THE OPTIMAL THERMAL DESIGN OF RESIDENTIAL BUILDINGS USING ENERGY SIMULATION AND FUZZY SETS THEORY

Arkadiusz Węglarz[1,3], Piotr Narowski[2]
[1]Warsaw University of Technology, Faculty of Civil Engineering, Warsaw, Poland
[2]Warsaw University of Technology, Faculty of Environmental Engineering, Warsaw, Poland
aw@il.pw.edu.pl, piotr.narowski@is.pw.edu.pl
[3]The Polish National Energy Conservation Agency, Warsaw, Poland

ABSTRACT

The introduction of the Energy Performance of Buildings Directive (EPBD) in Poland established minimal building energy performance requirements for new and retrofitted buildings without changing the U-value requirement for the building envelope in the building code. This change in the Polish law has sometimes caused investors to draw the wrong conclusions about thermal standards for single-family residences. With this in mind, this paper seeks to optimise the thermal performance of buildings using both fuzzy sets and Zadeh probability with simple hourly 6R1C building energy simulation. An optimal design is important especially for victims of a recent flood who are constructing new housing and face multiple objective constraints.

INTRODUCTION

The minimal building energy performance requirements for new and retrofitted buildings in the Polish building code are lower than in others countries with similar climate characteristics. This is true even though the U-value requirement for building envelopes is relatively high. This situation allows developers or investors to build or refurbish residential houses with minimal thermal requirements to reduce overall investment costs. As a consequence, those buildings are not thermally well insulated according to contemporary requirements and climate severity. This fact, coupled with steadily increasing energy prices result in a high cost of energy used for heating such buildings. The high cost of heating comes at a time when some face financial problems as flood victims in most cases are forced to lower internal air temperature during the heating season to decrease energy costs. As a matter of consideration, some are choosing to retrofit or sell the house.

The decision to lower household heating expenditures must be considered alongside the current cost of energy and the cost of a building retrofit. The building user's inclination to accept something other than optimal thermal comfort and the investment and operational heating costs can be presented as fuzzy sets. The annual energy used for heating and the index of internal thermal comfort can be simulated using simple hourly methods that take into account the characteristics of the building.

This paper presents a method of optimising the thermal characteristics of small residential buildings which are being designed as inexpensive housing for flood victims. This analysis is carried forward with two objectives in mind – thermal comfort and acceptable costs.

OPTIMISATION METHOD FOR SMALL RESIDENTIAL BUILDING DESIGN

Multi-objective optimization can be defined as the process of simultaneously optimizing two or more conflicting objectives subject to certain constraints. Multi-objective problem solving together with fuzzy sets and membership functions can be employed to find the best possible design of a building (Panek, 2008). The optimization problem consists of three objective functions. The first objective function is defined as thermal comfort or better satisfaction with the internal air temperature, a variable which should be maximized. The second objective is defined as annual heating costs satisfaction – this should be maximized. The last, namely the third objective, is defined as the additional investments costs – which should be minimized. All objectives functions were defined as dimensionless within the real numbers range <0, 1>.

The optimization problem analysed in this paper was defined as the maximization of a goal function consisting of three described objectives, which can be understood as an overall investor satisfaction with three constraints:

- acceptance of internal air temperature during the heating season – ATI – defined as a fuzzy set number,
- acceptance of annual building heating costs – AHC – defined as a membership function of a linguistic variable,
- acceptance of additional investments costs – AIC – defined as membership function of a linguistic variable.

The goal function can be written as (1):

$$\max\left[\sum_{i=1}^{3} w_i\mu_i\left(x_1, x_2, x_3, x_4, t_{set}\right)\right], \qquad (1)$$

where:

μ_1 – internal temperature satisfaction – objective function,

μ_2 – annual heating costs satisfaction – objective function,

μ_3 – additional investment costs – objective function,

x_1 – external walls insulation thickness or external walls U-value,

x_2 – roof insulation thickness or roof U-value,

x_3 – slab on the ground insulation thickness or U-value,

x_4 – windows U-value,

t_{set} – building conditioned space heating set point temperature,

w_i – weight factors for objective functions.

The internal air temperature satisfaction objective function μ_1 is defined as a Zadeh (1965) probability for a defined fuzzy numbers set of internal air temperature acceptance ATI. The value of this function is obtained as a sum of normalized annual internal air temperature frequency and the fuzzy set numbers product. The fuzzy set for μ_1 is defined as: ATI{(<18°C, 0); (19°C, 0.2); (20°C, 0.5); (21°C, 1.0); (22°C, 0.9); (23°C, 0.7); (24°C, 0.5); (25°C, 0.3); (26°C, 0.1); (>26°C, 0)}. The ATI fuzzy numbers set is shown on figure 1.

