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Model of Steam Consumption in Central Heat Transfer Network

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Introduction

Currently, as the non-renewable resources are running short, new sources of energy such as solar power plants are being investigated. Another attitude is to activate current sources and try to increase their efficiency not only from the producer's viewpoint. One very promising area seems to be represented by the heat stations. In Europe, thousands of heat stations can be found – most of urban areas have at least one supplier. The primary objective of these facilities is to produce thermal energy, but all of them are equipped with turbines and generators to produce electric energy.

Even if the output of a heat station can hardly be compared to a classic power plant, owing to the total number of these facilities in Europe, their importance as a source of electric energy may compete with any of alternative resources.

However, as long as the production of electric energy is not the main sphere of action of heat stations, the amount of produced electric energy depends strongly on the amount of steam consumption in the central heat transfer networks supplied by these facilities. Therefore, a predictive model of such consumption would be very useful tool, because it could be helpful to predict the amount of electric energy produced by back-pressure turbines as well as to plan the steam production and the use of condensing steam turbine. As a result, the costs caused by varying production volume could be reduced.

A semi-empiric model predicting the consumption in a medium-sized central heat transfer network has been successfully developed and tested in our research centre over the last two years. The results of the work conducted in this period are presented in this article. The first part of this article describes typical groups of consumers in a medium-sized central heat transfer network. This part is followed by an introduction of the model derived from the structure of consumers. This model is universal and can be (with help of some estimation data set) simply adapted to any specific heat station. Finally, the model is applied to a particular heat station and it is verified with help of a validation data set.

Brief Description of Consumers' Structure

Thermal energy produced by a medium-sized heat station is in general distributed among three groups of consumers – heating of building objects, water heating and consumption of technological processes. In addition, some of the energy is spent to cover losses. This is schematically displayed in Fig. 1. The specifics of each group are explained in the following paragraphs.

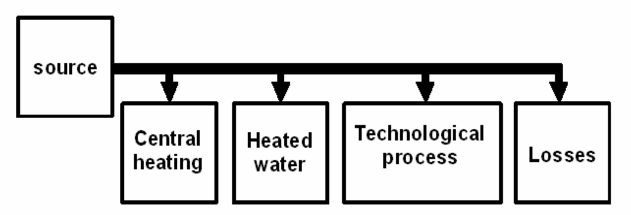

Fig. 1. The structure of consumers

Heating of Building Objects

This part of energy is used to cover the thermal losses of buildings caused by heat transmission through walls and by ventilation. Currently, almost all buildings are regulated to keep constant indoor temperature. Therefore, the heat consumption correlates with the outdoor temperature.

Water Heating

In this case, the energy is consumed to cover the citizens' demands on hot water. Reasons for this demand are the sanitation needs of consumers. As a result, this consumption is independent on outdoor temperature, but it is a seasonal variable depending among other things on the structure of citizens and their employment. Even if many small consumers heat the water randomly during a day, from the producer's point of view, the consumption has a statistical distribution in time as the number of consumers in an urban area exceeds thousands.

Technological Processes

Many processes require thermal energy. Their consumption depends strongly on the concept of the production. One- and two-shift productions require a periodic distribution of thermal energy, continual-production requires a constant distribution.

Losses

The distribution of thermal energy is impossible without losses. The energy spent to cover losses can be divided in three groups. The first and second type is heat penetration through the isolation of the transport pipe-lines. The first type is describing the effect of temperature difference of the transfer medium and the outdoor environment and by the quality of isolation. Owing to this, this component depends strongly on the outdoor temperature. The second type of losses is describing the effect of fluctuating velocity of the medium. In the case of the flow under the optimal level the temperature of the medium declines. On the other hand, in the case of the flow over the optimal level the steam pressure declines. The pipe-lines must be designed for the winter part of the year and as a result, this component of the losses rises in the summer period. This component of losses correlates strongly with the velocity of the transfer medium, derived from the actual consumption. The last component of losses is a random component caused by failures of the distribution network. This component can not be described by the model.

All three components act together and their importance oscillates in time. However, in order to keep the simplicity of the model, losses were neglected whereas they become part of other components in the model.

Theoretical Hypothesis of the Model

The distributed thermal energy covers all types of consumption mentioned in the previous part of this article. Therefore, the temporal behavior of the consumption can be approximated by the function presented in Fig. 2. It is a bathtub-shaped time function.

