CONTROL OF SUPPLY TEMPERATURE IN DISTRICT HEATING SYSTEMS

T.S. Nielsen, H. Madsen
Informatics and Mathematical Modelling,
The Technical University of Denmark,
DK-2800 Lyngby, Denmark
Tel: +45 4525 3428, Fax: +45 4588 2673, E-mail: tsn@imm.dtu.dk

ABSTRACT The paper describes a concept for controlling the supply temperature in district heating systems using stochastic modelling, prediction and control. The controller minimizes the supply temperature under the restriction that the consumer requirements to inlet temperature are fulfilled and that the flow rate in the system is kept within acceptable limits. The controller is implemented as a set of sub-controllers which operates the system as close to the minimum supply temperature as possible and such that the probability of violating the restrictions is small. The proposed controller has been implemented in a software package - PRESS - which are used operationally at Roskilde Varmeforsyning. The results obtained for the Roskilde district heating utility are evaluated with respect to obtained savings as well as to security of supply.

1 Introduction

District heating plays an important part in covering the heating demands in the Nordic countries, hence the subject of optimal operation of district heating systems has a huge economical potential. This is by no means a trivial subject though, as district heating systems are inherently non-linear and non-stationary, and the issue is further complicated by the fact, that district heating systems are very diverse with respect to production facilities, operational requirements and so forth.

A district heating system can be seen as consisting of three primary parts: one or more central heat producing units, a distribution network and finally the consumer installations for space heating and hot tap water production. The heat production units and the distribution network are often owned by different utilities, thus it makes economic sense from a company point of view to optimize the operation of heat production units and distribution network separately.

Traditionally supply temperature in a district heating system is determined without any feedback from the distribution network. Thus the supply temperature control is in fact an open loop control, and the supply temperature has to be determined conservatively to ensure a sufficiently high temperature in the district heating network at all times.

This paper considers optimal operation of the distribution network and it is argued that optimal operation is achieved by minimizing network supply temperature under certain restrictions. The proposed control scheme has two objectives. First of all it optimizes the operation of the distribution network with respect to operational costs. Secondly it brings the supply temperature control into a closed loop context thereby making the control a more objective matter compared to the traditional ad hoc approach.

The paper is organized as follows. Section 2 describes the control objectives and restrictions and the control criterion is derived. Hereafter the controller implementation is described in Section 3. In Section 4 the results obtained for Roskilde Varmeforsyning are evaluated, and finally some conclusions are made in Section 5.

2 Control problem

The objectives of the present section is to identify the main conditions under which an optimization of the operational costs for a distribution system is carried out. The operational costs are separated into heating and distribution costs.

For a time interval, $]t-1,t]$ indexed t, the integrated energy balance for the distribution network can be formulated as

$$E_t^{supply} = E_t^{loss} + E_t^{cons} + \bigtriangledown E_t^{netw} \qquad (1)$$

where E_t^{supply} is the energy feed into the network at the supply points, E_t^{loss} is the energy loss in the network, E_t^{cons} is the energy delivered to the consumers, and $\bigtriangledown E_t^{netw}$ is the energy accumulated in the network. The use of an external energy storage – a heat accumulator – is not included in (1) as heat accumulators typically are part of the production system. Any redistributions of heat load within the distribution system must rely on energy storage in the distribution network, which is useful for smoothing of peak loads, but normally does not allow larger rescheduling of heat load.

Following (1) and disregarding energy storage in the distribution network the accumulated heating costs C^{heat} over a period T can be written as

$$C^{heat} = \sum_T (E_t^{loss} + E_t^{cons}) * P_t \tag{2}$$

where P_t is the cost per unit energy during time interval t. In (2) only E_t^{loss} and for some systems P_t is controllable whereas E_t^{cons} is given.

The heat loss in the network is a (complex) function of the supply temperature, but experience shows that down to a certain limit a decrease in supply temperature implies a lower temperature in the network in general and consequently a decrease in the heat loss from the network. Below the limit the return temperature will increase with decreasing supply temperature (see e.g. Figure 5).

P_t will for some systems be fixed but for other systems increasing levels for supply and return temperature and peak load will imply a higher price per unit energy.

The distribution costs are dominated by the cost of the electricity consumption for the pumps in the distribution network. The supply temperature has direct impact on the pumping costs as flow rate and thus pumping costs will increase with decreasing supply temperature. For most district heating utilities in Denmark the pumping costs are an order of magnitude less than the energy costs associated with the heat loss in the distribution network – hence pumping costs are left out of the optimization. It should be noted though, that an optimization of the pumping strategy may be carried out independent of the control strategy proposed in the following.

