

# Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools

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## Abstract

The paper deals with an optimization of parameters, which influence the energy and investment cost as well as the thermal comfort. The parameters considered in this study are: the insulation thickness of the building envelope, the supply-water temperature and the heat exchange area of the radiators. A combination of the building energy simulation software *EnergyPlus*<sup>1</sup> and the generic optimization program *GenOpt*<sup>1</sup> has been used for this purpose. The paper presents the application of a one-objective optimization algorithm solving the problems with two objectives, because the optimization algorithm is one-objective and the problem has two objectives, which are minimal total costs and

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satisfied thermal comfort. The total costs represent the sum of energy consumption and the investment costs. The thermal comfort is represented by Predicted Percentage of Dissatisfied (*PPD*) in this study. The optimization is used to determine the values of parameters that give the lowest sum of investment and energy cost, under the condition that the thermal comfort is satisfied. In addition, the optimization processes show the mutual influence of parameters on both the total cost and the thermal comfort.

**Key words:** Building energy optimization, simulation, thermal comfort, hydronic heating.

## **1. Introduction**

The application of simulation and optimization tools for solving a variety of energy management problems in HVAC system or building design problems is shown through works of Wright [1], Fong [2], and Wenjian [3]. The example of insulation optimization in order to minimize the Life-Cycle Cost is shown in [4]. The design of building is a multi-parametric problem with few objectives or constraints. Usually, the objectives and constraints do not have the same physical meaning.

For the rational energy consumption, the analysis of the energy cost considering the thermal comfort is necessary. Building energy analysis is done for a school building with a hydronic heating system. The school building and its heating system is modeled in *EnergyPlus* software by using the weather data for the heating season in Belgrade.

The aim of the study is optimization of several parameters that influence both the total costs in the school building and thermal comfort by use of computer-based tools. The parameters optimized in the study are: the insulation thickness of the building envelope, the supply-water temperature and the heat exchange area of the radiators. In addition, the aim is to show how to proceed with two objectives using the one-objective optimization algorithms. The first objective function for optimization is the total cost that takes into account the energy consumption and the investment cost. The second objective function deals with the resulting thermal comfort. The thermal comfort is represented by Predicted Percentage of Dissatisfied (*PPD*), which is lower if thermal comfort is better.

## **2. Methods**

For the purpose of energy analysis, the software package *EnergyPlus* is connected with the generic optimization program *GenOpt*.

*EnergyPlus* is a building energy simulation program that calculates the building heating and cooling loads and simulates the operation of HVAC systems and central plant equipment. *EnergyPlus* deals with different building data, which include weather data, the building envelope, the geometry of the building, internal loads (occupancies, internal loads, etc.) and the HVAC system. There are other simulation programs such as

BLAST<sup>2</sup> or DOE-2, which are sequential simulation, while *EnergyPlus* is integrated simulation [5].

*GenOpt* is a generic optimization program that must be connected to some simulation program such as SPARK, *EnergyPlus*, TRNSYS or DOE-2, in order to conduct an optimization of parameters from simulation programs [6]. *GenOpt* allows one-parametric and multi-parametric optimization [7].

The coupling of *EnergyPlus* and *GenOpt* is only one example in solving the simulation-optimization problems of energy management in the HVAC systems. The energy management problems could be solved using evolutionary programming as it is done in [2], or using adaptive neuro-fuzzy algorithms as in [3]. In addition, a trade-off problem between investment costs, operating cost and occupant thermal comfort could be solved using the genetic algorithm as in [1]. *GenOpt* is chosen in this study because it is developed for the optimization of the objective function from an external simulation program, such as SPARK, *EnergyPlus*, TRNSYS or DOE-2.

### *2.1. Description of the case study building*

The case study is performed for a school building located in Belgrade. The building consists of 134 rooms. The building envelope is a light construction, with the outside walls made of wood, while the windows and outside doors consist of three-layer glass

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<sup>2</sup> BLAST - Building Loads Analysis and System Thermodynamics.

with air filling. The partition walls are of light concrete, while the inside doors are wooden. A general plan of the first floor of the school building is shown in Fig. 1.

