MULTIFACTORIAL ANALYSIS OF FUNCTIONING EFFICIENCY OF BUILDING HEAT CONSUMPTION INTELLIGENT DISTRIBUTED CONTROL SYSTEM

Pavel A. Strizhak[1] and Maxim N. Morozov[1]
[1]National Research Tomsk Polytechnic University, Tomsk, Russia

ABSTRACT

A model of the building heating system, consisting of energy source, a distributed automatic control system, elements of individual heating unit and heating system is designed. Application Simulink of mathematical package Matlab is selected as a platform for the model. There are the specialized application Simscape libraries in aggregate with a wide range of Matlab mathematical tools allow to apply the “acausal” modeling concept. Implementation the “physical” representation of the object model gave improving the accuracy of the models. Advanced weather block allowed to investigate the efficiency of the control system with dynamically changing the numerous factors affecting the building energy consumption for maintaining optimal climate parameters. The conducted research of heating system and automatic control system allowed estimate efficiency of control system regulating process. The results of research of thermal condition premises, situated in the different sides of the building facade are given. The conclusions about the possibility of increasing the operational efficiency of heating system in the implementation of distributed control systems are presented.

INTRODUCTION

The energy resources price increase enhances interest to energy modelling of buildings and constructions (Maestre et al., 2013; Amado and Poggi, 2012; Tagliabue et al., 2012) which allows performing optimization taking into account capital and forecasting maintenance costs at the designing stage.

Many factors influence on the simulation accuracy such as detalization of walling models, engineering systems and weather conditions (wind load, insolation etc.).

The issues of energy efficiency play important role especially during changes in weather conditions. A climate research of Siberia territory shows a negative trend of sharp increase of daily differential temperature. Nowadays, the changes in outdoor temperature at 15-20 °C are common occurrence.

The aim of the present work is to investigate influence of the different type disturbing factors on the climate control system functioning and on the thermal regime and heat consumption parameters.

IMPORTANT DISTURBING FACTORS

One of the main goals of the life support systems during the operation of buildings and structures – is maintaining comfort conditions for human livelihood. Requirements for climatic parameters are set in normative documents. There is a climate system is destined in the building for solving this problem. The system consist of various heat exchange equipment, piping, microprocessor-based automation equipment and others.

Structure of the modern building climatic system is strongly dependent on the geographic location of the object: buildings in the northern regions are different, as a rule, by the most powerful heating system, while in the south regions on the contrary – air conditioning system is necessarily, but heating system can be absent at all. Specialists of HVAC-systems are allocate a lot of factors affecting the dynamics of the thermal regime of the building rooms:

- weather conditions change: solar radiation, wind load, the outside air temperature;
- internal heat sources: electrical appliances, people, technological equipment, etc.;
- instability of the coolant parameters from a central heat source;
- heating system can also be associated as a disturbance source, for example in case of applying specialized low heat consumption modes, calls as thermal modes.

RESEARCH OBJECT

The object of research is an administration building which is located in West Siberia (Tomsk city). Heat supply of the building is carried out by a central heat supply station.

The object is the block of weather conditions, heat supply system and envelopes of the room. The heating system consists of the individual heating plant (IHP), main pipes (inlet and outlet pipes), water risers, heating appliances and control valves. The structure of the object is described in (Strizhak and Morozov, 2014). The possibility of the weather conditions variation in a wide range is the distinctive feature of the model under investigation in this paper.

Four rooms were selected in building for achieving goals of the article. All the external envelopes of one room are characterized by the same spatial orientation. Identical conditions of heat supplying are provided for heating system with parallel connection of heating appliances. For approximation to the truth operating conditions the spatial orientation of the rooms exterior wall envelopes was selected with following manner:

- room №1 – West;
- room №2 – South;
- room №3 – North;
- room №4 – East.

Rooms are characterized by identical space planning with following materials: square is 41.52 m^2, volume is 112.1 m^3 (Figure 1).