The optimization of production cost is carried out under restrictions imposed by the distribution network and consumer installations. The restrictions are mainly due to a maximum limit on the flow rate as well as requirements to a minimum inlet temperature at the consumers installations. Both of these restrictions can be fulfilled by maintaining a sufficiently high supply temperature.

The operation of a district heating utility has a direct impact on the maintenance costs for the network. Large and frequent variations in supply temperature (and pressure) will increase the maintenance costs compared to a more steady operation, hence large and frequent fluctuations in the supply temperature should be avoided.

Based on the above considerations the operational costs of the distribution network can be optimized by minimizing the supply temperature under the restriction that flow rate, consumer inlet temperatures and variations of supply temperature are kept within acceptable bounds.

It is here assumed that diurnal peak load and return temperature are not adversely affected by the optimization.

3 Controller implementation

In the following a control scheme for optimal operation of a certain class of distribution networks is proposed; namely distribution networks which primarily are supplied from a single supply point. The optimization is implemented as a set of controllers, which operates the system as close to the minimum supply temperature as possible without actually violating the restrictions. The flow rate is monitored by a single controller whereas the consumer inlet temperature is monitored by introducing a set of *critical points* in the distribution network. The critical points are selected so that if the temperature requirements for the critical points are satisfied then the temperature requirements for all consumers are satisfied. Thus, as illustrated in Figure 1, the control system consists of a flow controller and a net-point temperature controller for each critical net-point. At a given time the supply temperature implemented is then selected as the maximum of the recommended supply temperatures from the individual controllers. The sub-controller determining the supply temperature at a given time is called the *active* controller.

The restrictions on the variability of supply temperature are fulfilled by a tuning of the controller design parameters in the flow rate and net-point temperature controllers.

The controller implements a number of additional features:

- Rate of change for supply temperature is restricted. In Roskilde $\bigtriangledown T_s^{max} = 1.5$°C.
- Minimum and maximum values for supply temperature. In Roskilde $T_s^{min} = 70.0$°C and $T_s^{max} = 95.0$°C.
- Diurnal increase for supply temperature in order

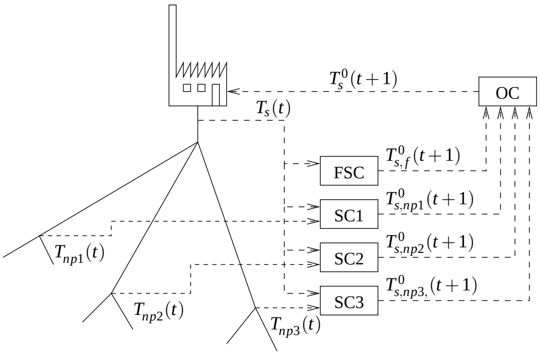

Figure 1: Overview of a district heating network, with 3 critical points and the controllers. OC is the overall controller, FSC is the flow sub-controller, SC# are the supply temperature sub-controllers, $T_{np\#}$ are the supply temperatures in the network, T_s is the supply temperature from the plant, and $T_{s,\#}^0$ are the supply temperatures required by the sub-controllers.

> to reduce peak loads. In Roskilde T_s is increased with 2.0°C from 05:00 to 08:00 in the morning.

The dynamic relationships between supply temperature and flow rate and net-point temperatures are time-varying and difficult to establish due to the time-varying heat load in the system. Hence the control problem calls for methods, which will operate reliable under these circumstances. The flow and net-point temperature controllers are described in Section 3.1 and 3.2, respectively, whereas the subject of determining reference values for controllers monitoring restrictions are referred to Section 3.3.

3.1 Net-point temperature sub-controller

The net-point temperature controller depends on a model describing the dynamic relationship between supply temperature and net-point temperature(s). Due to the changing heat load this relationship exhibits a diurnal as well as an annual variation. In (Søgaard 1988) a stochastic model describing the relationship between (hourly) observations of supply and net-point temperatures is identified. The model is given as

$$\begin{aligned} A_t(q^{-1})T_{np,t} &= B_t^1(q^{-1})T_{s,t} + \\ & \quad B_t^2(q^{-1})\cos\frac{2\pi t}{24}T_{s,t} + \\ & \quad B_t^3(q^{-1})\sin\frac{2\pi t}{24}T_{s,t} + e_t \qquad (3) \\ A_t(q^{-1}) &= 1 + a_t^1 q^{-1} \\ B_t^i(q^{-1}) &= q^{-\tau}(b_t^{0,i} + b_t^{1,i}q^{-1} + b_t^{2,i}q^{-2}) \end{aligned}$$

where T_t^s and T_t^{np} are supply temperature and net-point temperature given at time t, respectively, q^{-1} is the back-shift operator, a_t^1 and $b_t^{0..2,1..3}$ are time-varying model parameters and τ is a time delay. The diurnal variation in the system dynamics is incorporated directly in the model, whereas the slow drift in the model parameters caused by the annual changes are accommodated by estimating the model parameters adaptively using a Recursive Least-Squares algorithm. The model formulated in (3) is a 1-step prediction model, where j-step predictions are obtained by recursive use of the 1-step prediction model.