The annual heating costs satisfaction objective function μ_2 is defined as an affiliation of the linguistic variable AHC. By a linguistic variable we mean a variable whose values are words or sentences in a natural or artificial language.

The objective function μ_2 is calculated within linguistic variable AHC for determined annual heating costs of a specified building energy standard and specified heating set point. The fuzzy set for μ_2 is defined as: AHC{(<500€, 1.0);...(>1250€, 0.0)}.

The additional investment costs objective function μ_3 is defined as a membership function of linguistic variable AIC. The objective function μ_3 is calculated as a membership function with linguistic variable AIC for specified building energy characteristics and heating set points. The fuzzy set for μ_3 is defined as: AIC{(<2500€, 1.0);...(>8750€, 0.0)}.

The ATI membership function was prepared with information gathered from a survey which was conducted among inhabitants of one- and multifamily residential buildings. The study was conducted on a sample of 120 persons whose age range ran from 14 to 72 years. Persons participating in the study were asked to notify three times per day during one week in February his or her thermal comfort as: "too hot", "neutral", "too cold" and after this assessment indicate the internal air temperature and the time. Survey participants were asked not to make any exercises or hard work while registering the degree and circumstances of their thermal comfort.

All additional investment costs were estimated from construction work costing databases. As the criteria set and variant set are finite, discrete methods of optimisation can be utilised. The multi-objectives optimisation problem was solved by maximising weighted averages of objective functions in accordance with equation (1). Weights used for calculation of objective functions were determined from the survey.

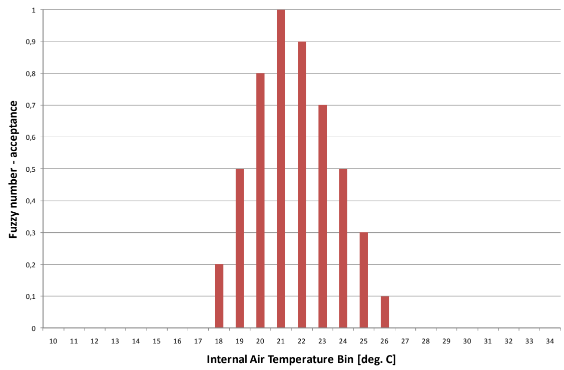

Figure 1 Fuzzy set numbers for internal air temperature acceptance

All essential values for solving the optimisation problem connected with the designed building, such as energy consumption or internal air temperature variation, were simulated with the 6R1C building model. A simple hourly lumped resistance and capacitance building model was utilised to determine the normalised internal air temperature frequency and annual energy use for specified building thermal characteristic and fixed heating set points.

INTEGRATED 6R1C ENERGY SIMULATION METHOD

Lumped heat capacitance and resistance method and its electrical analogy

The simple hourly method used for building energy simulations is based on a lumped heat capacitance and resistance method with one capacitor and a few resistors in a network. This is the simplest building simulation method and is commonly used in European countries as described in the EN ISO 13790 standard (EC Concerted Action, 2011). The simulation method 6R1C is a development of the method presented in the standard EN 13790. The lumped parameters methods are commonly used for simple and fast building energy simulations. This method was used to develop the "International Building Physics Toolbox" (Rode et. al). Another example is EPA-NR, an IEE-project that has developed a method and tools for the Energy Performance Assessment of existing Non-Residential buildings in Netherlands. The simple hourly method 5R1C for building simulations was developed by many experts from European countries working for CEN (Van Dijk, 2004), (PASSYS-II, 1993). The lumped capacitance, resistance method 5R1C is commonly used across European countries (Millet, 2007), (Orosa, 2010) but it can be improved by being integrated along with AHU (Mijakowski, 2009) which leads to the 6R1C method described below.

One of the most common transient conduction problems deals with a solid body exposed to a sudden change of its thermal environment. One can consider a solid, concrete wall at constant uniform temperature which is exposed to a sudden change in the surrounding air temperature. Lumped capacitance method makes the assumption that the solid has high thermal conductivity and the surface heat transfer is low compared to the conductance. The essence of the lumped capacitance method is the assumption that the solid internal temperature is spatially uniform at any instant during the transient process of heat exchange with the surrounding environment. It means that the temperature gradient within the solid is neglected at any time in the transient process. In the example, the initial temperature of the solid is assumed to be T_0 and is spatially uniform. The temperature of water $T\infty$ in which the solid is immersed is lower than the solid initial temperature T_0 at the initial instant $t = 0$. After immersing the solid temperature will decrease for time $t > 0$, until it eventually reaches $T\infty$. This reduction is due to convection heat transfer at the solid-liquid interface.

