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Simulation models for the analysis of space heat consumption of buildings

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ABSTRACT

This study develops and analyzes an original methodology for the simulation and prediction of space heating energy consumption in buildings connected to a district heating system, characterized by lack of individual control systems for end-users. The identification of the input parameters is based on both classical engineering equations and statistical analysis of collected data. Two main factors play important roles in the model: (i) climate and (ii) human behavior. Model validation was undertaken through the analysis of field data collected during the winter, via a monitoring system working in a partially-controlled district heating system. The comparison between the results obtained with the proposed model versus classical methods points out the possibility to implement, using the proposed methodology, management policies for a district that offer significant cost-effective energy savings opportunities.

1. Introduction

It is estimated that projects promoting energy efficiency at all levels in the European Community could save at least 20% of its present energy consumption in a cost-effective manner, equivalent to 60 billion Euros per year. The annual amount of heat delivered through district heating systems worldwide is about 11 EJ [1]. District heating systems represent well-known technologies and constitute a practice that has been used for many decades in Europe. In some countries, like Denmark, district heating systems are considered to be ethically and thermodynamically the most attractive mode of generating heat [2]. If European district heating sales were doubled, the results would be: (i) higher energy efficiency since the primary energy supply would be reduced by 2.14 EJ/year; (ii) reduced import dependency by 4.45 EJ/year, corresponding to 5.5% of all European primary energy supply; and (iii) lower carbon dioxide emissions corresponding to 9.3% of the total CO_2 emissions from fuel combustion [3].

Major differences exist between district heating systems from Western European countries (designed to be demand-driven) and those from Central and Eastern European countries (designed to be production-driven). In demand-driven systems, consumers use as much heat as they want by means of thermostatic valves and the task of the District Heating Company is to adjust the production accordingly, usually using multiple power plants. In production-driven systems, the District Heating Company produces as much heat as it considers to be appropriate, usually in a single power plant without any feedback from the consumers. When more heat than necessary is supplied, the only way for occupants to decrease the indoor temperature is to open the windows and pay higher bills [4, 5]. The case of less heat supplied than needed is worse, because the thermal comfort diminishes and the agreement with consumers guarantees a minimum indoor temperature. Thus, District Heating Companies generally prefer an oversupply. The result of this policy is well known in Eastern Europe: some consumers disconnect their apartments from the district heating system, even if the building is a block of flats. Therefore, there are fewer paying consumers and a higher production cost per energy unit. As a result, the district heating companies experience financial problems and most of them are currently at risk of collapse. The general consensus is that district heat production according to demand is the best way to have satisfied consumers at the minimum production price. Understanding what factors influence the consumption and the heat demand in the near future are therefore important requirements for a good management.

The issue of predicting energy demand loads was thoroughly studied for electricity networks and many solutions mainly based on time-series analysis models have been identified and implemented [6–8]. Unfortunately, research results cannot be extended to district heating systems. In this case, forecast must be based on

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Nomenclature

A_E	exposed area of the building [m^2]
H	shape factor, $H = A_E/V_i$ [m^{-1}]
Q	building heat consumption [kW]
$\dot{m}_{24h}$	mass flow rate in previous 24 h [m^3/h]
k_i	coefficients of input parameters
R	correlation coefficient
RMS	residual mean square
S	solar radiation [W/m^2]
STE	standard error
T_O	outdoor temperature [°C]
T_i	indoor temperature [°C]
T_{O24h}	outdoor temperature in previous 24 h [°C]
T_S	hot water temperature at the exit from the substation [°C]
V_i	building internal volume [m^3]
w	wind velocity [m/s]
z	ratio of heat load supplied from the DHS to total heat consumption [%]

specific models for the production unit, substations, pipeline network and buildings, each of them quite complicated [9–12]. Review of the current technical literature shows that previous works on these topics refers to Western European district heating systems, which are completely controlled and highly monitored.

The aim of this paper is to develop and analyze some soft computing methods for the simulation and prognosis of space heating energy consumption of buildings connected to partially-controlled district heating systems. A detailed model of heat consumption in buildings is hardly meaningful and not possible without measurements. The study investigates how different statistical models perform in terms of past heat demand measured in buildings and proposes a new model to be implemented in a computer program to predict future heat consumption in the context of climate forecast. The presented technique may be used either to develop more realistic production plans according to demand [13], or as a computer subprogram which may be included in more sophisticated software for heat load control [14]. Statistical analysis and artificial neural networks modeling allow for double cross validation of the model. Experimental data used in this study was extracted from the database of the monitoring system implemented by the District Heating Company of the city of Iasi (Romania).