The time delay specified in the model is time-varying and has to be estimated. Here the time delay is determined using a scheme based on maximizing the cross correlation between the supply and net-point temperature time series. More details are found in (Madsen, Nielsen & Søgaard 1996).

The model (3) gives raise to a number of requirements on the net-point temperature controller. It must be robust toward non-minimum face system (due to the possibility of wrongly specified time delays in the model) as well as being capable of handling time-varying systems. The controller should also be reasonably easy and robust to derive since the controller parameters are likely to change hourly as the model parameters are updated. The net-point temperature control is based on the Extended Generalized Predictive Controller (XGPC) proposed in (Palsson, Madsen & Søgaard 1994), which is a further development of the Generalized Predictive Controller (GPC) presented by Clarke, Mohtadi & Tuffs (1987). The main difference between the XGPC and GPC algorithms is found in the derivation of the control law. The XGPC uses conditional expectation to separate model output into a term with a linear dependency on future input values (control values) and a term depending on past input and output values, where a similar separation for the GPC is achieved by recursively solving a Diophantine equation. Furthermore the formulation of the GPC depends on a specific model structure (ARIMAX) whereas the only requirement on the model structure posed by the XGPC is that the future model output is separable as described above.

Formulation of the XGPC control law is illustrated in the following for an ARMAX model. Consider a ARMAX model with time varying parameters

$$A_t(q^{-1})\,y_t = B_t(q^{-1})\,u_t + C_t(q^{-1})\,e_t \qquad (4)$$

Using conditional expectation the j-step output prediction is easily calculated as

$$\begin{aligned} \hat{y}_{t+j|t} &= -\sum_{i=1}^{n} a_{i,t+j}\hat{y}_{t+j-i|t} + \sum_{i=1}^{m} b_{i,t+j}u_{t+j-i} + \\ & \sum_{i=1}^{r} c_{i,t+j}\hat{e}_{t+j-i|t} \quad , \; j-i \geq 1 \qquad (5) \end{aligned}$$

where

$$\begin{aligned}
\hat{y}_{t+j|t} &= -\sum_{i=1}^{n} a_{i,t+j}\hat{y}_{t+j-i|t} + \sum_{i=1}^{m} b_{i,t+j}u_{t+j-i} + \\
&\sum_{i=1}^{r} c_{i,t+j}\hat{e}_{t+j-i|t} \quad , \; j-i \geq 1 \qquad (6)\\
\hat{y}_{t+j|t} &= y_{t+j} \quad , \; j < 1\\
\hat{e}_{s|t} &= \begin{cases} e_s = y_s - \hat{y}_{s|s-1} & \text{if} \quad s \leq t \\ 0 & \text{if} \quad s > t \end{cases}
\end{aligned}$$

and n, m, r in (5) are the order of the A_t, B_t, C_t polynomials in (4). The separation of model output is achieved by using conditional expectation:

- The system impulse response denoted $h_t(q^{-1})$ is calculated as the model output conditioned on a unit impulse control at time t and otherwise zero.

- The input free system response denoted v_t is calculated as the predicted output conditioned on future controls equal zero.

The conditional j-step prediction is now written as

$$\hat{y}_{t+j|t} = \sum_{i=1}^{j} h_{i,t+j}u_{t+j-i} + v_{j,t} \qquad (7)$$

Using matrix notation the output predictions (7) for horizons between 1 and N is written as

$$\hat{\mathbf{y}}_t = \mathbf{H}_t\mathbf{u}_t + \mathbf{v}_t \qquad (8)$$

where

$$\begin{aligned}
\hat{\mathbf{y}}_t &= (\hat{y}_{t+1|t}, \ldots, \hat{y}_{t+N|t})^T\\
\mathbf{u}_t &= (u_t, \ldots, u_{t+N-1})^T\\
\mathbf{v}_t &= (v_{1,t}, \ldots, v_{N,t})^T\\
\mathbf{H}_t &= \begin{pmatrix} h_{1,t+1} & 0 & \cdots & 0 \\ h_{2,t+2} & h_{1,t+2} & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ h_{N,t+N} & h_{N-1,t+N} & \cdots & h_{1,t+N} \end{pmatrix}
\end{aligned}$$