Glazing ratio K_{gl} is set to 0.23, which corresponds to the surface area of opaque constructions – 17.85 m^2 and translucent structures – 5.38 m^2 (net of area of opaque multiple glass pane profile)

There is intelligent heat consumption system with distributed structure (Scattolini, 2009) were assumed: the main regulator adjusts the coolant temperature (supply and return) in IHP, local regulators adjust the individual room climate. Unique features are provided by multi-loop control system of heat consumption. In this case, local control loop is limited to the physical boundaries of controlled space. The main regulator spreads to the whole building and interfaces technological parameters of urban heating network and heating system of building.

However, when choosing of distributed control system (DCS) (Scattolini, 2009; Tian-Wei et al., 2011; Morosan et al., 2010; Barata, et al., 2014), automation specialists are faced with the complicated problem of design, software synthesis and adjustment of such systems. As a rule, to solve these problems, engineers apply computer simulation models (Wallace et al., 2012; Privara et al., 2012). The use of computer simulation provides a small labor cost and reduces time of experimentation.

THERMAL MODEL

The thermal model of the building was developed to simulate operation of the heating system of the described above object. Simulink by Matlab was selected as the platform of a model (Kıyan et al., 2013). This choice is motivated by wide capabilities of software: tools to analyse system dynamics in time, connection with Workspace and other Matlab applications (for instance, Control System Toolbox), simulation of various disturbances (determined or random with different distribution laws) and situations (regular or non-regular, including emergency) which occur when in operation of the technical system. The block-oriented approach was applied to simulation and visual programming of heat supply system of building in combination with the wide range of Matlab mathematical tools. Simscape extension package which implements the concept of a “physical” simulation was also applied to develop the model (Broman and Fritzson, 2008).

Realization of the thermal model in Matlab is based on representing of each individual functional part in the form of *s*-functions and subsystems blocks. During simulation it is observed redistribution of heat flows between sources, medium of heat energy transfer and consumers. Figure 2 shows basic blocks of the thermal model of the building.

However, there are problems associated with the creation of complex models containing thermal, hydraulic and mechanical functional units. These problems are related to configuring blocks, which functional is limited by the Simscape developers.

For example - convective heat transfer block. There are several parameters acording to the Newton-Richmann law: thermal transfer coefficient (W/m^2·K), heat transfer surface area (m^2), time-dependent thermal gradient between environment and object (K). However, there is no way to dynamically change these parameters during the simulation, which is essential limit for the energy modelling.

For solving this problem a specialized unit (subsystem) with «controlled» inputs has been created. Using such new functional block allows to dynamically change the input parameters, which is especially important for the investigations of the influence of the wind load, insolation processes and the ambient air temperature on the thermal regime of premises, engineering system, as well as on local control system.

CHARACTERISTICS OF DISTURBING FACTORS

There is all of above mentioned factors except for the instability coolant parameters from a centralized heat source were assumed for research. Description of the simulated factors is given bellow.

Weather conditions

- Solar radiation

The power of solar radiation depends on many factors. The most considerable factor is latitude of the object location, cloud amount, orientation of the walling surface. Additionally, it is necessary to take into account the uneven distribution of the radiation due to the daily and seasonal variations of sunshine duration. Also, engineers offer introducing the corrections in calculations for dust content and air pollution of atmosphere which reduce the light transmitting characteristics of air layer (Avanev et al., 2003).

Taking into account that the horizontal and vertical surfaces of different spatial orientation for most of buildings are widespread, the surface density of solar radiation can be determined in accordance with the procedure specified in Standard SP 23.101.2004.

Depending on location the effect of the insolation can achieve 30 % of overall balance of heat inside buildings (Avanev et al., 2003).

Modelling carried out under the insolation conditions, which are typical for the research object location. Vertical surfaces of different spatial orientation are characterized by the following values of the average daily surface solar irradiance Q_{insol} (Malyavina and Borshchev, 2006):

South – 1032 W·h/m^2;

West – 290 W·h/ m^2;

East – 290 W·h/ m^2;

North – 129 W·h/ m^2.

Figure 3 shows the solar irradiance toward the 1 m^2 of vertical and horizontal envelopes with different spatial orientation.