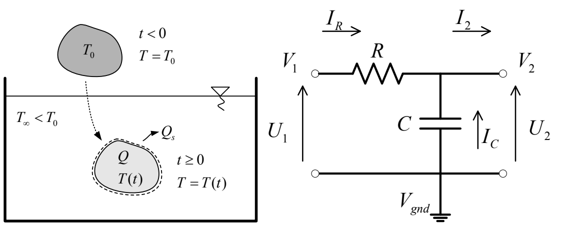

Figure 2 Cooling down hot solid (left) and discharging of capacitor C through resistor R (right) - two different phenomena described by the same differential equation.

The process of transient heat transfer in the lumped capacitance method is described by the ordinary differential equation (2) or (3):

$$C\frac{d\Theta}{dt} = -H\Theta \quad , \quad \frac{d\Theta}{dt} = -\frac{1}{RC}\Theta. \qquad (2, 3)$$

where: Θ – temperature or electric potential, t – time, C – capacitance (thermal or electric), H – conductance (thermal or electric), R – resistance (thermal or electric).

There is an equation in the electric circuits' theory which is analogous to equation (3). The equivalent of the transient heat transfer in the lumped capacitance method in circuits theory is the electric current flow in the circuit composed with electric capacitor and resistor known as four-terminal RC network or RC quadripole shown in figure 2. This quadripole is a filter that passes low-frequency signals but attenuates (reduces the amplitude) of signals with frequencies higher than the cutoff frequency $f_c = 1/(2\pi RC)$:

$$\frac{dV_2(t)}{dt} = -\frac{1}{RC}V_2(t). \qquad (4)$$

So the two different phenomena – the discharging of capacitor C through resistor R and the cooling down a hot solid are described by the same differential equation (figure 2). This observation allows modeling the lumped capacitance heat exchange process with electrical circuits composed of capacitor and resistors. Many models of heat exchange were built on that base by starting with a simple one node 2R1C lumped capacitance building model (the model depends only on the building heat capacity, the external envelope surface heat resistance and the heat flux delivered to the building construction). Modifications of the 2R1C model can lead to more sophisticated models (e.g. the 5R1C model presented in European / International standard EN ISO 13790 which makes it possible to calculate additionally: the transient internal air temperature in the building, the masonry temperature and the internal surface temperature.

6R1C method of estimation of annual energy use in building

The 6R1C model (Narowski, 2010) used for annual energy use estimation in buildings is a further development of the 5R1C model. The basic reason for the modification was the fact that the 5R1C model does not contain separate ventilation air flux with a controlled supply temperature and infiltration flux of external air. The modified model presented in figure 2 describes two ways of air coming into the building – controlled ventilation and uncontrolled infiltration. The model, which is similar to 5R1C, allows supplying heat to three nodes – the building construction, the internal surface of building construction and the indoor air.

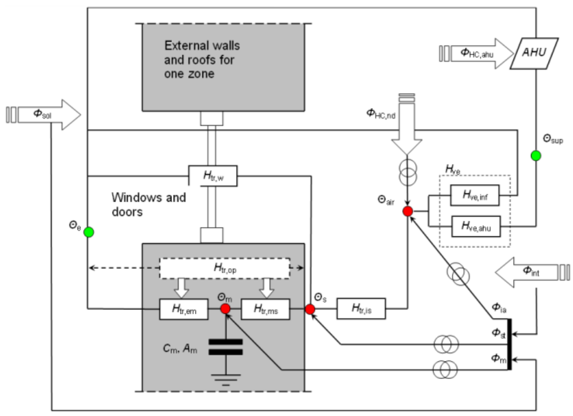

Figure 3 Schema of 6R1C building model.