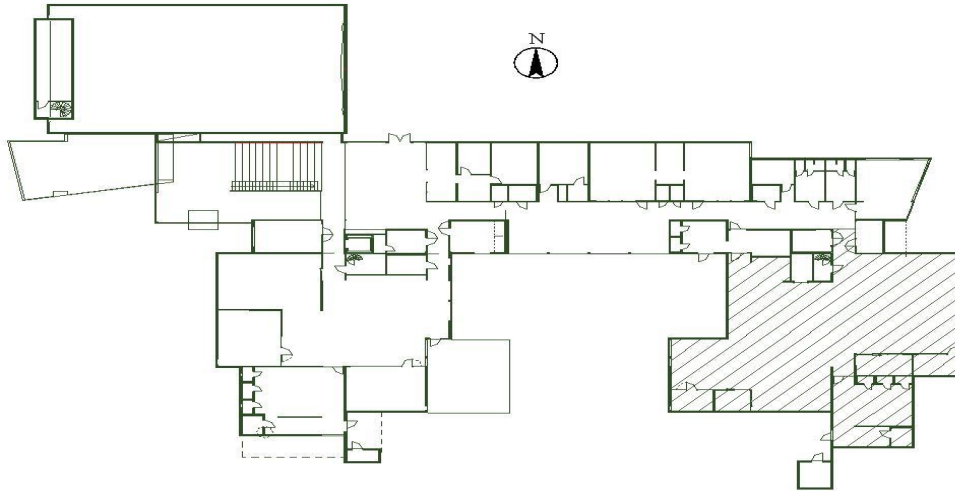


Fig. 1. A general plan of the school building

In Fig. 1 the north orientation is noted by “N”. For hatched zone in Fig.1 (“Class Zone 2” in the below text) the results are given in the below text. The building facade is shown in Fig. 2.

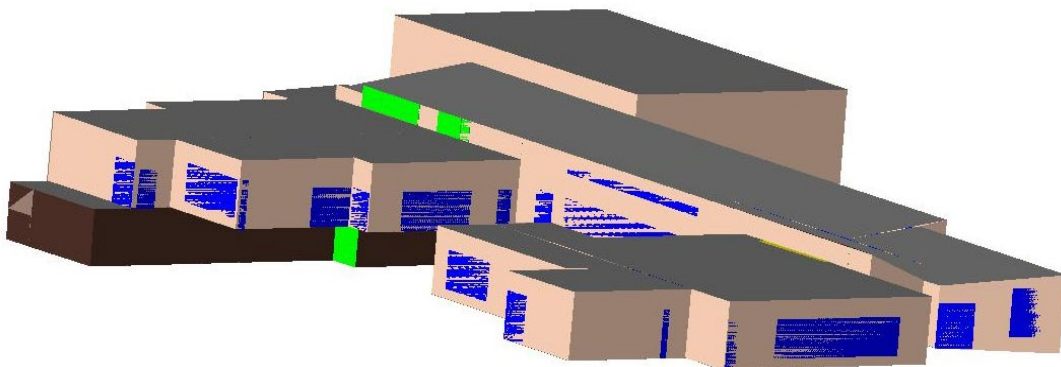


Fig. 2. The school building facade

Weather data for Belgrade, for the year 1995, given by ASHRAE are used in this study [8]. These data imply that the minimal temperature in wintertime is  $-11.5^{\circ}C$  and the maximal temperature in summertime is  $33.4^{\circ}C$ .

For defining the building geometry in *EnergyPlus*, it is necessary to define the zones. The purpose, the orientation and the air-conditioning system of the rooms must be considered in defining the zones. For the given building, 21 zones are identified. After simulations by *EnergyPlus*, using the algorithm for determining the heat loads, the analysis of the results is done. Based on the heat loads, the thermal comfort and considering the most occupied zones, the radiators are proposed for nine zones [9].

## 2.2. Forming the Objective Function

To determine the optimal values of some parameters, it is necessary to define the objective function. The objective function should be defined so that the total cost is the lowest and at the same time the thermal comfort is satisfied. The thermal comfort is represented by *PPD* [10, 11] in this study. *PPD* is calculated using Predicted Mean Vote (*PMV*), which can be obtained easily from *EnergyPlus* as an output. In addition, the *PPD* is convenient for results representation, because the lower the *PPD*, the better the thermal comfort.

*GenOpt* allows that only the first function defined in the initial file can be the objective function to be minimized or maximized. The range of values for optimized parameter is defined in the command file [7]. Considering the command and the initial file, *GenOpt* makes the input for *EnergyPlus*. The objective function and the paths that define the connections between the simulation and the optimization files are defined in the initial file. If there are more functions defined after the first one, they are just calculated for

particular combinations of parameters. This means that if we want to calculate the minimal value of certain function, it should be the first function to be defined in the initial file. However, if we have some constraints (for example: satisfying the thermal comfort, the sum of some parameters should be lower than some given value, etc.), it can be defined as the second function in the initial file. The minimums of these second or third functions are not sought. For solving the above problem, both the total cost and thermal comfort are calculated through the optimization process, but the total cost is the objective function. During the optimization process, the optimization program (*GenOpt*) passes several times through the simulation program (*EnergyPlus*) for the different combinations of the given parameters, calculating the total cost and the thermal comfort for every combination of parameters.

