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Model-based control of district heating supply temperature

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värmeforsk
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Modellbaserad framtemperaturreglering

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Abstract

A model-based control strategy for the supply temperature to a district heating network was tested during three weeks at Idbäckens's CHP plant. The aim was to increase the electricity efficiency by a lower supply temperature, without risking the delivery reliability of heat to the district heating customers. Simulations and tests showed that at high loads, the mean supply temperature could be reduced by 4ºC and the electricity production could be increased by 2.5%.

Sammanfattning

Höga elpriser och möjligheten att få gröna elcertifikat har under de senaste åren gjort det intressant för anläggningsägare att öka elverkningsgraden på sina kraftvärmeverk. En möjlighet att åstakomma detta är att sänka framledningstemperaturen till fjärrvärmenätet som anläggningen försörjer. Samtidigt är det viktigt att inte leveranssäkerheten för värme äventyras. I den här studien har en reglerstrategi för minimerad framledningstemperatur inom ramen för bibehållen leveranssäkerhet testats på fjärrvärmenätet i Nyköping. Resultatet visar att det är möjligt att sänka framledningstemperaturen med 4ºC i genomsnitt under höglast, genom att låta den följa en korttidsprediktion av lasten på nätet. Samtidigt jämnas flödet på nätet ut. Simuleringar visar att man med en sådan reglerstrategi kan öka elproduktionen med 2,5% vid höglast.

Den här rapporten riktar sig till anläggningsägare som vill höja sin elverkningsgrad. Den beskriver en modell och en reglerstrategi som möjliggör en sänkning av framledningstemperaturen och därmed leder till en högre elverkningsgrad. Målet med studien var att testa modellbaserad framtemperaturreglering och utvärdera den med avseende på alfavärde, elproduktion och leveranssäkerhet. Testerna utfördes på Idbäckens kraftvärmeverk under 20 dagar under november, december och januari 2009-2010. Efter analys av testresultaten gjordes några modifieringar av modellen. Testresultaten jämfördes sedan med simuleringar av den modifierade modellen med mätdata från september till maj säsongen innan.

Resultaten visar att framledningstemperaturen kan sänkas utan att leveranssäkerheten äventyras. Lägsta tillåtna framledningstemperatur i Nyköpingsnätet är 75ºC. Detta golv har även använts vid den modellbaserade regleringen. Vid utetemperaturer under +5ºC höjs framledningstemperaturen, och det är i dessa lägen det finns utrymme för modellen att föreslå en lägre temperatur, baserad på en prediktion av lasten på nätet. Prediktionen görs med hjälp av en dynamisk lastmodell, som använder data på nuvarande last, utetemperature och lasten vid samma tid tidigare dygn som underlag.

Idäcken beräknas kunna öka sin elproduktion med 1,8 GWh/år om modellbaserad framtemperaturreglering skulle implementeras. Detta motsvarar en ökad nettointäkt på 750 000 kr/år. Den största produktionsökningen skulle infalla vid utomhustemperaturer kring +2ºC. Alfavärdet förbättras mer vid utetemperaturer under 0ºC, men låga temperaturer är ovanliga i Nyköping, och bidrar därför inte så mycket till den sammanlagda produktionsökningen.

Nyckelord: Fjärrvärme, elverkningsgrad, dynamisk modellering, processreglering, framledningstemperatur.

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1 Introduction

1.1 Background

A low supply temperature to the district heating network is important in order to achieve high electricity efficiency for combined heat and power plants. At the same time, the supply temperature must not be too low, since that will endanger the delivery reliability. Generally there are two conditions that need to be fulfilled: The hot water temperature must not fall below 55ºC for any customer, and enough heat power must be transmitted to cover the heat load of the customers. The first condition determines the lowest allowed supply temperature regardless of load. The second condition is fulfilled by increasing the supply temperature at high loads, usually by scheduling it against the outdoor temperature. The scheduling control can be well tuned to the district heating network, but will still have the disadvantage of not being able to follow the social and seasonal variations of the load.