- Outdoor air temperature

This factor is directly affects the heat consumption characteristics of building, that shown at convective (Newton-Rikhman Law) and conductive (Fourier's Law) heat exchange laws.

Change of the daily outdoor air temperature T_{out} is characterized by periodicity with following parameters: mean value T_{out0} is -20 °C and -30 °C, amplitude of oscillation 6 °C, oscillation period 24 h. Figure 3 shows dynamics of outdoor temperature T_{out}.

- Wind load

Dynamics of wind load affects the following parameters:

- volume of outdoor infiltrating air;

- the thermal transmittance of external surface of walls and windows.

Taking into account the aerodynamic characteristics of the investigated building is one of the most important factor in researches of wind load influence. Also it is necessary to consider the impact of the closely-spaced buildings near the controlled object.

Constant direction of wind from South to North were assumed. Average flow velocity V_w is 3 and 4.5 m/s.

- Internal heat sources

Internal heat sources makes a considerable contribution to the building heat balance:

- losses in household and lighting electrical devices, computers: capacity of electrical devices in controlled rooms is assumed a 700 W, performance factor is 85 %.

- heat gains from people is directly depend on their activities and conducted work: each controlled room include 3 men, length of stay is 8 h, heat emission in case of quiet run is 116 W/man.

- Low heat consumption modes

Energy saving mode allows saving thermal energy by decreasing room internal air temperature T_{in}. This mode is important for all types of buildings with irregular working hours. Value of the indoor air temperature ΔT_{in} reducing is observed experimentally often. It's necessary to conduct the energy modelling for achieving the maximum of energy saving effect. Such approach allows considering of the features of the research buildings: the schedule maintenance of facilities, thermal characteristics of envelopes, heating system and control system configuration. Preliminary experiments showed that for research building optimal value of temperature ΔT_{in} is 3 °C.

DISCUSSION AND MODELING RESULT ANALYSIS

To achieve the purpose of the present work series of numerical experiments were performed to analyze influence of selected disturbing factor on building heat consumption and thermal regimes of controlled rooms.

Variations of the initial modelling data specified in Table 1.

Table 1
Initial data for modelling

VARIABLE PARAMETERS	NUMBER OF EXPERIMENT					
	№1	№2	№3	№4	№5	№6
Average outdoor temperature T_{out0}, °C	-20	**-30**	-20	-20	-20	-20
Average flow velocity V_w, m/s	3	3	**4.5**	3	3	3
Insolation heat gains Q_{insol}	no	no	no	**yes**	no	no
Internal heat sources Q_{int}	no	no	no	no	**yes**	no
Low heat consumption mode	no	no	no	no	no	**yes**

Values of parameters, obtained in experimental №1, are assumed as the basic in the following experiments and changes only one by one.

Researches of influence of different types disturbing factor on heat consumption characteristics and estimation of energy saving at specialize room thermal regimes application are of particular interest for HVAC-engineers and energy managers. An estimation of heat consumption values of controlled rooms $Q_{rm\ i}$ (i = 1…4) was given at present work.

Table 2 shows heat consumption data of research rooms.

Table 2
Daily heat consumption by control rooms

NUMBER OF EXPERIMENT	CONTROL ROOMS			
	Room №1	Room №2	Room №3	Room №4
№1 (basic)	21.49	20.37	18.89	21.49
№2 (T_{out0} = -30 °C)	37.47	36.28	34.42	37.74

№3 (V_w = 4.5 m/s)	23.93	22.67	21.12	23.93
№4 (insolation heat gains)	20.16	14.44	18.17	19.65
№5 (internal heat gains)	16.76	15.56	14.01	16.76
№6 (energy saving thermal regime)	13.13	12.7	12.11	13.13

Data submitted in Table 2 allow carrying out a comparative analysis. The lowest consumption of thermal energy was obtained for room №3 (North) in the 1-st experiment. This is explained by several factors: absence of solar irradiation, wind direction (to the North). Wind load creates aerodynamic shadow on the exterior of room №3. This reduces the value of air environment velocity along the surface of the outdoor envelopes and thus the thermal transmittance of external surface.