The XGPC utilizes a cost function of the form

$$\begin{aligned}
\min_{\mathbf{u}_t} J(\mathbf{G}_t, \mathbf{L}_t, \mathbf{o}_t; t, \mathbf{u}_t) &= \\
E\left[(\mathbf{y}_t - \mathbf{y}_t^0)^T \mathbf{G}_t (\mathbf{y}_t - \mathbf{y}_t^0) + \mathbf{u}_t^T \mathbf{L}_t \mathbf{u}_t + 2\mathbf{o}_t^T \mathbf{u}_t\right] & \quad (9)
\end{aligned}$$

where $\mathbf{y}_t$ is a vector of future outputs, $\mathbf{y}_t^0$ is a vector of future reference values, $\mathbf{G}_t$ is a positive semidefinite and symmetric matrix weighting the control errors, $\mathbf{L}_t$ is a positive semidefinite and symmetric matrix weighting the squared control values, and $\mathbf{o}_t$ is a vector weighting the control values linearly.

Inserting $\mathbf{y}_t = \hat{\mathbf{y}}_t + \mathbf{e}_t$ and (8) into (9) and minimizing with respect to $\mathbf{u}_t$ results in the XGPC control law

$$\begin{aligned}
\mathbf{u}_t &= \\
&-[\mathbf{H}_t^T \mathbf{G}_t \mathbf{H}_t + \mathbf{L}]^{-1} [\mathbf{H}_t^T \mathbf{G}_t (\mathbf{v}_t - \mathbf{y}_t^0) + \mathbf{o}_t] \; . \quad (10)
\end{aligned}$$

The choice of the control parameters $\mathbf{G}_t$, $\mathbf{L}_t$ and $\mathbf{o}_t$ determines the behavior of the XGPC. Selection of control parameters is treated in (Madsen et al. 1996).

3.2 Flow sub-controller

A prediction model relating the future mass flow to past and future supply temperatures has to take the future heat load into account, i.e. it will have to depend on heat load predictions. Instead of identifying a mass flow model which depends on output from a heat load model, the control scheme proposed in the following employs the heat load predictions directly to calculate the minimum necessary supply temperature imposed by the mass flow restrictions. Using the energy balance equation

$$p_t = c_w \, q_t \, (T_{s,t} - T_{r,t}) \quad , \qquad (11)$$

where c_w is the specific heat of water, p_t is the heat load, q_t is the flow rate and $T_{s,t}$, $T_{r,t}$ are supply and return temperature, respectively, and considering only the system response to the next time point this leads to the following control

$$T_{s,t+1}^1 = \hat{T}_{r,t+1|t} + \frac{\hat{p}_{t+1|t}}{c_w \, q^0} \qquad (12)$$

where the observed return temperature $T_{r,t}$ and mass flow q_t in (11) have been replaced by the predicted return temperature $\hat{T}_{r,t+1|t}$ and the maximum value for the mass flow q^0, respectively.

A change of supply temperature at time t will affect the mass flow in the system until the introduced temperature gradient has reached the most remote (distant) consumers which in a large district heating utility will take several hours. The flow control should therefore be based on the heat load predictions for the horizons mostly affected by a change in supply temperature as opposed to (12), where only the heat load prediction to time $t+1$ is considered. The controller is based on (12) for the considered horizons, and then calculating the supply temperature as a weighted sum of the individual $T_{s,t+1}^{(j)}$

$$\begin{aligned}
T_{s,t+1}^{(j)} &= \hat{T}_{r,t+j|t} + \frac{\hat{p}_{t+j|t}}{c_w \, q_{t+j|t}^0} \qquad (13)\\
T_{s,t+1} &= \sum_{j=N_1}^{N_2} \gamma_j \, T_{s,t+1}^{(j)} \quad , \sum_{j=N_1}^{N_2} \gamma_j = 1
\end{aligned}$$

The weights γ_j is found as the fraction of the heat produced at time t, which is consumed at time $t+j$. In (13) $\hat{T}_{r,t+j|t} = T_{r,t}$ have been used as a predictor for the return temperature – a simplification which seems reasonable due to the small variations in $T_{r,t}$.