In the degree project “Modelling and control of a district heating system” [1], a model-based control strategy for the supply temperature of Idbäcken’s CHP plant in Nyköping was developed. The load of the district heating network was modelled by a dynamic blackbox model working on the diurnal (day-to-day) difference of the load. The network was approximated as an equally distributed load with a transport delay time varying with the flow on the network. Simulations indicated that the supply temperature could be decreased with 1ºC in average if the model-based control strategy was used. A 24-hour test of the model-based control on the plant was carried out in 2009. The test result showed that the transport delay time on the network was shorter than had been expected, and the model was revised according to this. New simulations indicated that the performance of the model had improved after the changes, and that the model-based control would give a 2ºC lower average supply temperature. However, it was realized that more tests would be needed to further tune and evaluate the model and the control strategy.

1.2 Description of the research area

Methods for modelling and control of district heating networks have been developed and described by many researchers. Static models of district heating networks are described in several reports [4], [5], [6], and the benefits of using distribution models in production planning are discussed [6], [7], [8]. The heat load on a district heating network depends on weather factors (mainly outdoor temperature) and social load (which depends on the time of the day, the day of the week and holidays). There are many different approaches in how to model it. In many cases, static models (which do not include differential equations) are used [8], [9], [10], [11], [12], [13]. Dynamic models have been used in a couple of Värmeforsk projects [14], [15], and by researchers at The Faculty of Engineering at Lund University [16] and Technical University of Denmark [20].

There have been two Värmeforsk projects regarding modelling of district heating systems. Malmström et al [14] made time series analyses of outdoor temperature prognoses and heat load variations of a district heating network, and compared this approach to a neural networks model in 1996. They used SARIMAX and ARX models, and concluded that these time series models were better suited to predict district heating loads than the neural network model.

In another Värmeforsk report from 2007 [15], Kvarnström et al discuss load prognoses based on measurements from district heating substations and from building models. A prognosis is made from a linear regression model of outdoor temperature, mean temperatures the last days and night (corresponding to heat stored in building structures), a function describing the load behaviour for weekdays and weekends respectively, wind speed and solar irradiation. This model is not dynamic (in the sense of using derivatives) like the models used by Malmström et al. The modelled network (Stockholms Södra) is large and complex, and it is modelled as several subsystems interconnected with transport delays.

Research on district heating network models has also been done at the Faculty of Engineering at Lund University. A physical model of a network, including pumps, pipes and heat exchangers was made in a degree project 1981 [17], describing heat losses and the heat exchange in the substations. In a thesis from 2001, Arvastson presents a dynamic greybox model of the heat load of Malmö’s district heating network. The model is based on physical models of the heat consumption in buildings, including a daily curve for the hot water consumption and monthly correction factors, and is completed with an ARMA filter that models the 24 hour correlation of the data. Hourly mean values from district heating substations and the production plant are used to estimate parameters in the model. This model structure was probably unnecessarily complex.

Researchers from the Technical University of Denmark have published several research reports and papers on district heating modelling and control, and a spin-off company from this research area, ENFOR, has been started. With the method for supply temperature control developed by Madsen et al [19], they use a load model to determine the lowest possible supply temperature at some critical network points, where the supply temperature is measured. The dynamic load model uses hourly values of the load p(t), p(t-1), p(t-23), p(t-24), the outdoor temperature Ta(t), Ta(t-24), and supply temperature change ΔTs(t+1), ΔTs(t-24) together with trigonometric functions for weekdays and weekends. Sejling used a similar model in his thesis 1993 [20], but with separate models for different seasons. Evaluating the applicability of the 24-hour difference and the 168-hour (weekly) difference, he found that the daily but not the weekly difference could be used successfully to predict the load variations. The variation between weekday and weekend was instead modeled by a trigonometric function.