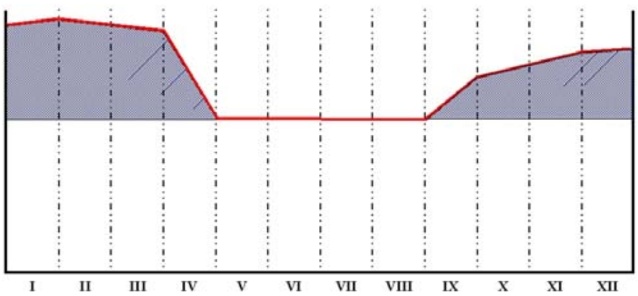

Fig. 2. Simplified consumption over the period of a year

This function can be analyzed by means of time series analysis, which is presented e.g. in [1] or [2]. In general, the consumption can be described by any model used by the theory of system identification e.g. ARX, ARMAX, Box-Jenkins etc. However, in our previous research a semi-empiric model based on the division into components that can be assigned to the groups of consumers was successfully applied. This model was chosen for the analysis, because its results seem to be as good as the results of other models, but its simplicity makes it easy to implement to the real-time production control system.

In the beginning, the consumption was according to the theory of time series analysis divided in three components – trend component $T(t)$, seasonal component $S(t)$ and random component $e(t)$. The division can be additive as well as multiplicative. In our case, the additive division was chosen, because the assignment to the consumers' types is more obvious and the results can be easier interpreted in the physical sense.

$$F(t) = T(t) + S(t) + e(t). \quad (1)$$

The description by formula (1) was refined so that the specifics of central heat transfer networks were included and the residuals of the model were minimized. As it was already mentioned, the distributed energy is used to heat buildings, to heat water and to cover demands of technological processes and to cover losses. Using the hypothesis from the previous part of the article, a significant part of the energy consumption correlates with the outdoor temperature. This is the trend component. The seasonal consumption described by the seasonal component of the model is in fact described by two components with different periods – day and week. These periods are derived from the general production concepts. Moreover, the seasonal component with period of one day differs in the case of weekday and weekend. This results from the different behavior of some citizens during the week. Finally, the model will besides the random component contain a basic component. This component will describe the consumption of continual production as well as losses unmapped by other components. Owing to this, the formula (1) was turned in to a new form.

$$F(t) = T(t) + S_{dd}(t) + S_{de}(t) + S_w(t) + B(t) + e(t), \quad (2)$$

where

$T(t)$ is the trend component dependent on outdoor temperature;

$S_{dd}(t)$ is the seasonal component with period of one day describing workdays ($S_{dd}(t) = 0$ on weekends);

$S_{de}(t)$ is the seasonal component with period of one day describing weekends ($S_{de}(t) = 0$ on workdays);

$S_w(t)$ is the seasonal component with period of one week;

$B(t)$ is the basic component;

$e(t)$ is the random component.

Decomposition in Separate Components

According to the theory of time series analysis (e.g. [2]), the analysis must begin with detrending. As the trend component is removed, the search for seasonal components may begin. Finally, the basic component can be determined. Even if the model alone is quite simple, all the decomposition algorithms calculating the exact coefficients for a specific producer must be able to deal with huge quantity of estimation data (over million values) and therefore an implementation of these algorithms in MATLAB environment was selected.

Detrending

The trend component depends strongly on the outdoor temperature. With decreasing temperature, the consumption increases and vice versa. Therefore the outdoor temperature $\zeta(t)$was transformed in a temperature function $\theta(t)$ according to formula (3):

$$\theta(t) = \mathrm{C} - \zeta(t). \qquad (3)$$

Coefficient C [°C] is a decision level for the beginning of heating in buildings. In Czech Republic, this level is 13°C. If a average temperature over last few days exceeds this level the heating in buildings is turned off. As long as the values of function $\theta(t)$ are positive, it can be expected that the thermal energy will be distributed for the purposes of heating in buildings. Therefore, the total consumption will be strongly influenced by the temperature function $\theta(t)$. This trend component is displayed as the hatched area in Fig. 2. The trend component is calculated with help of regression analysis. The detrending algorithm uses the decomposition of the Vandermonde matrix. Finally, we obtain the distributed amount of transfer medium as a polynomial function of temperature function $\theta(t)$. Different estimation data sets from several producers were tested and it was concluded that a linear function describes the trend component with satisfactory accuracy.