The heat load predictions in (13) are calculated using the model

$$\begin{aligned} A_t^k(q^{-1})p_t &= B_{1,t}^k(q^{-1}) \bigtriangledown T_{s,t} + B_{2,t}^k(q^{-1})T_{a,t} + \\ & \quad \mu_{1,t}^k + I_{a,t}\mu_{2,t}^k + l^k + e_t^k \end{aligned} \tag{14}$$

where $A_t^k(q^{-1})$, $B_{1,t}^k(q^{-1})$ and $B_{2,t}^k(q^{-1})$ are time-varying polynomials in the back-shift operator (q^{-1}), $\bigtriangledown$ is the difference operator, $I_{a,t}$ is an indicator function which is 0 on work days and 1 otherwise, $\mu_{1,t}^k$ and $\mu_{2,t}^k$ are diurnal profiles for working and non-working days, respectively, l^k is a mean value and e_t^k is a noise term.

3.3 Controller reference value

The XGPC control law (10) requires, that an output reference is specified. The reference may be constant over time or given as a function of one or more explanatory variables. In the latter case predictions of the explanatory variable(s) is needed in order to calculate the future reference values.

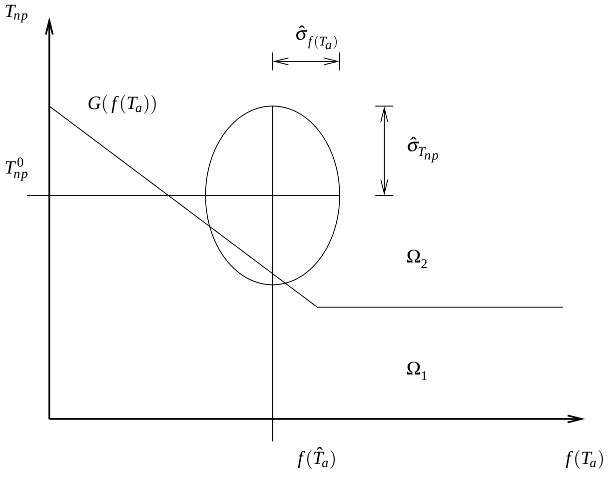

Figure 2: Reference net-point temperature curve. The reference curve determines the required net-point temperature as a function of the low pass filtered air temperature – $f(T_a)$.

In a traditionally controlled district heating system the supply temperature is often determined as a function of the current air temperature, and it seems reasonable to let the minimum acceptable net temperature in the critical net-points be governed by a similar function as illustrated in Figure 2. The increasing net temperature with decreasing air temperature reflects the limited capacity in the consumers room heating installations, whereas the minimum is determined by the hot tap water installations. This is also in accordance with (Hansen & Bøhm 1996), where the requirements on supply temperature is investigated for a number of building.

The heat capacity of the total thermal mass of the buildings acts as a low pass filter on the influence of air temperature on heat demand, hence the required net-point temperature is determined as a function of the filter air temperature. The filter function $f()$ is implemented as a rectangular weight function of the air temperature for the past 24 hours

$$f(T_a,t) = \frac{1}{24}\sum_{i=0}^{23} T_{a,t-i} \quad . \tag{15}$$

The use of (15) reduces the diurnal variation of the net-point temperature significantly and reflects the expected filtering of the buildings reasonably well. A more physical motivated filter is proposed in (Nielsen & Madsen 2000), where model studies have indicated, that the ambient air temperature should be filtered through a simple first-order filter

$$f(T_a,t) = \frac{0.06}{1-0.94q^{-1}} T_a(t) \ , \tag{16}$$

before the relationship between heat load and ambient air temperature is estimated, and it seems reasonable to expected the required net-point temperature to exhibit a similar dependency on ambient air temperature. (16 has recently been implemented in PRESS.

The XGPC cost function (9) penalizes the quadratic control errors, hence positive and negative control errors are weighted equally in the control criterion. This implies, that the controller will aim at minimizing the control errors, but not discriminate between realizations above or below the reference signal. In many situations this is as intended, but in some applications the reference signal acts as an output restriction and the uncertainty in the predictions of system output and explanatory variable(s) must be taken into account, when the output reference values are determined. In PRESS the reference values are determined so that the probability of future net-point temperature observations below a value given as a simple function of the future air temperature is fixed (and small).

Figure 2 establishes the “legal” area Ω_2 as the area above $g(f(T_a))$ as well as the “illegal” area Ω_1 below $g(f(T_a))$, where in the latter case the consumer inlet temperature restriction is violated. The reference net-point temperature $T^0_{np,t+j|t}$ is determined so that

$$\begin{aligned} P\{\ (\ f(T_{a,t+j}), T_{np,t+j}\ ) \in \Omega_2 \mid I_t\} &= \pi\ ,\ j>0 \\ \{(f(T_{a,t}), T_{np,t}) \mid T_{np,t} \geq g(f(T_a))\} &= \Omega_2 \qquad (17) \end{aligned}$$