1.3 The purpose of the research assignment and its role within the research area

In this project, control of the supply temperature with a model developed in the degree project “Modelling and control of a district heating network” [1] is tested on a CHP plant. Although load models have been used to control supply temperature to district heating networks before, there are some new characteristics in the approach in this study:

- The main objective is to increase the electric efficiency of the CHP plant. The result is evaluated in terms of improved alpha value and electricity production. Earlier studies in this area have mainly focused on production planning or flow stability.
- No flow or temperature measurements from distant locations on the network are used in the model, only data from the CHP plant. In earlier studies, the network models often depend on data from the network. However, this type of data is not always available.
- A greybox model of the load, consisting of a diurnal difference model and a blackbox ARX model with parameters estimated from data is used. This is a rather simple and straightforward model structure, which have not been used in earlier studies.

1.4 Goal and audience

The goal of this study is to test and evaluate the benefit of model-based control of the district heating supply temperature in order to increase the electric efficiency and the electricity production.

The audience of this report is owners of heat production plants where the supply temperature affects the performance or economy, such as CHP plants, heat pumps and utilisation of industrial waste heat. The results are particularly applicable on small to medium sized district heating networks supplied from one source, but can be valid for larger and more complex networks as well with the proper adjustments.

2 Idbäcken CHP plant and the district heating network of Nyköping

The main production of the district heating plant Idbäcken in Nyköping is handled by an 105 MW boiler connected to a 35 MW turbine. The plant is also equipped with a flue gas condenser of 12 MW, an accumulator tank of 400 MWh and some smaller production units used at extreme high load and in the summer. Connected to the district heating network, but not on the site, is a recooler with a cooling capability of 25 MW. The recooler, “Beriden”, is used to increase the heat demand on the network in order increase the electricity production of the CHP plant. It is controlled from Idbäcken and the load is typically varied irregularly on a daily basis.

The electricity efficiency of a CHP plant is often expressed by the quota of produced electricity and produced heat, the α-value, see equation (1).

$$\alpha = \frac{P_{el}}{P_{heat}} \tag{1}$$

The α-value depends on many parameters, among them the condensation temperature of the steam exiting the turbine, which in turn depend on the supply temperature to the district heating network. For Idbäcken, the relation between α-value and supply temperature in equation (2) has been calculated through simulations with a mass and energy balance model with the software Ebsilon in an internal Vattenfall study in 2008.

$$\frac{d\alpha}{dT_s} = -0.0029 \tag{2}$$

The supply temperature to the district heating network is controlled by the control curve in Figure 1. The lowest level, 75ºC, is set to ensure that all customers get at least the regulated tap water temperature, 55ºC. For outdoor temperatures below +5ºC, the supply temperature is increased so that more heat can be distributed with the same flow.

Load variations that are not compensated by an adjusted supply temperature are regulated by the flow to the network. Each district heating substation regulates the flow from the supply pipe through the local heat exchangers to the return pipe. To ensure that all customers get the flow they require, the differential pressure between the supply and return pipes must be kept at a sufficient level throughout the network. This is the job of the district heating pump located at Idbäcken. If the flow becomes too high, the differential pressure starts to fall and the pump has to work harder to restore the pressure. If the pump reaches its limit, the differential pressure falls and the consumers in the periphery of the network will not be able to get their heat. To avoid this, the supply temperature is increased when the load is expected to be high (that is when the weather is cold). It is desirable to keep as low supply temperature as possible without risking heat deficit on the network, in order to get a high efficiency of the turbine.