Comparison of experiments №2 and №3 provides the following results: at 50% increase of the values of T_{out} и V_w relative to the basic values (experiment №1), the highest growth of heat consumption was obtained by carrying out an experiment №2 (increasing of parameter $Q_{rm\,2}$ was 82.2 %), whereas in experiment №3 heat consumption increased by 11.8 %.

Comparison of heat gains from solar irradiation and internal heat sources (experiments №5 and №6 respectively), which was conducted for research object, shows a great importance of insolation influence. It should be noted a considerable spread of values of $Q_{rm\,i}$ for rooms with different spatial orientation: DCS provided savings 5.93 kW·h (29.11 %) in room №2, whereas in room №3 energy saving effect is only 0.72 kW·h (3.8 %). In case of availability of internal heat sources energy saving attains a maximum value of 4.88 kW·h (25.83 %) and average value of 4.79 kW·h (23.36 %).

Experiment №6, characterized by applying specialized thermal regimes should be noted particularly. Analysis of obtained data allows to conclude about energy conservation of 8.36 kW·h or 38.9 % (in rooms №1 and №4). Actual value ΔT_{in} obtained for research object at T_{out0} = -20 °C is 2.2 °C (rooms №1 and №4), that can be explained by considerable value of specific thermal capacity. The same experiments at T_{out0} = -30 °C shows that temperature T_{in} was reduced to the value of 21 °C (ΔT_{in} = 3 °C) under otherwise equal conditions.

Conducted researches allows estimating individual influence of each factor on a heat consumption and thermal regimes of controlled rooms. Multifactorial analysis play a key role in investigations of buildings thermal regimes and functioning of control systems and technological equipment. In this case simultaneous influence of many factors is taken into account and simulation conditions as realistic as possible. Figure 5 shows changing of indoor temperature T_{in} in controlled rooms in case of applying the low heat consumption mode under simultaneous influence of following factors: outdoor temperature T_{out0} = -30 °C, wind velocity V_w = 3 m/s, availability of solar irradiation and internal heat gains.

Figure 5 shows possibility of realization of thermal regime (low heat consumption mode) at ΔT_{in} = 3 °C. The maximum deviation of indoor air temperature does not exceed 0.59 °C (maximum dynamic control error) from the set value of $T_{in\,set}$ = 23 °C. Activation of low heat consumption mode start at 16 o'clock (1 hour before finish a work day). It is interesting to note that specific shape of the graph caused by nulling the internal heat sources (end of work day). Further special energy saving mode is deactivated and parameter $T_{in\,set}$ assume a value 23 °C at 7 o'clock (1 hour before start a work day). Control error (deviation of T_{in} from set value) does not exceed 0.05 °C in steady state operating modes.

CONCLUSION

Modelling for the winter climate conditions (February) of Western Siberia was conducted. Researches of heat consumption of rooms, which are characterized by different spatial orientation were conducted.

Dynamics analysis of heat consumption parameters of controlled rooms allows to conclude about the potential of energy savings that can be achieved on real object in the implementation of intelligent distributed control system of building heat consumption, that can effectively compensate all considered disturbing influences. Applying the specialize low heat consumption mode allows the energy conservation of 8.36 kW·h or 38.9 % at the average outdoor temperature -20 °C.

Distributed control system effectively compensates the deviation of indoor air temperature in case of multifactorial influence: maximum dynamic control error does not exceed 0.59 °C after deactivation of low heat consumption mode.

Obtained modelling results (heat consumption, dynamic of indoor air temperature and the temperature distribution in the building envelopes) can be used to develop energy conservation measures for existing or planned buildings.

ACKNOWLEDGEMENT

The reported study is supported by the Ministry of Education and Science of the Russian Federation (contract 2.1321.2014).

REFERENCES

Maestre, I.R., Perez-Lombard, L., Foncubierta, J.L. and Cubillas, P.R. 2013. Improving direct solar shading calculations within building energy simulation tools. *Journal of building performance simulation*, 6 (6), 437-448.