The potentials θ in the nodes are θ_e – the external air temperature, θ_v – the ventilation air temperature, θ_m – the building construction temperature in the lumped capacitance method, θ_s – the temperature of the internal surfaces of the building's external walls, θ_i – the internal air temperature. The resistances of the electric 6R1C circuit are equivalent to the heat resistances in the building: R_{Tr1} – the heat transfer resistance of the outside construction assembly, R_{Tr2} – the heat transfer resistance of the internal part of a construction assembly, R_S – the heat convection resistance of the internal surface of the building , R_W – the external windows and doors heat transfer resistance, R_{Ve} – the heat transfer resistance of controlled ventilation, R_{Vi} – the heat transfer resistance of uncontrolled infiltration. The electric currents which supply the circuit of the 6R1C model are equivalent to internal heat gains and the energy delivered by the building heating or cooling systems.

The energy streams Φ are: Φ_{Tr1} – heat flow through the external surface of an opaque building envelope, Φ_{Tr2} – heat flow through the internal surface of an opaque building envelope, Φ_C – heat flow accumulated in the building construction, Φ_S – convection heat flow from an internal surface of the building construction to internal air, Φ_W – heat flow transferred through external windows and doors, Φ_{Ve} – heat flux carried with controlled ventilation air, Φ_{Vi} – heat carried with infiltration air. There are six ideal energy sources in the scheme of the building model.

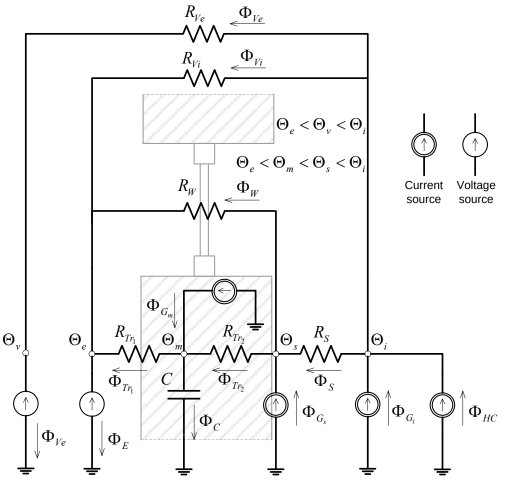

Figure 4 Lumped capacitance and resistance heat exchange 6R1C building model.

The potential θ_e modelled by the ideal voltage source is equivalent to the varying external temperature. The temperature of ventilation air supplied to the building's rooms is modelled by the ideal voltage source of potential θ_v. Other energy streams feeding the circuit are ideal current sources. They represent solar and internal heat gains and heat delivered by the building's heating and cooling systems. The source current Φ_{HC} corresponds to system heat. The currents Φ_{Gi}, Φ_{Gs} and Φ_{Gm} represent the energy of solar and internal heat gain divided into three parts and balanced in the internal air, the internal surface of the building and the mass of building. The replacing conductivity H_2 of the 2R1C circuit can be represented as a circuit of five resistors in the 6R1C circuit. The conductivity of this replacing resistor can be calculated using the partial conductance of serial and parallel connected resistors:

$$H_{Z_1} = \frac{H_S H_{Ve}}{H_S + H_{Ve} + H_{Vi}}, \qquad H_{Z_2} = \frac{H_S H_{Vi}}{H_S + H_{Ve} + H_{Vi}} \tag{5, 6}$$

$$H_{Z_3} = H_{Z_1} + H_{Z_2} \quad \text{and} \quad H_{Z_4} = H_{Z_3} + H_W \tag{7, 8}$$

with the formula:

$$H_{Z_5} = \frac{H_{Tr_2} H_{Z_4}}{H_{Tr_2} + H_{Z_4}} \tag{9}$$

The replacing conductance H_{Z5} in the 6R1C model can be treated as conductance H_2 of the 2R1C model, then it can be said that $H_2 \equiv H_{Z5}$. The replacing current source $\Phi \equiv \Phi_{mtot}$ supplying the capacitor with the potential θ for circuit 2R1C can be calculated as the sum of currents in that node supplied by current sources Φ_{HC}, Φ_{Gi}, Φ_{Gs}, Φ_{Gm} for two voltage sources with potential θ_v and θ_e with short circuit of capacitor C. The potential $\theta_{m,n+1}$ in the current instant of time $(n+1)$ depends on the potential in the previous instant of time (n) and can be calculated with the modified *Euler's* method as in:

$$\Theta_{m,n+1} = \frac{\Theta_{m,n}\left(C/3600 - 0{,}5\left(H_{Tr_1} + H_{Z_5}\right)\right) + \Phi_{mtot}}{C/3600 + 0{,}5\left(H_{Tr_1} + H_{Z_5}\right)}. \tag{10}$$