The supply-water temperature is the parameter defined as the schedule type. The option schedule type in *EnergyPlus* is used for defining the parameters that change hour by hour (for example: supply-water temperature, desired indoor temperature, zone occupancy). The optimization, considering the supply-water temperature, is performed in the following way: the optimizations are performed for the insulation thickness of the building envelope and the heat exchange area of the radiators, but with constant supply-water temperature through one optimization. Each optimization is performed for the different values of the supply-water temperature, covering the range from  $35^{\circ}C$  to  $90^{\circ}C$  with steps of  $5^{\circ}C$ . The minimum of the total cost is determined for each value of the supply-water temperature by considering the thermal comfort. After the optimizations are performed, the post-processing of the results is done by analyzing the total cost in the range where  $PPD < 10\%$ . This means that the sizing is done with

boundary values for B class of the thermal comfort based on [12]. The procedure for solving the above problem is given in Fig. 3.

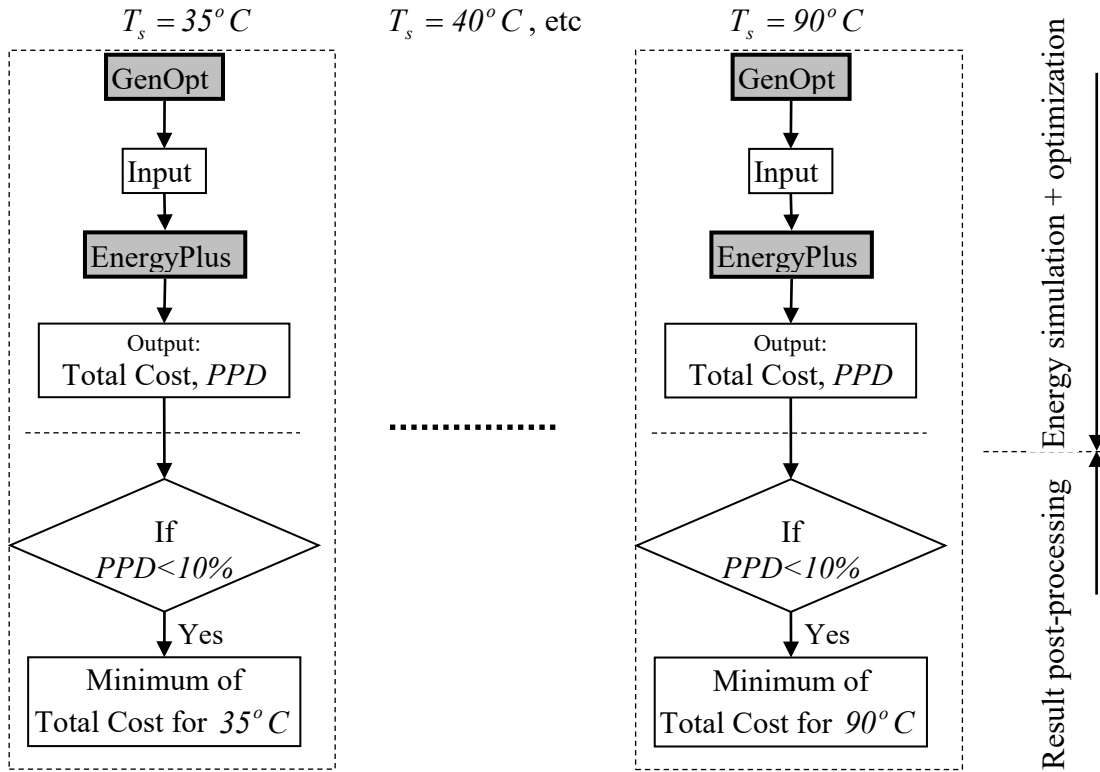


Fig. 3. The information flow between energy simulation and optimization

The objective function for this optimization will be formed as a sum of the energy costs, the insulation cost and the radiator cost:

$$C = C_E + C_I + C_R \quad (1)$$

where  $C$  (€) is the total cost,  $C_E$  (€) is the cost of energy,  $C_I$  (€) is the cost of insulation, and  $C_R$  (€) is the radiator cost.



Since the optimization is performed for the design day, energy cost for the whole season will be calculated by using the degree-day method. It is calculated as in [13]:

$$C_E = \frac{Q_{DD}}{3600 \cdot 1000} \cdot \frac{DD \cdot y \cdot e}{t_i - t_o} \cdot c_E + P \cdot c_P \quad (2)$$

where  $Q_{DD} (J)$  is energy consumption during the design day;  $c_E (\text{€/kWh})$  is the price of energy per kWh, the used value is 0.034 €/kWh given by the “Belgrade Power Plant”;  $P (W)$  is the installed power of heating equipment, (*EnergyPlus* does not calculate the maximum power for certain period of time during performing the optimization and because of that the mean power for design day is used for this optimization);  $c_P (\text{€/kWyear})$  is the annual energy price for kW of installed power equipment (12.42 € for kW per year given by the “Belgrade Power Plant”);  $DD (^\circ C \cdot \text{day})$  is the number of degree-days, which is 2520 for Belgrade, based on [14];  $e(-)$  is the coefficient of limitation, which consists of both coefficient of temperature limitation ( $e_t$ ) and exploitation limitation ( $e_b$ ), adopted values for the coefficient are:  $e_t = 0.75$  based on [14] (table 9.III) and  $e_b = 0.75$  based on [14] (table 9.IV);  $y(-)$  is the coefficient of simultaneous effect of unfavorable conditions, which is 0.6 for normal windy terrain and open terrain situation of building, based on [14];  $t_i (^\circ C)$  is the indoor temperature, in this case  $t_i = 19^\circ C$ ;  $t_o (^\circ C)$  is the outside design temperature which is  $-11.5^\circ C$  for Belgrade, adopted from ASHRAE [8].