Amado, M. and Poggi, F. 2012. Towards solar urban planning: a new step for better energy performance. *Energy Procedia*, 30, 1261-1273.

Tagliabue, L.C., Buzzetti, M. and Arosio, B. 2012. Energy saving through the sun: analysis of visual comfort and energy consumption in office space. *Energy Procedia*, 30, 693-703.

Strizhak, P.A. and Morozov, M.N. 2014. Building thermal mode in case of emergency termination of heat supply. *Glavnyy energetik*, (7), 39-45.

Scattolini, R. 2009. Architectures for distributed and hierarchical. Model Predictive Control. – A review. *Journal of Process Control*, 19 (5), 723-731.

Tian-Wei, Q., Xiang, H. and Jun-mei, W. 2011. Design of Air conditioning distributed control system for an office building in Xi'an. *Procedia Environmental Sciences*, 11 (B), 643-649.

Morosan, P.-D., Bourdais, R., Dumur, D. and Buisson, J. 2010. Building temperature regulation using a distributed model predictive control. *Energy and Buildings*, 42 (9), 1445-1452.

Barata, F.A., Felix, N. and Neves-Silva, R. 2014. Distributed MPC for green thermally comfortable buildings based on an electro-thermal modular approach. *Procedia Technology*, 17, 772-780.

Wallace, M., McBride, R., Aumi, S., Mhaskar, P., House, J. and Salsbury, T. 2012. Energy efficient model predictive building temperature control. *Chemical Engineering Science*, 69 (1), 45-48.

Privara, S., Vana, Z. and Zacekova, E. 2012. Building modeling: Selection of the most appropriate model for predictive control. *Energy and Buildings*, 55 (12), 341-350.

Kıyan, M., Bingol, E., Melikoglu, M. and Albostan, A. 2013. Modelling and simulation of a hybrid solar heating system for greenhouse applications using Matlab/Simulink. *Energy Conversion and Management*, 72 (8), 147-155.

Broman, D. and Fritzson, P. 2008. Higher-order acausal models, proc. *2nd International workshop on equation-based object-oriented languages and tools*, Paphos, Cyprus, 59-69.

Avanev, V.A., Balueva, L.N. and Galperin, A.D. 2003. Ventilation and air-conditioning systems. Theory and practice, Interdialect, Moscow.

SP 23.101.2004. Designing buildings thermal protection. Izdatel'stvo standartov, Moscow.

Malyavina, E. G. and Borshchev, A. N. 2006. Calculation of solar radiation in winter. *ABOK*, (7). Available at: http://www.abok.ru/for_spec/articles.php?nid=3374 [Accessed December 24, 2014].