The current Φ_{Tr2} can be calculated by replacing the ideal current source connected to a node with potential θ_s, connected to the ground (short circuit) and with branch currents caused by current sources Φ_{Gi} and Φ_{HC}, and voltage sources θ_v and θ_e. The current supplying the node θ_s from current sources Φ_{HC} and Φ_{Gi} can be calculated from the equation:

$$\Phi_S^{(\Phi_{HC}+\Phi_{G_i})} = \frac{H_S}{H_S + H_{Vi} + H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right) = H_{Z_1}\frac{\Phi_{HC} + \Phi_{G_i}}{H_{Ve}}. \tag{11}$$

The current supplying the node θ_s from voltage source θ_v can be calculated as:

$$\Phi_S^{(\Theta_v)} = \frac{H_S}{H_S + H_{Vi}}\left(\frac{H_{Ve}\cdot\left(H_S + H_{Vi}\right)}{H_{Ve} + \left(H_S + H_{Vi}\right)}\Theta_v\right) = H_{Z_1}\Theta_v \tag{12}$$

The current supplying the node θ_s from the voltage source θ_e generates current in node θ_s which equals:

$$\Phi_S^{(\Theta_e)} = \frac{H_S}{H_S + H_{Ve}}\left(\frac{H_{Vi}\cdot\left(H_S + H_{Ve}\right)}{H_{Vi} + \left(H_S + H_{Ve}\right)}\Theta_e\right) + H_w\Theta_e = \left(H_{Z_2} + H_W\right)\Theta_e. \tag{13}$$

Substitute the circuit scheme with the node θ_m shorted to ground and supplied with replacing ideal current source shown in figure 12. The current supplying the node θ_m in that circuit equals:

$$\Phi_{Tr_2} = \frac{H_{Tr_2}}{H_{Tr_2} + H_{Z_4}}\left(\underbrace{\Phi_{G_s} + \Phi_S^{(\Phi_{HC}+\Phi_{G_i})} + \Phi_S^{(\Theta_v)} + \Phi_S^{(\Theta_e)}}_{\Phi_{S,tot}}\right) = \frac{H_{Z_5}}{H_{Z_4}}\Phi_{S,tot}. \tag{14}$$

The branch current Φ_{Tr1} flowing to node θ_m generated by voltage source with potential θ_e equals:

$$\Phi_{Tr_1}^{(\Theta_e)} = H_{Tr_1}\Theta_e \quad (15)$$

and with another current and voltage sources equals 0. The total current Φ_{mtot} in node θ_m generated by all sources except the voltage of the capacitor can be calculated as:

$$\Phi_{mtot} = \Phi_{G_m} + H_{Tr_1}\Theta_e + \frac{H_{Z_5}}{H_{Z_4}} \cdot \left(\Phi_{G_s} + H_{Z_1}\left(\frac{\Phi_{HC} + \Phi_{G_i}}{H_{Ve}} + \Theta_v \right) + \left(H_{Z_2} + H_W \right)\Theta_e \right) \quad (16)$$

Applying *Kirchoff's* currents law for the node with potential θ_s allows one to derive the balance equation for the node of 6R1C circuit and determine its potential:

$$H_{Tr_2}\left(\Theta_s - \Theta_m\right) + \left(H_{Z_2} + H_W\right)\left(\Theta_s - \Theta_e\right) + H_{Z_1}\left(\Theta_s - \Theta_v\right) = \Phi_{G_s} + \frac{H_{Z_1}}{H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right) \quad (17)$$

$$\Theta_s = \frac{H_{Tr_2}\Theta_m + \left(H_{Z_2} + H_W\right)\Theta_e + H_{Z_1}\Theta_v + \Phi_{G_s} + \frac{H_{Z_1}}{H_{Ve}}\left(\Phi_{HC} + \Phi_{G_i}\right)}{H_{Tr_2} + H_{Z_4}} \quad (18)$$

The same procedure can be applied by determining potential θ_i:

$$H_S\left(\Theta_i - \Theta_s\right) + H_{Vi}\left(\Theta_i - \Theta_e\right) + H_{Ve}\left(\Theta_i - \Theta_v\right) = \Phi_{HC} + \Phi_{G_i} \quad (19)$$

$$\Theta_i = \frac{H_S\Theta_s + H_{Vi}\Theta_e + H_{Ve}\Theta_v + \Phi_{HC} + \Phi_{G_i}}{H_S + H_{Vi} + H_{Ve}} \quad (20)$$

The lumped capacitance 6R1C building model allows one to calculate the masonry temperature θ_m, the temperature of internal surfaces of building θ_s and the internal air temperature θ_i, taking into consideration the variable external air temperature θ_e and the variable temperature of ventilation air θ_v and the transient heat fluxes Φ_{HC}, Φ_{Gi}, Φ_{Gs} and Φ_{Gm} supplying the nodes of circuit. Those heat streams can represent the energy of heating or cooling systems delivered to internal air, as well as the heat gains in the form of radiation and convection from external e.g. solar and thermal radiation, and internal sources such as people, appliances or lighting. All these heat streams are calculated in accordance with the EN ISO 13790 standard.