The insulation cost is calculated as follows:

$$C_I = 1.4 \frac{A_I \cdot c_I}{n} \quad (3)$$

where  $A_I (m^2)$  is the insulation surface of all outside walls;  $c_I (\text{€/}m^2)$  is the insulation price per unit of surface that depends on the insulation thickness:  $c_I = 0.19 \cdot \delta - 0.15$ , where  $\delta (cm)$  is the insulation thickness;  $n (year)$  is the number of years for purchasing the insulation. In this case  $n$  is 10 years. The additional expense for installation is estimated at 40% of insulation cost.

The radiator cost is as follows:

$$C_R = \frac{c_{R1}}{A_1} \cdot \frac{UA}{U} \cdot \frac{1}{n} \quad (4)$$

where:  $c_{R1} (\text{€/section})$  is the radiator price per one section; adopted in this study is 10.5 €,  $A_1 (m^2)$  is the surface of one section, in this case is  $0.3 m^2$ , adopted from [14] (table 7.III);  $UA (W/K)$  is the radiator characteristic in *EnergyPlus*;  $U = 8W/m^2K$  is the mean value of the overall heat transfer coefficient for radiators, based on data from [14] (table 7.III).  $UA$  value is the optimized parameter in this analysis and it represents the sum of all  $UA$  values from all nine zones. The interest rate and the inflation are not taken into consideration in this analysis [13].

The thermal comfort is calculated by using the Fanger model:

$$PPD = 100 - 95 \cdot \exp(-0.03353PMV^4 - 0.2179PMV^2) \quad (5)$$

where  $PMV$  is predicted mean vote on the Fanger thermal sensation scale.

Nine parameters are set for the heat exchange area of the radiators in each zone with radiators and one parameter is for the insulation thickness of the building envelope. This gives the total number of ten parameters in this study.

### 3. Simulation results

The influence of the supply-water temperature on the indoor temperature and the radiator heat rate during the design day is shown for one of the 21 calculation zones of the school building [9]. The “Class Zone 2” is shown in Fig. 1 by hatch. The desired value of the indoor temperature is  $20^\circ C$  during the occupancy period from 0700 to 1900, while outside of this period it is  $15^\circ C$ . The radiators are in use the entire day.

The influence of the supply-water temperature on the obtained indoor temperature ( $T_z$ ) in the zone during the design day for the insulation thickness of  $9.8\text{ cm}$  is shown in Fig. 4 [13]. In addition, the heat exchange area of the radiators is the same for different supply-water temperature.

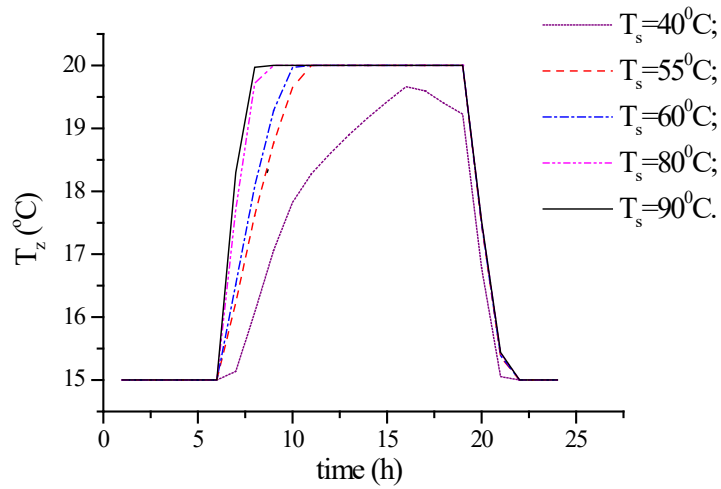


Fig. 4. Influence of the supply-water temperature on the indoor temperature

Fig. 4 shows that the supply-water temperature has influence on the time necessary to reach the desired indoor temperature in the zone. The time diminishes when the supply-water temperature increases. The set point is reached after one hour with the supply-water temperature of  $90^\circ\text{C}$ , while it is not reached at all for the supply-water temperature of  $40^\circ\text{C}$ .

The diurnal variation of the radiator heat rate in “Class Zone 2” for the design day, for different supply-water temperatures and for the insulation thickness of  $9.8\text{ cm}$ , is shown in the Fig. 5.