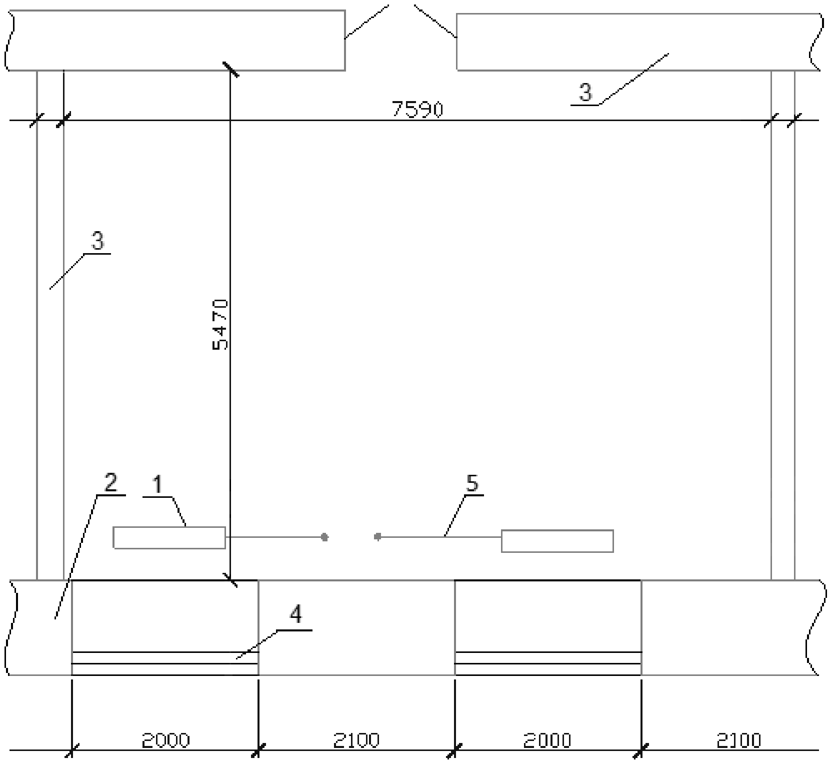

Figure 1 A schematic illustration of simulation object (a) plan of a room, (b) axonometric scheme of the one-pipe heating system: 1 - heating appliance; 2, 3 – interior and exterior envelopes; 4 – multiple glass pane; 5 - water pipe

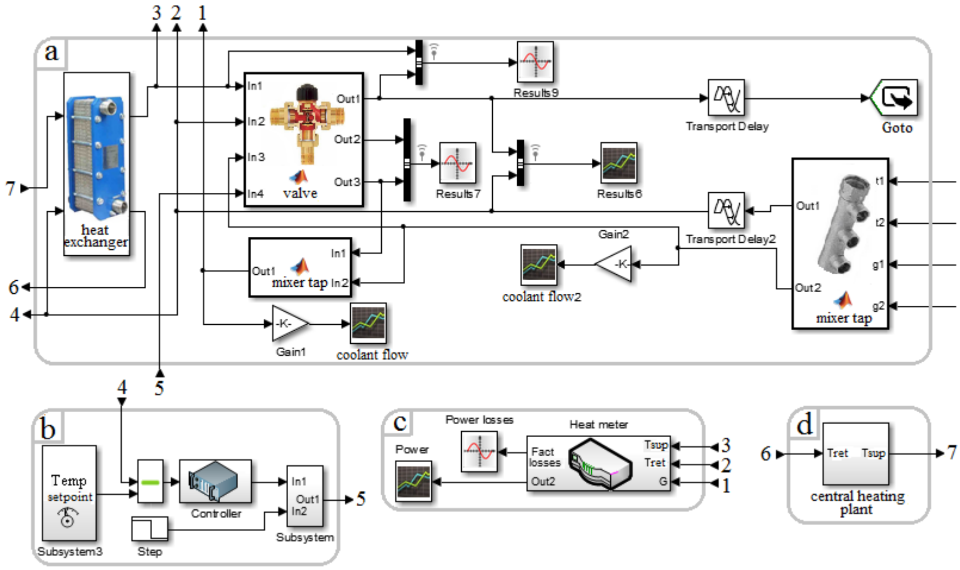

Figure 2 The main blocks of the thermal model of the heating system: (a) blocks of individual heating plant; (b) controller of heat consumption; (c) heat calculator; (d) heat supply source