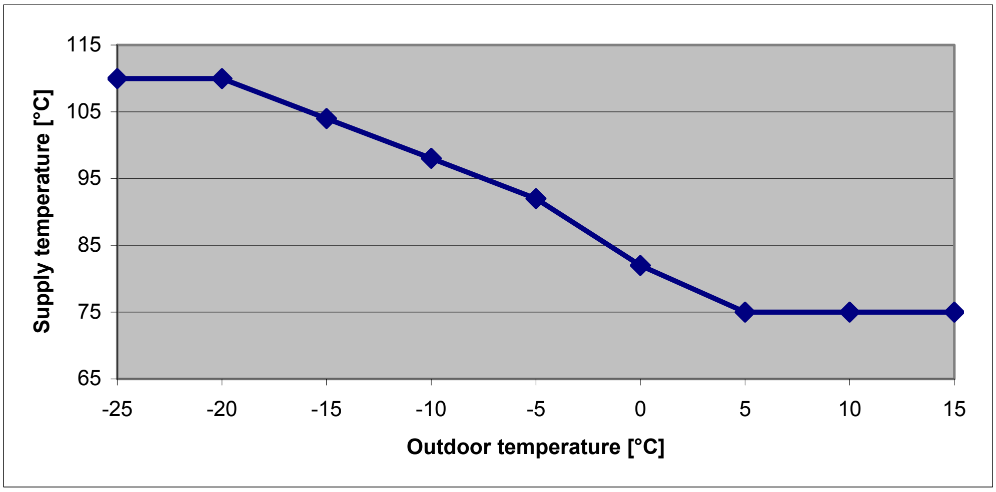


Figure 1. Supply temperature control curve.

A map of the district heating network of Nyköping can be seen in Figure 2. The pipe system contains of 130 km pipe with a volume of 8000m^3, of which half is the supply line and half is the return line. The total water volume of the system is about 18 000m^3, since there is also an accumulator tank for heat storage at the heat plant in Idbäcken, which is connected to the network.