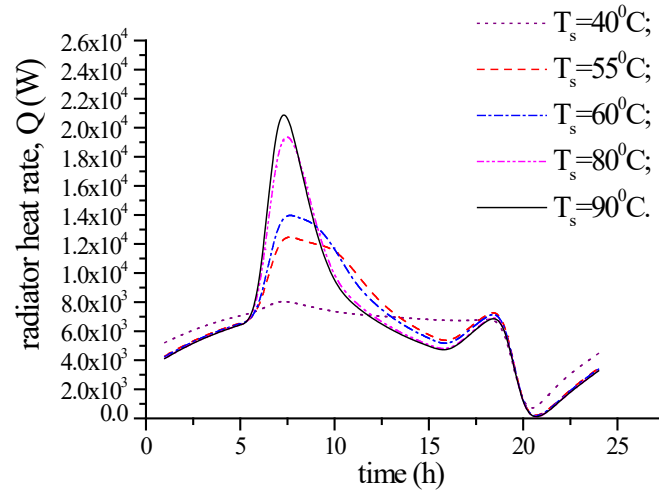


Fig. 5. Influence of the supply-water temperature on the radiator heat rate

The radiator heat rate is the highest during the transition period (at 0700) for the highest supply-water temperature of  $90^\circ\text{C}$ . The heat exchange area of the radiator is oversized for the supply-water temperature of  $90^\circ\text{C}$  and because of that the radiator heat rate is the highest in the transient period. The indoor temperature in the zone is maintained at the desired value during the whole occupancy period for the highest supply-water temperature. In this case, the heat losses are the highest because the indoor temperature is high [13].

#### 4. Optimization results

The optimizations of the insulation thickness of the building envelope and the heat exchange areas of the radiators were done, for constant supply-water temperature, by using the objective function (1). As the number of the optimization parameters is ten, the hybrid algorithm was used as the optimization method. Since the objective function

was the total cost, the optimization algorithm minimized the function (1), while function (5) was calculated for the same combinations of parameters. Twelve optimizations of the insulation thickness and the heat exchange area of the radiators were made for the different values of the supply-water temperature. The optimization results for some values of supply-water temperature are given in Figs. 6a to 6j. The numbers of simulations at each optimization are different, because for the different values of the supply-water temperature, the optimization algorithm converges differently. If the supply-water temperature increases, the optimization algorithm needs more iteration steps to terminate. The figures show the values of the total cost and *PPD* at each simulation. Considering each couple of figures (from Figs. 6a and 6b to Figs. 6i and 6j), the minimum of the total cost can be found for the satisfied thermal comfort.