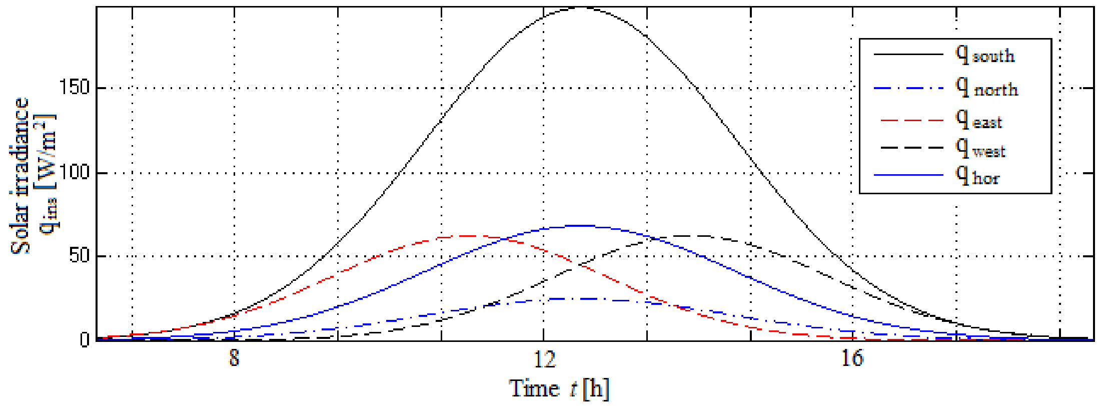

Figure 3 Daily solar irradiance q_{ins} (W/m^2) toward the surface of the different spatial orientation (Tomsk, January): q_{south} – vertical south orientation surface, q_{north} – vertical north orientation surface, q_{east} – vertical east orientation surface, q_{west} – vertical west orientation surface, q_{hor} – horizontal surface

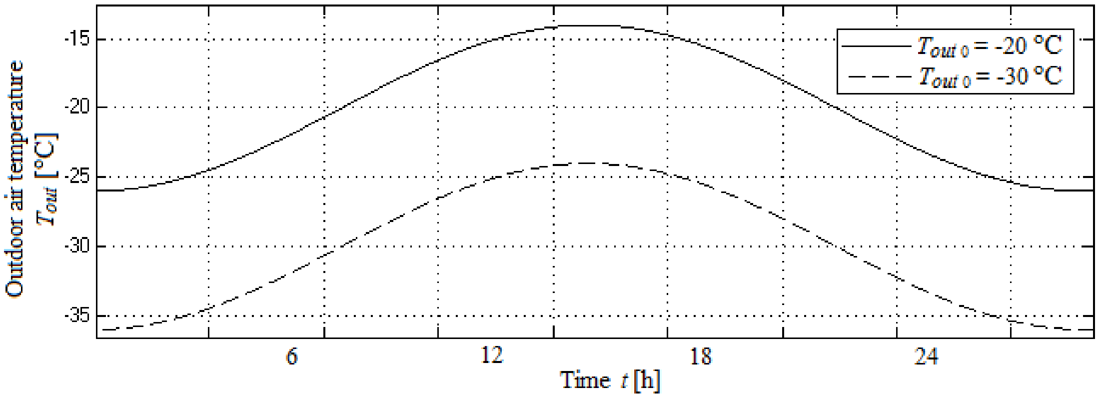

Figure 4 Daily change of outdoor air temperature T_{out}

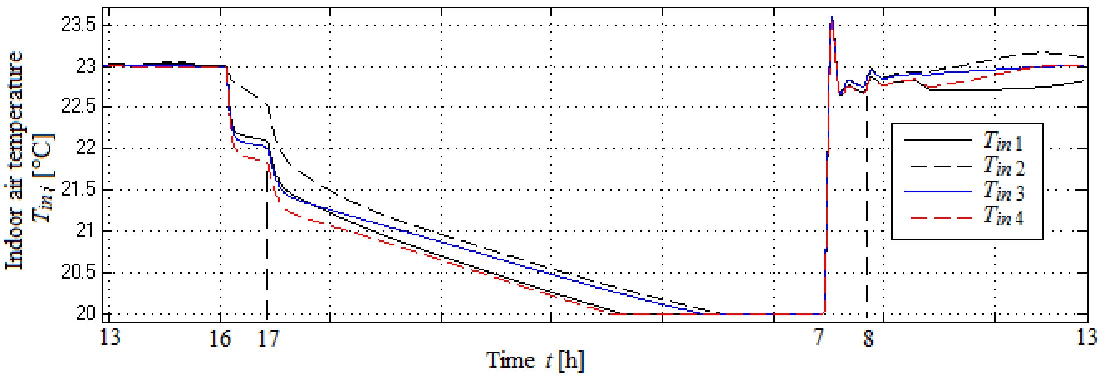

Figure 5 Changing of indoor temperature T_{in} in controlled rooms in case of assumed factors influence