE) estimation of the model for daily consumption for the period from 8 August to 8 September resulted in a value of 28.62% which corresponds to ASHRAE standard (<30%). It is hard to determine heat energy gains from the persons in the building as their number is changing during the daytime, thus some special sensors for human presence count detection is needed in order to improve the model precision.

Previously used 6R1C model, also used for cooling energy simulation, was supplemented with additional internal thermal mass (C) of the building, thus obtaining new model of 6R2C, which allows more accurate simulation of indoor temperature fluctuations. Also new AHU model was introduced, allowing precision improvements both for summer (cooling energy) and winter (heating energy) period energy value calculations.

The experimental results show that, if switch off the ventilation system during Sundays (no persons in building), it can save 7% of ventilation system consumption, if we don’t use the ventilation system during the energy maximum hours, we can potentially save energy costs (in EUR values) of 27% from “fixed rate” or 25% from Nordpool prices. If we just shift this consumption only by one hour earlier, we can easily save 3% of these costs. Also the second experiment shows that it is feasible to lower the blinds and use the artificial lighting, as energy balance will be positive in most cases, as chiller will use more energy to cool down the heat energy gains from sunlight.

In this way we can see that model is working, and the input data from the IoT sensors, improves the precision of the model and the results obtained, so it also proves the necessity for IoT sensors and their application in new intelligent control techniques to be applied in BMS.

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