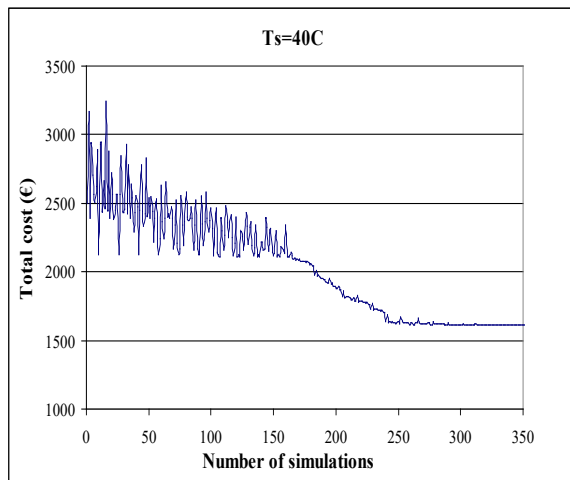


Fig. 6a. Total cost for  $T_s=40^{\circ}\text{C}$

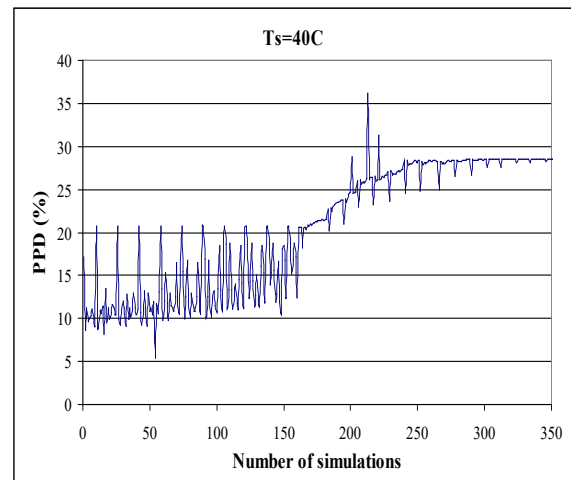


Fig. 6b. PPD for  $T_s=40^{\circ}\text{C}$

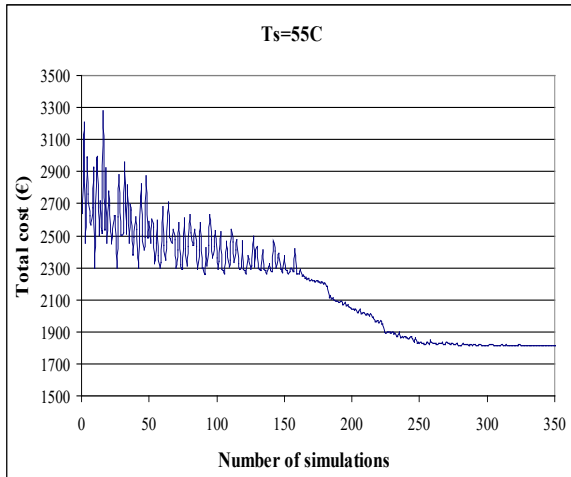


Fig. 6c. Total cost for Ts=55°C

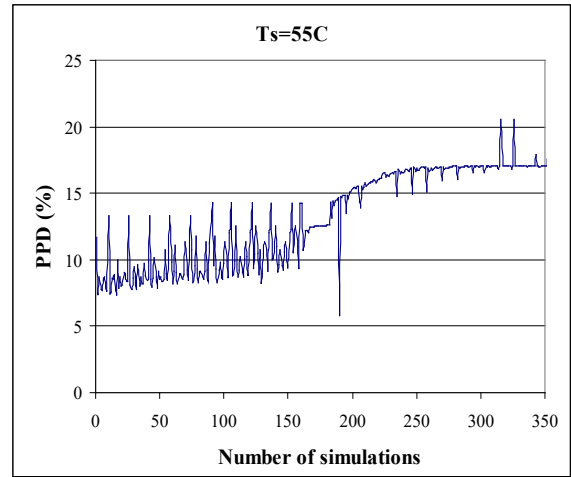


Fig. 6d. PPD for Ts=55°C

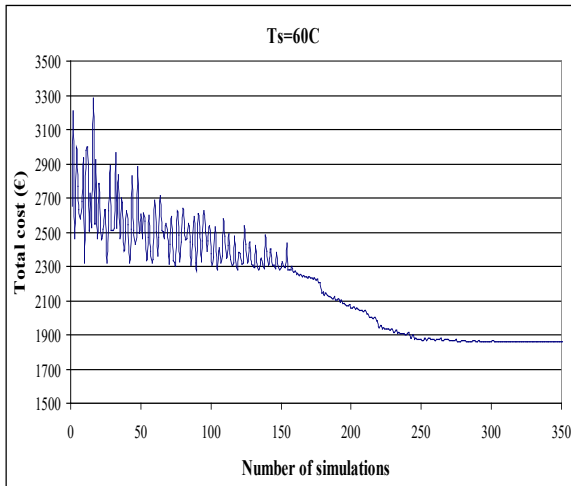


Fig. 6e. Total cost for Ts=60°C

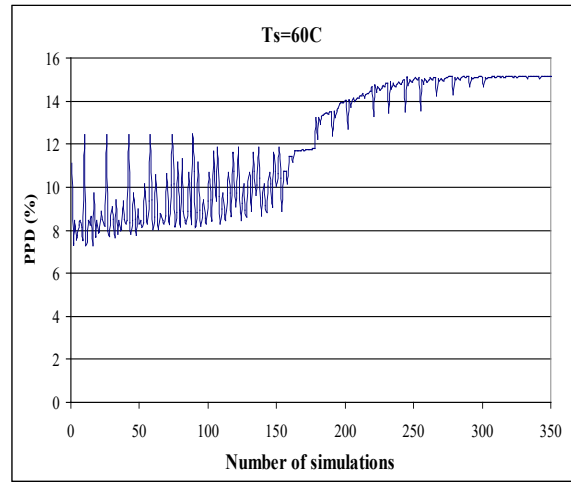


Fig. 6f. PPD for Ts=60°C

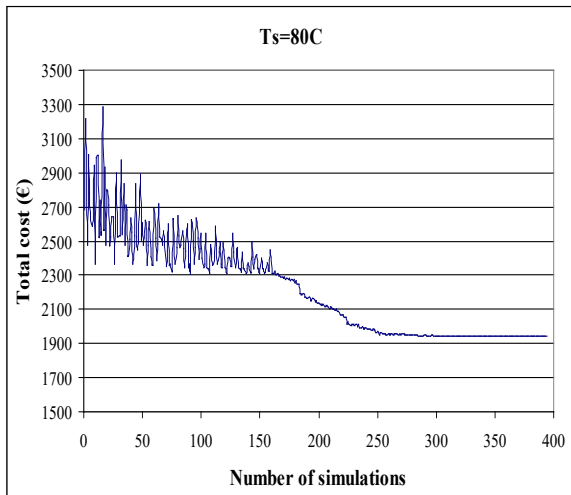


Fig. 6g. Total cost for Ts=80°C

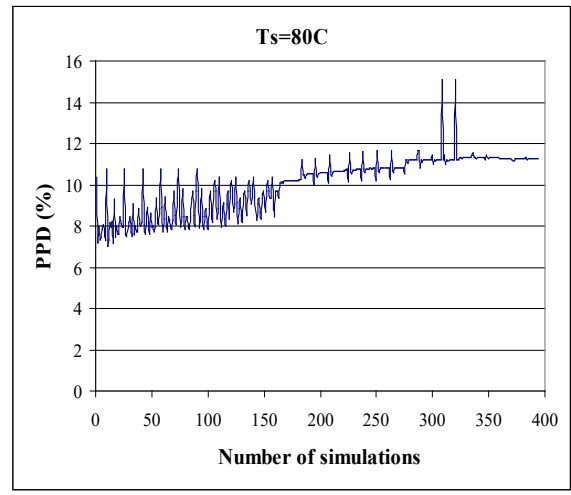


Fig. 6h. PPD for Ts=80°C

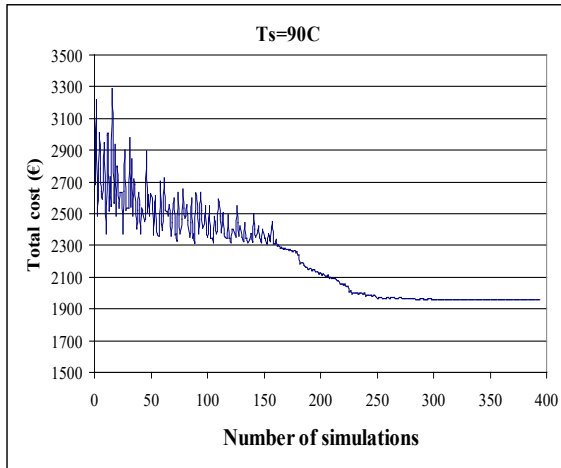


Fig. 6i. Total cost for  $T_s=90^{\circ}\text{C}$

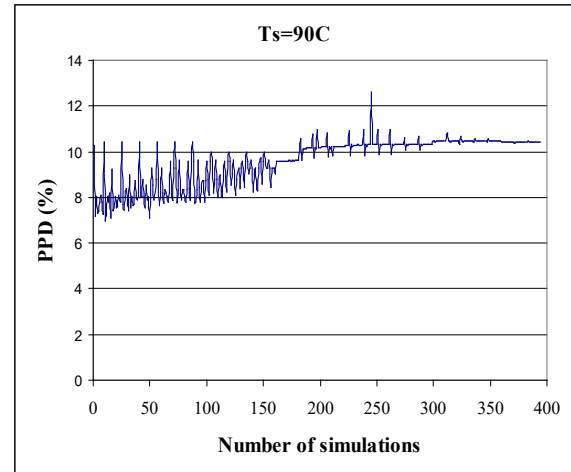


Fig. 6j. PPD for  $T_s=90^{\circ}\text{C}$

For each value of the supply-water temperature, the minimum of total cost was sought, but just for particular simulations, where  $PPD < 10\%$ . This means that for the supply-water temperature of  $60^{\circ}\text{C}$ , the minimum of total cost was sought between the first and the 150<sup>th</sup> simulation, because in that range  $PPD$  occurs to be lower than  $10\%$  (Figs. 6e and 6f). It