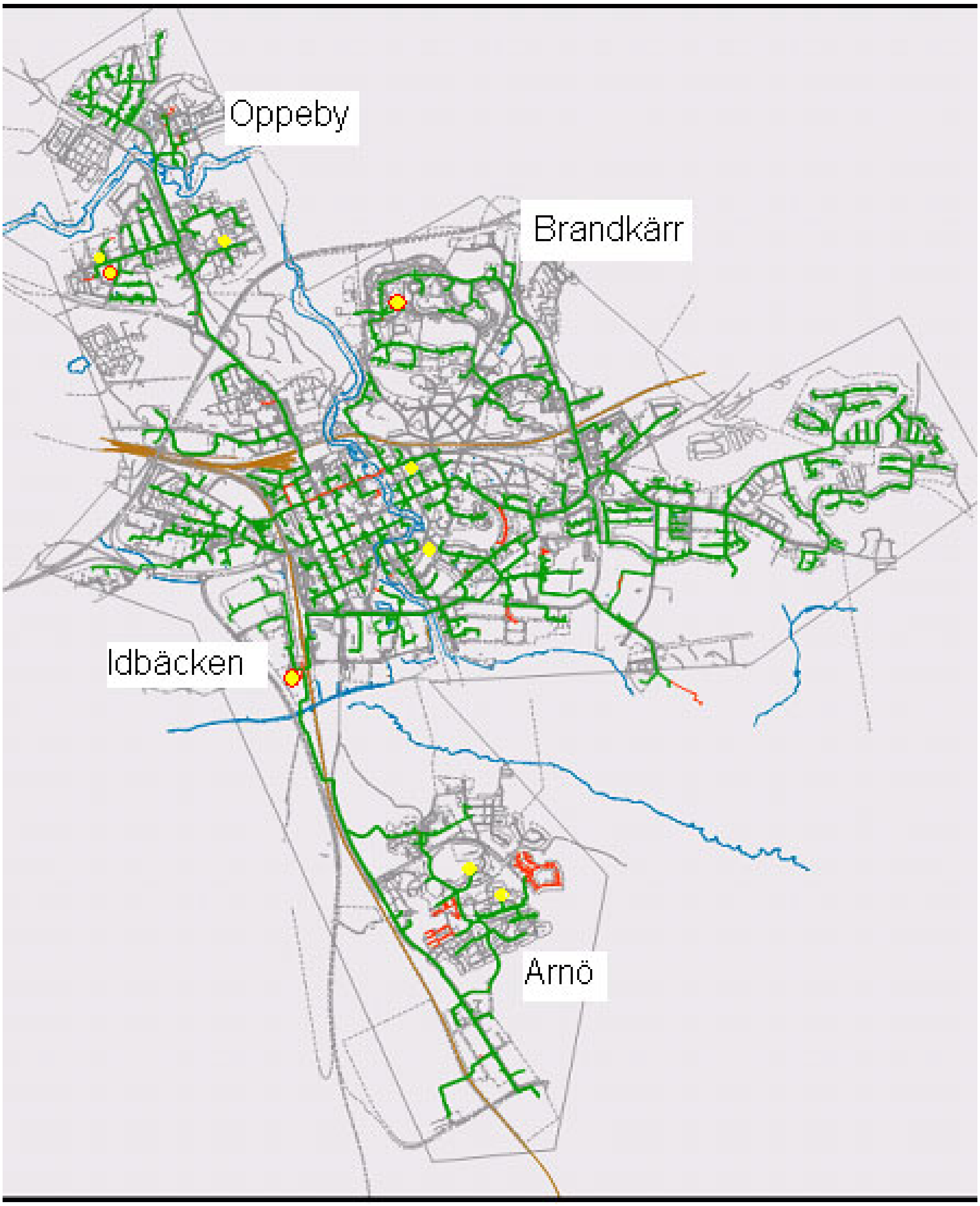


Figure 2. The district heating network of Nyköping. Yellow dots with red edge is Idbäcken CHP plant, Brandkärr reserve plant and the substation in Oppeby where the differential pressure controlling the district heating pump is measured. Yellow dots are the substations Oppeby gård and Regeringsvägen in Oppeby, Trollstigen and Sellerigången in Arnö, Östra Promenaden in the south-east city centre and Östra Rundgatan in the north-east city center.

3 Model and control strategy

The model of the district heating system used in this project was first presented in the degree project “Modelling and control of a district heating system” [1]. In this chapter, the model structure and parameters will be described. In the degree project, many model structures were simulated and compared, including models using not only outdoor temperature but also wind speed and solar irradiation as input data to the model. However, these models did not give better predictions than the models using only the outdoor temperature for prediction of the heat load, probably because the slowly changing influence of the wind and sun are detected by other parts of the model, and the data quality was probably not good enough to provide accurate information on the fast changes. For further information about the model development and validation, see the degree project report [1].

3.1 Network model

High resolution data on the heat consumption of the district heating customers is not available from the Nyköping network. Therefore, the heat load has to be modelled using data from the heat plant, Idbäcken. In the long run, the heat dispatched from Idbäcken is equal to the heat consumed by the customers and the heat losses of the network. Within a shorter timeframe however, the load is not necessarily the same as the dispatched heat, since heat can be loaded to or unloaded from the network itself.

The heat dispatched from Idbäcken heat plant is

$$P_s(t) = c_p \dot{m}(t)(T_s(t) - T_r(t)) \tag{3}$$

with

P_s	=	heat power supplied to the district heating system
c_p	=	specific heat capacity of water
$\dot{m}$	=	mass flow of the water
T_s	=	supply temperature at Idbäcken
T_r	=	return temperature at Idbäcken

The heat load of the customers is approximated as

$$P_{del}(t) = c_p \dot{m}(t) \left(\frac{\int_{t-\Delta t}^{t} T_s(\tau) d\tau}{\Delta t} - T_r(t) \right) \tag{4}$$

with

P_{del}	=	delivered heat power (the load)
Δt	=	transport time from Idbäcken to the periphery of the network

Equation (3) and (4) are written with continuous time. However, in the following chapters, the model is a discrete time model, and equations will be expressed in discrete time.