Searching for the Seasonal Components

Generally, the search for seasonal components may be based on different methods – e.g. regression analysis, Winters' Method etc. However, in our case there are three seasonal components - $S_{dd}(t)$, $S_{de}(t)$ and $S_{w}(t)$. The specific nature of $S_{dd}(t)$, $S_{de}(t)$ required methods allowing different seasonal component for weekends and workdays. Owing to this, the method based on averaging over time intervals of different lengths described in [2] was selected:

$$S(t) = \frac{1}{I} \sum_{\tau \in T} \alpha_\tau x_\tau \ , \qquad (4)$$

where $\alpha_\tau = 1$ if $\tau = t + kL$, else $\alpha_\tau = 0$;
x_τ is the value of time series in time τ;
I is number of available intervals for given t;
L is the length of interval been described;
T is the whole range in which x_τ data are available.

The procedure of searching for seasonal components must be an iterative process. In the first phase, the components with period of one day are calculated and subtracted from the detrended function. Secondly, the component with the period of one week is calculated and subtracted.

Searching for the Basic Component

If the trend component and the seasonal components are removed, the obtained function represents the basic component and the random component. The random component is expected to be white noise and it is removed by averaging. The mean value can be understood as a result of digital low-pass filtering.

Application of the Model on a Real System

The above presented model was tested on real system so that its validity can be proved. The observed real system was the central heat transfer network in the town Ústí nad Labem. This town is supplied by thermal energy from the heat station run by company Dalkia a.s., division Ústí nad Labem. This heat station produces steam using 6 boilers with total output approx. 470 MWt and 5 turbogenerators for the production of electric energy with total output 88 MWe. Primary steam pipe-lines with total length of 110 km serves for approx. 1,300 supply points representing approx. 26,800 households and most of the industrial facilities in the town. The data set used was measured in the period over years 2005 and 2006. The data from 2005 were used as an estimation data set and the validity of the model was tested on data from January to May 2006. The data are collected by a network of measurement devices in different locations with intervals of 5 minutes.

Model parameters

The trend component was determined as mentioned above. Following linear formula was obtained

$$C(t) = 98{,}03 + 9{,}08\ \theta(t)\ [\mathrm{t/h};\ °\mathrm{C}], \qquad (5)$$

where $C(t)$ represents the total consumption in the network.

The temperature function $\theta(t)$ for the validation data-set is displayed in Fig. 3.

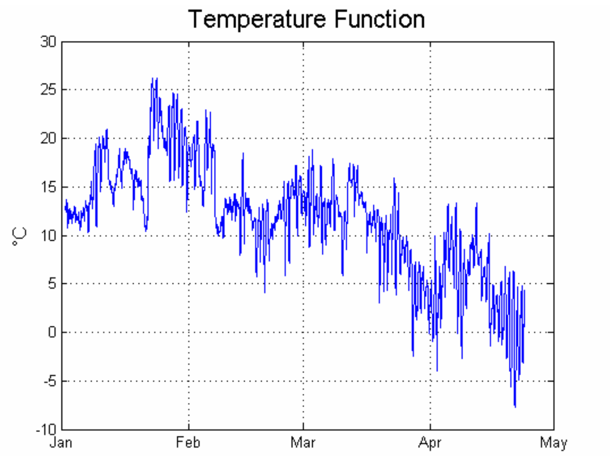

Fig. 3. Temperature function

The trend component can be easily determined as follows

$$T(t) = 9{,}08\ \theta(t)\ [\mathrm{t/h};\ °\mathrm{C}]. \qquad (6)$$

Since the data was detrended the seasonal components could be calculated. These components are presented in the Fig. 4–6. The seasonal component with period of one day describing the workdays is in Fig. 4. Fig. 5 displays the consumption in weekends and finally Fig. 6 represents the seasonal component over one week.

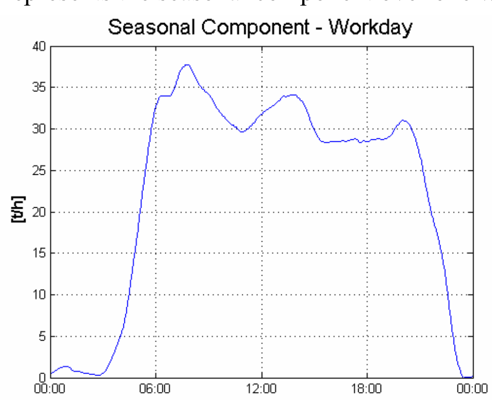

Fig. 4. Seasonal component – workday

Finally, the basic component was calculated. Its value was calculated as $B(t)$ = 60 t/h. The data set estimated according to the model was compared with the real consumption. This comparison is presented in Fig. 7.