Integration with simple air handling unit

The behavior of ventilation and air-conditioning and the calculation of the energy used for preparation of outside air in AHU is based on European standard EN 15241 "Ventilation for buildings – calculation methods for energy losses due to ventilation and infiltration in commercial buildings".

The main idea is to calculate the energy needed for transferring the air from outdoor conditions to required values at the supply. The following processes were taken into account (figure 5): heat recovery (sensible and latent) during winter and summer, heating, humidifying, cooling, dehumidifying, preheating and pre-cooling of air in a ground heat exchanger.

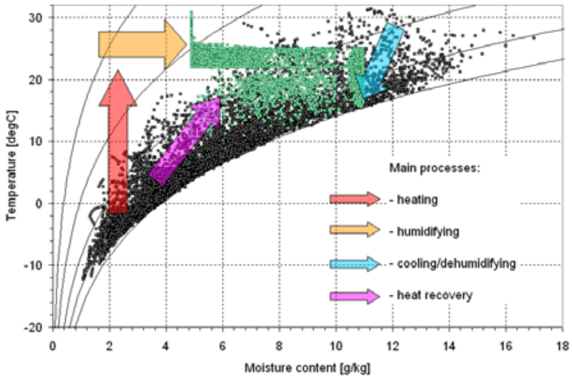

Figure 5 AHU calculations integrated with 6R1C simple hourly method.

Sub-models of air treatment processes provide energy consumption (if there any, for example heat recovery does not need energy – the additional energy for fans etc. is calculated separately) and air parameters which are modified by the process. Although the equations describing processes are simple and well know, the annual behavior of AHU may be quite complex. The advanced logical analysis (the substitution of control system modeling) is often necessary. The quantitative and qualitative changes of processes can be forced by both weather changes and variations of building loads. At the same time the available processes are limited by the level of functionality of the HVAC system.

Verification of the model with BESTEST method

In order to verify the 6R1C model, tests 600, 620, 640, 650, 900, 920, 940 and 950 were performed. Climate data for Denver were used for all diagnostic models. Basic test 600 is used to model the thermal loads in the building. This one zone model is a cube-shaped without internal partitions and low thermal capacity of building envelope as described in ASHRAE Standard 140. The model 6R1C passed all tests mentioned above (Narowski, 2010) except energy use for cooling in test 950. As the optimised building is a very simple construction without any external shading elements and is equipped with the electric heating system described, the 6R1C model can be used to simulate the annual energy consumption and internal air temperature variation which are used for building design optimisation.

EXAMPLE OF RESIDENTIAL BUILDING THERMAL DESIGN OPTIMISATION

The multi-objective optimisation with fuzzy sets and membership functions together with the 6R1C model employed for building energy simulations described in a previous part of this paper were used to carry out the optimisation of a small residential building design.

Table 1
"Ekopolis I" building parameters for 6R1C model - the base variant – St 1 and the St 9 variant

Parameter	St 1	St 9	Unit
Thermal transmission coefficient for opaque building elements – $H_{tr\ op}$	100,2	69,4	W/K
Thermal transmission coefficient for building windows and doors – $H_{tr\ w}$	31,8	21,5	W/K
The coupling conductance between internal air and internal surface – $H_{tr\ is}$	1611,5	1611,5	W/K
The area of all surfaces facing the building zone – A_{tot}	467,1	467,1	m^2
The effective thermal mass area – A_m	259,5	259,5	m^2
The internal zone heat capacity – C_m	17127000	17127000	J/K

The "Ekopolis I" building is designed as a one-family inexpensive house for flood victims. The basic architectural plans show the design as a one-floor detached house without basement at ground level with a usable attic. The total floor area is 104 m^2 and the volume is 406 m^3. The design specifications indicate the external walls to be lime brick masonry with insulation as EPS or rock wool. The gable roof is wood framed and insulated with rock wool. The picture of the "Ekopolis I" building is shown in figure 6.