The delivered heat actually depends on the return temperature $T_r(t)$ to $T_r(t+\Delta t)$. The momentary value is used instead to reduce the disturbances from the cooling device, “Beriden”, which is situated about 20 minutes from Idbäcken and causes rapid changes in the return temperature when it is turned on and off. On occasions when the cooling device is not used, the return temperature varies slowly with the time of day and the outdoor temperature. High social load (mornings) results in a low return temperature, since the heat is mainly exchanged to cold tap water, producing hot tap water. High radiator load (cold outdoor temperatures) on the other hand results in high return temperature, since the heat is exchanged to the relatively warm water in the radiator circuits.

3.1.1 Transport time

The supply temperature is measured at some of the substations of the district heating network of Nyköping. Data with one-minute resolution is available for 24 hours, but after this only hourly mean values are saved. Only one measurement point, at Brandkärr where a reserve power unit is situated, is logged and saved to the historical data of Idbäckens CHP plant.

The 28th of October at 07:20, the supply temperature from Idbäcken made a sharp drop of almost 5ºC. This temperature drop could clearly be detected in the measurement at Brandkärr and in the measurements from the other district heating substations. The flow to the district heating network was at this time was dropping from 2000 tons/h at 07:00 to 1300 tons/h at 10:00 due to shut down of the recooler “Beriden”. In Figure 3, the supply temperatures at Idbäcken and Brandkärr are plotted. It is clear from looking at the figure that the transport time between these two measurements is 2 hours. Data for the other district heating substations was also retrieved this day, and the transport times were determined in the same way. These are listed in Figure 4. The longest transport time measured was almost 4 hours, but for most parts of the network the transport time seem to be 3 hours or less.