where $f(T_{a,t+j})$ and $T_{np,t+j}$ are future values of filtered air temperature and net-point temperature, respectively, $1-\pi$ is the probability of violating the restriction, and I_t is the information set at time t. Given the distribution of the prediction errors for $f(T_{a,t+j})$ and $T_{np,t+j}$ (17) and inserting

$$\begin{aligned} f(T_{a,t+j}) &= f(\hat{T}_{a,t+j|t}) + e_{f(T_a),t+j|t} \\ T_{np,t+j} &= T^0_{np,t+j|t} + e_{T_{np},t+j|t} \end{aligned}$$

into (17) the resulting equation is readily solved with respect to $T^0_{np,t+j|t}$ by numerical methods.

4 Results obtained in Roskilde

The models and controllers are implemented in a software system called PRESS described in (Madsen et al. 1996) and (Nielsen, Madsen & Nielsen 2001). PRESS is installed at Roskilde Varmeforsyning – a district heating utility supplying Roskilde City and suburbs. Heat is supplied from the VEKS transmission system, which distributes the heat production from CHP and waste incineration plants in the eastern part of Zealand. A peak load boiler is installed in the distribution network, but is rarely used.

The annual heat purchase is 1.700.000 GJ with a maximum heat load of 110 MW. The supply area of Roskilde Varmeforsyning consists of two separate distribution network, where PRESS controls the larger of these. The controlled area corresponds to 55% of the supply area.

PRESS has been used operationally at Roskilde Varmeforsyning since the beginning of January 2001. Prior to the installation of PRESS the supply temperature was controlled manually based on the experience of the operators. In Section 4.1 the savings obtained by PRESS compared to the previously used control strategy is assessed whereas the controllers ability to observe the imposed restrictions is evaluated in Section 4.2.

4.1 Savings

In order to evaluate how PRESS has influenced the operational costs two data periods are examined: The first period prior to the installation of PRESS covers nine months from January 1st 2000 to September 30th 2000 whereas the second period after installation of PRESS consists of the data from the similar months in 2001. The district heating system has not been affected by notable changes during the compared periods except for the installation of PRESS, hence it seems reasonable to attribute any differences found in heat and electricity purchases to the introduction of PRESS.

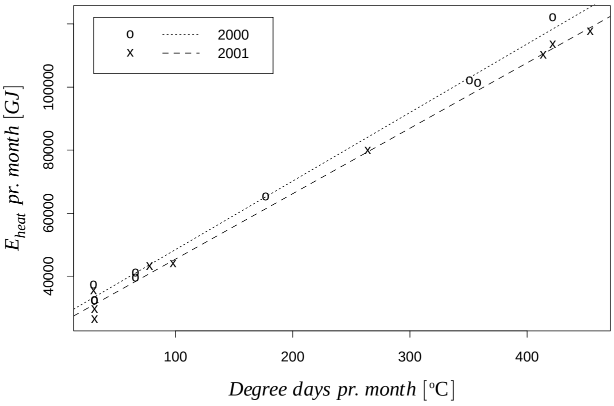

Figure 3: Heat purchase per month versus monthly degree days for the nine first months of year 2000 and 2001. The lines are the Ordinary Least Squares estimate of the relationships for the two periods.

Figure 3 shows the heat purchase per month versus the monthly degree days for the two periods. The monthly degree days T^{dd}_{mon} are calculated as

$$T^{dd}_{mon} = \sum^{\textit{Days in month}} \max(0, 17 - \bar{T}^{diur}_a)$$

where $\bar{T}^{diur}_a$ is the diurnal average temperature for the days in the month.

From the figure it seems reasonable to model the relationship between heat purchase and degree days by a straight line for both periods. The Ordinary Least Squares fit of the relationship is given as

$$\begin{aligned} 2000: \quad E^{heat}_{mon} &= 217\frac{GJ}{^{\text{o}}\text{C}}T^{dd}_{mon} + 26700GJ \quad (18) \\ 2001: \quad E^{heat}_{mon} &= 208\frac{GJ}{^{\text{o}}\text{C}}T^{dd}_{mon} + 24700GJ\ . \end{aligned}$$

Using (18) for each of the first nine months of a normal year[1] the total difference in heat purchase before and after the installation of PRESS is calculated to -37,400 GJ corresponding to a reduction in heating costs of 1,760,000 Dkr.

Figure 4 shows the electricity purchase per month versus the monthly degree days for the two periods. For year 2001 the relationship between electricity purchase and degree days is modelled by a straight line, but for year 2000 this is not a reasonably model. Instead a non-parametric line is estimated using local

---

[1] In the Roskilde area a normal year corresponds to 2805 degree days.