2. Simulation modeling of consumption

2.1. Theoretical basis and numerical simulation

Approaches to calculate the space heating demand may be classified into two categories. The first category focuses on the

Table 1
Models studied in the present paper. Results for building A.

	Model's equation	R	RMS
M1	$Q = k_1 + k_2T_o$	0.8116	42.4298
M2	$Q = k_1 + k_2T_o + k_3(T_i - T_o)w^{4/3} - k_4S$	0.8218	40.3574
	$Q = k_1 + k_2T_o + k_3(T_i - T_o)w^{4/3} - k_4S + k_5T_{o24h}$	0.8401	36.5778
	$Q = k_1 + k_2T_o + k_3(T_i - T_o)w^{4/3} - k_4S + k_5T_{o24h} + k_6\dot{m}_{24h}^{4/5}$	0.9211	18.8535
M3	$Q = k_1 + k_2T_o + k_3(T_i - T_o)w^{4/3} - k_4S + k_5T_{o24h} + k_6\dot{m}_{24h}^{4/5} + k_7T_S$	0.9823	4.3548

Table 2
Specific set of coefficients for building A.

	$k1$	$k2$	$k3$	$k4$	$k5$	$k6$	$k7$
M1	46.8733	−1.9725	–	–	–	–	–
M2	45.4329	−1.9328	0.0069	−0.0150	–	–	–
M3	−33.5635	−0.1117	−0.0068	−0.0049	−0.1932	0.0785	1.3667

nominal heat load based on thermal causes for heat losses through the building envelope. The second category models the real consumption based on the analysis of acquired data collected by a monitoring system.

The calculated nominal heat load is useful for the design stage of the building in order to establish the best options in terms of heating equipment. The quantity of heat load for a prescribed level of thermal comfort depends on the building characteristics and the climate parameters. The most significant parameters to be taken into consideration are expected to be: heat loss through the building envelope by transmission, heat losses by natural and forced ventilation and infiltration, solar heat gain through windows and passive solar installations, internal gain by electrical apparatus, number and ages of occupants, etc [15]. This approach is used by software such as DOE-2, EnergyPlus, ESP-r, IDA, TRNSYS, Bsim2000, BLAST, BDA [16–18].

District Heating Companies do not have information about the architectural features or the construction materials of each building, therefore prediction of heat consumption must be done by using different methods. Moreover, practice shows that real heat consumption is very different from nominal heat load. First, inhabitants may have different opinions about what thermal comfort means, so different indoor temperatures may be preferred by different occupants. Second, in Eastern European countries in the same block of flats, some households are disconnected from the district heating system while other owners have made investments in better insulation of their apartments or rooms. In this case, the only way to have a realistic view of the quantity of heat to be supplied by the district heating system is through ongoing surveys or monitoring of the factors affecting consumption. Modeling of the real space heating consumption can only be based on the analysis of acquired data.

There are several computer programs that have been designed for district heating systems such as CONDOR, EcNetz, RNET, SYSTEM RORNET, TERMIS, BoFiT, ANSYS, DH SIM that can predict space heating consumption using prior data [19]. The procedure for modeling heat consumptions must depend on the terms of prognosis, considering that the shorter is the period of forecasting the higher is the accuracy needed. Various solutions for medium-term and short-term simulation using seasonal operation hours, timetable of the heating service distribution [20], or social behavior of the consumers [21] are presented in the scientific literature. Artificial neural networks analysis represents an alternative. The approach of Beausoleil-Morrison and Krarti uses a multilayer forward – feed neural network with a back-propagation learning algorithm [22] and leads to very good results.

Unlike Western European countries, the majority of buildings in Eastern European countries that are connected to district heating systems lack controlling devices. Therefore it is difficult to use one of the above mentioned software packages as they are based on the assumption that the district heating system is fully automatic. In recent years, efforts have been made in Eastern European countries to move towards more efficient operation: thermostatic valves were installed on some radiators, control loops were added to a few substations, and monitoring SCADA systems were partially implemented. Thus, nowadays some district heating systems in Eastern European countries may be considered partially modernized. The