Figure 6 Ekopolis I small one-family house – subject of thermal design optimisation.

The optimal thermal design of the "Ekopolis I" house was altered. There were 11 versions of building design analysed. The external wall, roof and slab on grade insulation and windows U-value were changed. Additional alternatives of the building ventilation system were proposed. The original building design, called "St-1", was the base variant for cost calculations. The additional cost for other variants were calculated as the difference between the investment cost of the varied and base considerations. All variants of the building design and additional investment costs are presented in table 2. The energy use for all building variants was calculated with the 6R1C model with typical meteorological year WYEC2 for Warsaw. The internal heat gains were calculated for every hour with the assumption of typical operational schedules as described in ASHRAE for residential buildings occupied by a 4 person family. These occupants, the lighting and the appliances' internal heat gains were calculated independently. The solar heat gains were calculated in accordance with EN ISO 13790 standard. The electric energy cost from the utility was assumed to be 0.125 €/kWh.

Table 2
"Ekopolis I" building design variants used for optimisation

Variant	**External walls insulation**	**Roof insulation**	**Slab on ground insulation**	**Windows U-value**	**Ventilation system***	**Additional investments**
	cm	cm	cm	W/m^2K	-	€
St-1	12	20	5	1.8	N.V.	0
St-2	15	20	10	1.8	N.V.	1703
St-3	18	25	10	1.8	N.V.	2201
St-4	20	25	10	1.5	N.V.	2351
St-5	20	25	10	1.5	M.V. 60%	5858
St-6	20	30	15	1.3	M.V. 65%	6112
St-7	22	30	15	1.1	M.V. 65%	6264
St-8	24	30	15	1.1	M.V. 70%	6726
St-9	25	35	15	1.0	M.V. 75%	7444
St-10	30	40	20	1.0	M.V. 80%	8713
St-11	35	40	25	0.8	M.V. 85%	11080

*Ventilation system – N.V. = natural ventilation, M.V. = mechanical ventilation with heat recovery at level %

Building energy simulations with the 6R1C model were performed to obtain the energy consumption and internal air balance temperature for every hour during a given year. As the "Ekopolis I" building is equipped only with an electric heating system, the cooling set point for the simulations was set at 50°C to switch off the cooling energy in the model. The internal air temperature outside the heating season was the result of building solar and internal gains and ventilation air flux. The results of the simulations are presented in tables 2 and 3. The energy performance of various "Ekopolis I" alternatives are shown in table 3 while normalized internal air frequencies for the original design can be found in in table 4. The building is heated during the cold period and naturally ventilated during the hot period. There is no cooling system in the analysed building.

Table 3
*"Ekopolis I" building simulation results – energy performance EP**

Variant	Heating set point					
	18°C	**19°C**	**20°C**	**21°C**	**22°C**	**23°C**
St-1	62,5	70,2	78,1	86,4	94,9	103,8
St-2	61,8	69,4	77,3	85,5	94,0	102,9
St-3	56,8	64,0	71,5	79,3	87,4	95,8
St-4	50,8	57,4	64,4	71,7	79,3	87,1
St-5	40,7	46,2	52,2	58,4	65,0	71,8
St-6	31,5	36,2	41,1	46,4	52,0	57,8
St-7	27,5	31,9	36,4	41,3	46,4	51,9
St-8	25,1	29,3	33,6	38,2	43,1	48,2
St-9	21,4	25,2	29,3	33,5	37,9	42,7
St-10	15,5	18,5	21,9	25,6	29,4	33,3
St-11	10,0	12,2	14,7	17,5	20,6	23,9

*annual energy use per floor square meter – kWh/(m^2 annum)

Table 4
*"Ekopolis I" building St-1 simulation results – normalized internal air temperature frequency**

Histogram bin	Heating set point					
	18°C	**19°C**	**20°C**	**21°C**	**22°C**	**23°C**
<= 18	0,71	0,41	0,16	0,04	0,01	0,00
18-19	0,18	0,29	0,27	0,14	0,03	0,01
19-20	0,09	0,18	0,28	0,27	0,15	0,03
20-21	0,03	0,09	0,17	0,27	0,26	0,15
21-22	0,00	0,03	0,09	0,17	0,27	0,26
22-23	0,00	0,00	0,03	0,09	0,17	0,27
23-24	0,00	0,00	0,01	0,03	0,08	0,17
24-25	0,00	0,00	0,00	0,01	0,03	0,08
25-26	0,00	0,00	0,00	0,00	0,01	0,03
>= 26	0,00	0,00	0,00	0,00	0,00	0,01

*number of hours from histogram bin temperature divided by total year hours

The test case of the external air temperature from the typical meteorological year and the simulated internal air temperature for the original "Ekopolis I" design called "St-1" in this paper is presented in figure 7.