is necessary to perform each optimization to its end, which includes 350 or 400 simulations in each optimization, but the minimum of total cost was sought only in the range where the thermal comfort is satisfied. After determining the minimum of the total costs for each value of the supply-water temperature in the above explained way, the relations between both the total cost and the supply-water temperature, and the thermal comfort and the supply-water temperature could be established.

The relation between the total cost and the supply-water temperature is shown in Fig. 7 [13].



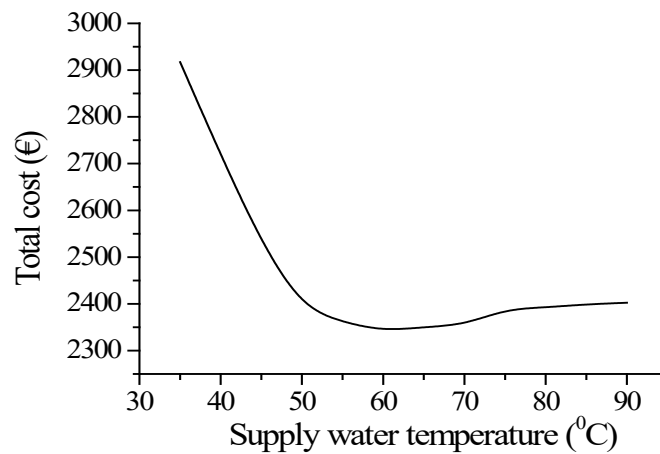


Fig. 7. The relation between the total cost and the supply-water temperature

Fig. 7 shows that the highest total cost can be expected for the lowest supply-water temperature because larger insulation thickness and the heat exchange area of the radiators are necessary. The total cost reaches minimum at the temperature of  $60^{\circ}C$ , for the given conditions. For higher temperatures of the supply-water, the total cost increases because the higher indoor temperature in the zone is maintained for longer period of time, and energy consumption is higher.