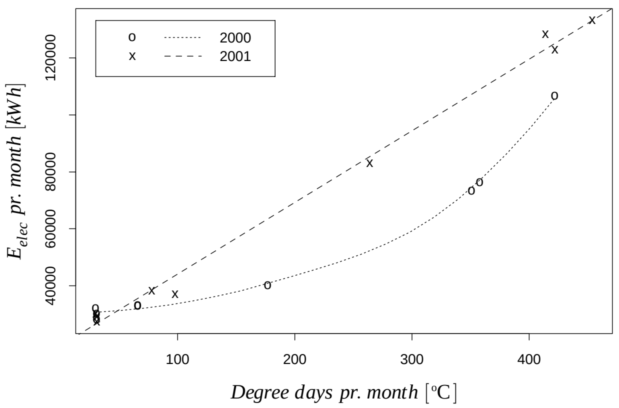

Figure 4: Electricity purchase per month versus monthly degree days for the nine first months of year 2000 and 2001. For year 2000 the relationship between degree days and electricity purchase is estimated using local polynomial regression whereas Ordinary Least Squares regression is used for year 2001.

polynomial regression with a second order approximation and nearest neighbor bandwidth of 100%. The relationships are given as

$$\begin{aligned} 2000: \quad E^{elec}_{mon} &= \hat{f}(T^{dd}_{mon}) \qquad (19) \\ 2001: \quad E^{elec}_{mon} &= 251\frac{kWh}{^{\circ}\mathrm{C}}T^{dd}_{mon} + 19000kWh \ . \end{aligned}$$

where $\hat{f}()$ is the estimated local regression line.

Using (19) for each of the first nine months of a normal year the total difference in electricity purchase before and after the installation of PRESS is calculated to 149,000 kWh corresponding to an increase in electricity costs of 194,000 Dkr.

For district heating utilities supplied from the VEKS transmission system excessive return temperatures and peak loads are penalized by an increase in the cost per unit energy.

According to Roskilde Varmeforsyning use of the peak load boiler has been reduced after the installation of PRESS, hence PRESS seems to have reduced the peak loads.

From Figure 5 it is seen that the return temperature mostly seems to be unaffected by PRESS and only for the lowest observations of degree days has the use of PRESS resulted in an increase in the return temperature. The increase is too small to imply any noticeable penalty in the energy costs, but could otherwise be countered by a minor increase of the minimum value of the net-point temperature reference curve in Figure 2.

Hereafter it may be concluded that PRESS has not adversely affected the cost per unit energy. In total the installation of PRESS has resulted in a reduction of the operational costs corresponding to 1,566,000 Dkr.

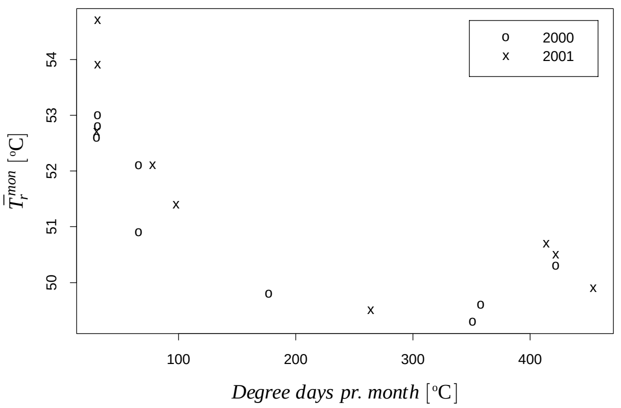

Figure 5: Monthly averages of return temperature versus monthly degree days for the nine first months of year 2000 and 2001.

4.2 Quality of control

The quality of control is evaluated with respect to the ability of the controller to observe the restrictions on maximum flow rate and minimum net-point temperatures. In Roskilde PRESS consists of a flow controller and three net-point controllers. Experience has shown that the flow sub-controller and one of the net-point temperature sub-controllers – Haraldsborg – alternate in being the active controller. During cold periods at winter time ($T_a < 0$°C) the flow controller is active most of the time; during early spring and late autumn the flow controller is active only during the morning peak load and the remaining part of the year the Haraldsborg net-point controller is active.