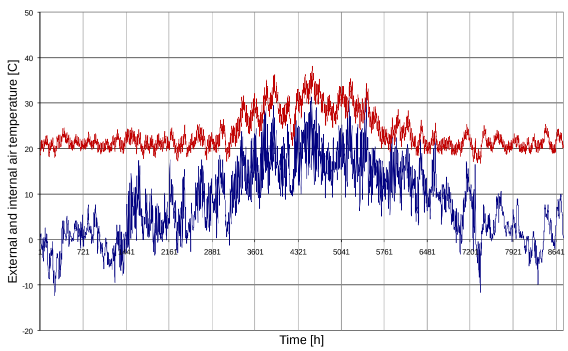

Figure 6 Annual runs of external air and simulated internal air temperature for original design of Ekopolis I.

Figure 7 presents the simulation with the 6R1C model annual run of heat loads for the "Ekopolis I" building in variant St-1 as the original design provided. The area below the line represents the annual energy use measured in kilowatthours.

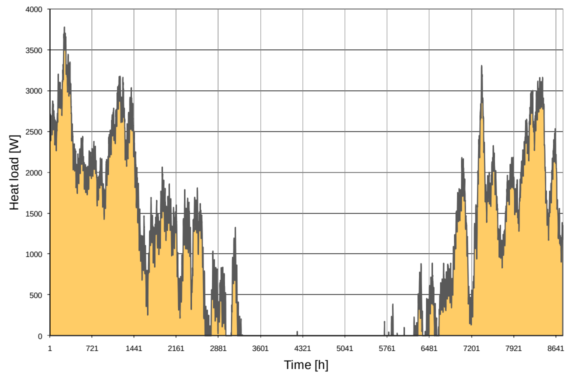

Figure 7 Annual heat load for Ekopolis I building – the base variant St-1.

A multi-objectives optimization goal function was calculated for all variants of the "Ekopolis I" building design in accordance with weights and membership functions of fuzzy sets for three defined objectives. The results of the goal function calculation for eleven variants and heating set points are displayed in table 5.

Table 5
"Ekopolis I" building design optimisation results

Variant	Heating set point						
	18°C	**19°C**	**20°C**	**21°C**	**22°C**	**23°C**	**Max**
St-1	0,49	0,47	0,47	0,49	0,51	0,48	0,51
St-2	0,50	0,48	0,48	0,50	0,52	0,49	0,52
St-3	0,54	0,53	0,53	0,52	0,52	0,49	0,54
St-4	0,59	0,58	0,59	0,58	0,54	0,48	0,59
St-5	0,51	0,51	0,53	0,53	0,49	0,40	0,53
St-6	0,57	0,59	0,61	0,62	0,59	0,50	0,62
St-7	0,56	0,61	0,64	0,65	0,62	0,54	0,65
St-8	0,54	0,59	0,64	0,65	0,63	0,27	0,65
St-9	0,51	0,56	0,62	**0,66**	0,63	0,55	0,66
St-10	0,45	0,50	0,56	0,61	0,61	0,56	0,61
St-11	0,45	0,50	0,56	0,61	0,61	0,56	0,61
Max	0,59	0,61	0,64	0,66	0,63	0,56	**0,66**

*annual energy use per floor square meter – kWh/(m^2 annum)

The analysis of the building design optimisation results in the table above shows that the maximum value 0.66 of the goal function is achieved for building variant St-9 with heating set point 21°C.

CONCLUSION

The multi-objectives optimisation with fuzzy sets together with the 6R1C building energy simulations were used to find the optimal building design. The most favourable modification was chosen to achieve the maximum satisfaction of the occupants defined as the lowest energy cost within a range of acceptable thermal comfort. The optimisation has shown that the small residential building "Ekopolis I" designed for flood victims should be very well insulated with external walls insulation thickness about 25 cm, roof insulation thickness 35 cm of rock wool, and 15 cm of slab on grade insulation as XPS (extruded polystyrene) placed entierly beneath the slab. This building should also be equipped with mechanical ventilation including heat recovery of an annual energy efficiency equal to 75%. This heat recovery efficiency can be obtained with high performance heat exchangers supported by air-ground heat exchangers.

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