The relation between the thermal comfort and the supply-water temperature can be established by using the corresponding values of *PPD* for each value of total cost from Fig. 7. This relation is shown in Fig. 8.

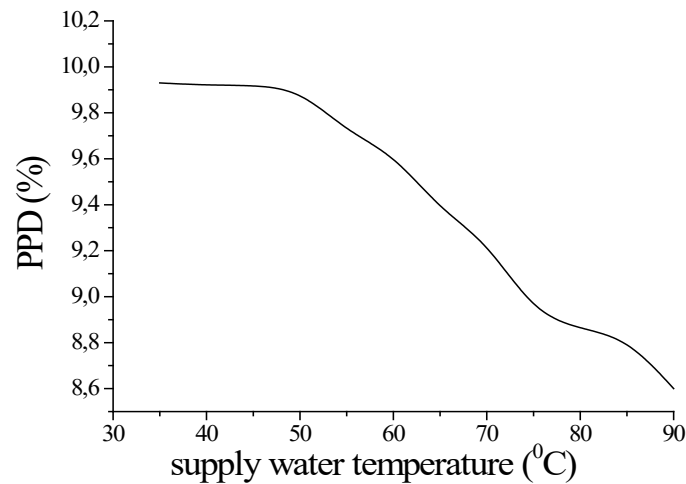


Fig. 8 The relation between the thermal comfort and the supply-water temperature

Fig. 8 shows that the value of *PPD* is satisfied for each value of the supply-water temperature. Consequently the constraint is fulfilled. The thermal comfort is better when the supply-water temperature is higher, because the desired indoor temperature is maintained almost through the entire occupancy period.

## 5. Conclusion

The design of buildings and HVAC systems is a multi-parametric problem with both objectives and constraints. The objectives and constraints usually have different natures. This paper shows how to analyze the problem of two physically different objectives by using one-objective problem and the practical use of mathematical optimization connected to simulation software.

The analysis shows that the supply-water temperature has influence on the time necessary to reach the desired indoor air temperature. In addition, the optimizations show that the highest total cost is expected for the lowest supply-water temperature. The optimization gives the overview of results obtained by the different combinations of parameters. This is useful in choosing the solution to a given problem. The optimization process gives the direction in which the considered parameters have to be chosen considering the objectives and constraints.

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## **REFERENCES**

- [1] Wright J.A., Loosemore H.A., Farmani R., Optimization of building thermal design and control by multi-criterion genetic algorithm, *Energy and Buildings* 34, pp. 959-972, 2002,
- [2] Fong K.F., Hanby V.I., Chow T.T., HVAC system optimization for energy management by evolutionary programming, *Energy and Buildings* 38 (2006) 220-231,
- [3] Lu Lu, Wenjian Cai, Lihua Xie, Shujiang Li, Yeng Chai Soh, HVAC system optimization – in building section, *Energy and Buildings* 37 (2005) 11-22,

- [4] Gustafsson S. I., Optimization of insulation measures on existing buildings, *Energy and Buildings* 33 (2000) 49-55,
- [5] *EnergyPlus*, An In-depth Guide to *EnergyPlus*, Berkeley National Laboratory, 2002,
- [6] Michael Wetter *GenOpt*<sup>®</sup>, A Generic Optimization Program, Seventh International IBPSA Conference, pp. 601-608, Rio de Janeiro, Brazil, 2001,
- [7] Michael Wetter *GenOpt*<sup>®</sup>, Generic Optimization Program, User Manual, Version 2.0.0 β, Berkeley, CA 94720, 2003,
- [8] ASHRAE Weather data, *EnergyPlus Simulation Software*, Weather Data, [www.eere.energy.gov/building/energyplus/weatherdata\\_int.cfm#YUG](http://www.eere.energy.gov/building/energyplus/weatherdata_int.cfm#YUG),
- [9] Đurić N., Optimization of Energy Consumption in Building with Low Temperature Hydronic Heating System, Project assignment, The long-term co-operative project, Master Degree Program: Sustainable Energy and Environment in Serbia, Trondheim, 2003,
- [10] Fanger, P. O., *Thermal Comfort-Analysis and Applications in Environmental Engineering*, Danish Technical Press, Copenhagen, 1970,
- [11] ASHRAE Handbook CD– 1997 fundamentals (ASHRAE, 1997),
- [12] Novaković V., *Energy Efficiency in Buildings*, Compendium for the Training Program at University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia, prepared by Norwegian University of Science and Technology, Trondheim, Norway, 2003,
- [13] Đurić N., Optimization of Energy Consumption in Building with Hydronic Heating System, Master thesis, Faculty of Mechanical Engineering, Belgrade, 2004,
- [14] Todorović B., *Designing the plants for central heating*, Faculty of Mechanical Engineering, Belgrade, 2000