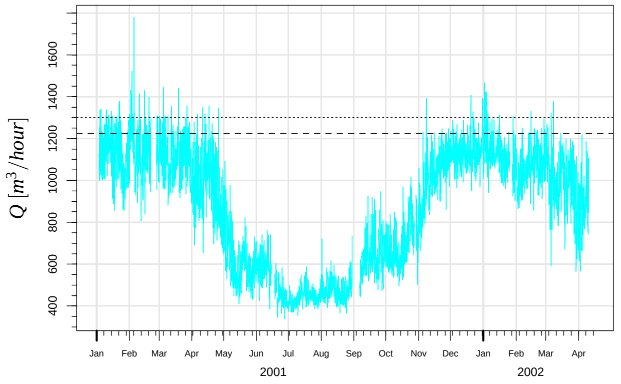

Figure 6: Hourly averages of flow rate versus time for a period from 3rd January 2001 to 10th April 2002. Unto the beginning of January 2002 the maximum flow rate of 1300 m3/hour (dotted line) was used, hereafter the maximum has been lowered to 1225 m3/hour.

Hourly average values of flow rate are plotted in

Figure 6 together with the maximum flow rate(s). From the figure it is seen that PRESS in general has kept the flow rate below the maximum limit, but also that some violations of the limit occur. In Roskilde the main supply point is equipped with two pumps and the maximum flow rate observed by PRESS has been selected to avoid starting the second pump but during prolonged periods with high heat load this is not possible. This and technical problems at the supply point explains most of the violations seen in Figure 6 and in general it is the assessment of Roskilde Varmeforsyning that PRESS is capable of observing the flow rate limit.

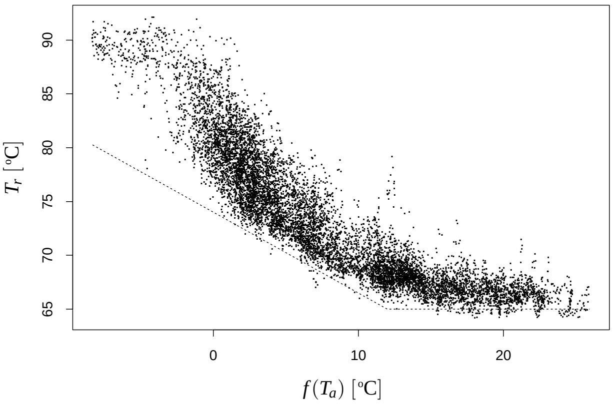

Figure 7: Hourly averages of net-point temperature at Haraldsborg versus filtered air temperature for a period from 3rd January 2001 to 10th April 2002. The dotted line is the minimum reference curve for minimum net-point temperature used at Haraldsborg.

In Figure 7 hourly average values of net-point temperature at Haraldsborg have been plotted versus filtered air temperature, where the filter is given by (15). From the plots it is readily seen that the part of the observations above the temperature requirement for the critical point (indicated by the dotted line) exceeds the specified $\pi = 95\%$ with some margin. It is therefore concluded that the PRESS controller has been capable of observing the imposed net temperature restrictions.

5 Conclusion

A new concept for controlling the supply temperature in a district heating system has been presented. The controller optimizes the operational costs for the distribution network by minimizing the supply temperature without compromising supply or consumers temperature requirements.

The controller has been installed at the district heating utility supplying Roskilde City and suburbs and compared to the previously used control strategy savings corresponding to approximately 5% of the operational costs has been estimated for a nine months period.

It is shown that the above savings have been obtained without adversely affecting the operation of the distribution network or sacrificing security of supply.

References

Clarke, D. W., Mohtadi, C. & Tuffs, P. S. (1987), ‘Generalized predictive control – part I. The basic algorithm’, *Automatica* **23**, 137–148.

Hansen, K. K. & Bøhm, B. (1996), Nødvendig fremløbstemperatur for eksisterende fjernvarmetilslutningsanlæg - med tilhørende afkøling, Technical Report ET-ES 96-04, Department of Energy Engineering, Technical University of Denmark, Lyngby, Denmark. In Danish.

Madsen, H., Nielsen, T. S. & Søgaard, H. (1996), *Control of Supply Temperature*, Informatics and Mathematical Modelling, Technical University of Denmark, Lyngby, Denmark.

Nielsen, H. A. & Madsen, H. (2000), Forecasting the heat consumption in district heating systems using meteorological forecasts, Technical report, Informatics and Mathematical Modelling, Technical University of Denmark, Lyngby, Denmark.

Nielsen, T. S., Madsen, H. & Nielsen, H. A. (2001), ‘Intelligent control’, *Danish Board of District Heating – News from DBDH* (3), 14–16.

Palsson, O. P., Madsen, H. & Søgaard, H. (1994), ‘Generalized predictive control for non-stationary systems’, *Automatica* **30**, 1991–1997.

Søgaard, H. (1988), Identification and adaptive control of district heating systems, Master’s thesis, Informatics and Mathematical Modelling, Technical University of Denmark, Lyngby, Denmark. In Danish.