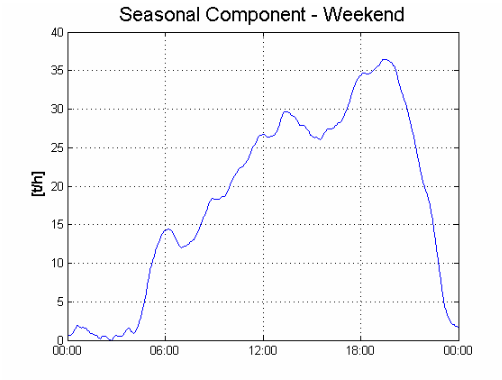

Fig. 5. Seasonal component - weekday

This figure proves that the model describes the real consumption with a satisfactory precision. Generally, the relative difference in 90% of cases does not exceed the level of 5%. The level of 10% is fulfilled in 95% of all cases.

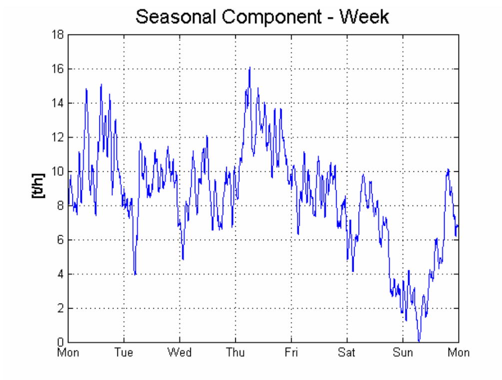

Fig. 6. Seasonal component - week

Conclusions

This article presents a semi-empiric model of consumption in a central heat transfer network. This model can be used to predict the consumption in the network. Such a prediction is an important for the producer, who can profit from it because of better planning of his production. Moreover, the producer can also use the model to predict the amount of produced electric energy. Ultimately, the model should save the operational cost of a medium-sized heat station.

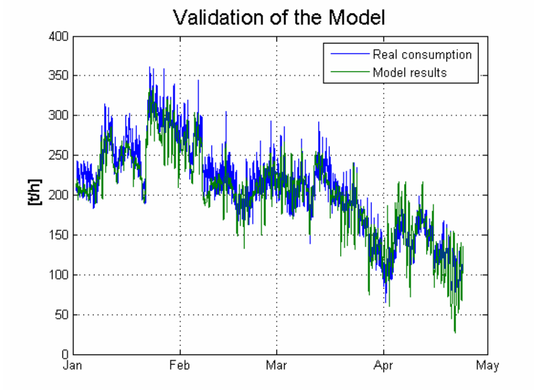

Fig. 7. Validation of the model

The model presented in this article has a general validity and only its coefficients must be calculated, if a specific network should be described. The coefficients for a network supplying the town Ústí nad Labem in Czech Republic were introduced and the very good match between the real consumption and the predicted consumption was shown as well.

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J. Šípal. Model of Steam Consumption in Central Heat Transfer Network // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 1(73) – P. 33–36.

A semi-empiric mathematical model capable to predict future consumption of heat energy in a central heat transfer network is presented. This prediction is important for producers, because it can help to save operational costs of a heat station and it can improve the efficiency of electrical energy production. This model is applied on real heat stations and a good match with real data is obtained. Ill. 7, bibl. 4 (in English; summaries in English, Russian and Lithuanian).

Я. Шипал. Модель потребления пара в центральной сети теплопередачи // Электроника и электротехника. – Каунас: Технология, 2007. – № 1(73). – С. 33–36.

Представлена полуэмпирическая модель, на основе которой возможно прогнозировать потребление тепловой энергии в центральной сети теплопередачи в будущем. Такое прогнозирование важно для производителей, так как позволяет уменьшить эксплуатационные расходы тепловой станции и увеличить эффективность производства электрической энергии. Ил. 7, библ. 4 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Šípal. Garo suvartojimo centriniame šilumos perdavimo tinkle modelis // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 1(73). – P. 33–36.

Pristatytas pusiau empirinis matematinis modelis, kuriuo remiantis galima prognozuoti ateities šilumos energijos suvartojimą centriniame šilumos perdavimo tinkle. Toks prognozavimas svarbus gamintojams, nes taip galima sumažinti šiluminės stoties eksploatacijos išlaidas bei padidinti elektros energijos gamybos efektyvumą. Il. 7, bibl. 4 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).