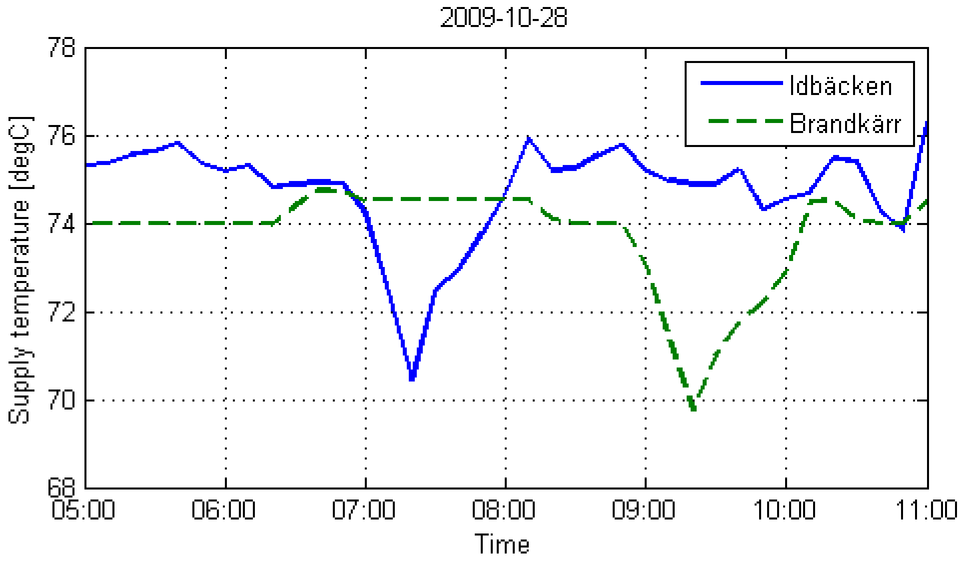


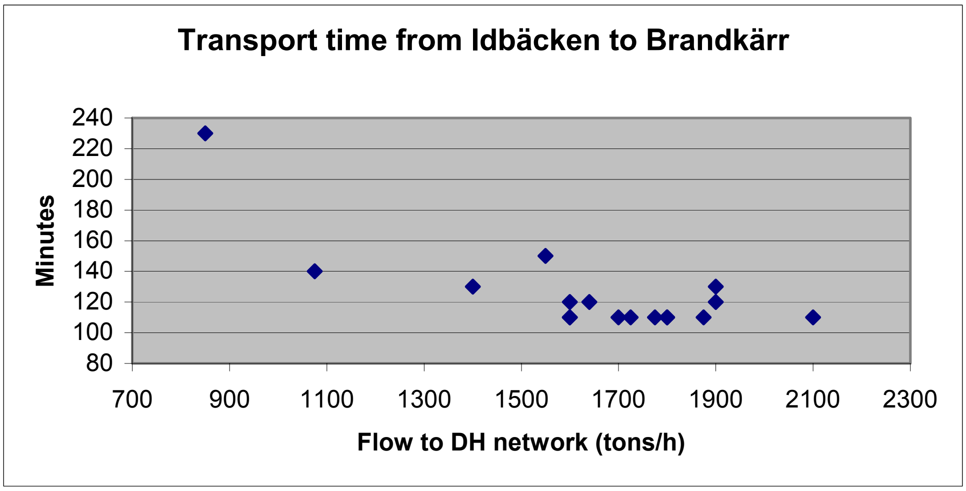
Figure 3. Determination of transport time on the district heating network.

Figure 4. Table of transport times for different parts of the network.

Area	*District heating substation*	*Transport time [h]*
Oppeby	Oppeby gård 217	2,05
	Regeringsvägen 33	1,30
	Oppeby gård centrum	1,30
Arnö	Trollstigen	2,45
	Sellerigången	3,55
	Mejramvägen	2,45
Centrum SO	Östra promenaden 3b	0,55
Centrum NO	Östra rundgatan 8	2,10
	Östra rundgatan 2	2,30
	Östra rundgatan 3	2,20
Brandkärr	Brandkärr	2

In Figure 5, the transport time from Idbäcken to Brandkärr at different flow levels is plotted. Each data point corresponds to an occasion when the supply temperature made a fast change that could be detected in the measurement data from Brandkärr. Generally, the flow is not constant during the time it takes the water to travel from Idbäcken to Brandkärr, but the mean value of the flow during the transport time is used in the plot. It can be seen that for flows over 1600 tons/h, the transport time is between 100 and 120 minutes. Since the model-based control will only be active at medium and high load, the transport time can be considered constant.

Figure 5. Measured transport time from Idbäcken to Brandkärr.



In the model, two values for the transport time are used. When the load is calculated, the transport time for *the majority of the network* is used, and it is approximated to be 3 hours. A mean value of the supply temperature for this period is used to calculate the load on the whole network. The other transport time is used as prediction horizon for the load. This is the transport time approximated to the load *centre-of-balance*, and it is approximated to be 2 hours.

3.2 Load model

The load of the district heating network consists of a social load (use of hot water) and a weather dependent load (heat for radiators). The distribution losses can also be seen as a slowly changing load.

The load model consists of two parts: Diurnal (day-to-day) load and a dynamic black box model of the so-called ARX-type. The diurnal part models slow variations such as seasonal changes, and most importantly the variation of the social load during the day and night. The ARX part models the weather dependence and other changes of the load that are faster than the daily variation. The delivered heat is the sum of the load of the diurnal load model and the ARX load model (equation (5)).

$$P_{del} = P_{diurnal} + P_{ARX} \tag{5}$$

3.2.1 Diurnal load model

The diurnal load model makes the gross assumption that the load at a certain time today will be the same as the mean value of the load at the same time the four last days. The model has a sampling time of 10 minutes, which makes one day and night 144 samples. The diurnal load is calculated according to equation (6).

$$P_{diurnal}(t) = \frac{P_{del}(t-144) + P_{del}(t-288) + P_{del}(t-432) + P_{del}(t-576)}{4} \quad (6)$$

Using the mean value of specifically 4 days was motivated empirically during the modelling process [1]. The number of days used in the mean value was increased until the improvement of the model with an added day was not substantial. It was tried to model the variation between weekday and weekend by using the load one week ago together with or instead of the load the recent days. That did not improve the model performance.

3.2.2 ARX model

The ARX model structure is a general discrete-time dynamic model. It can be used for simulation or prediction with an optimal observer. The model consists of polynom in the time shift operator q, see equation (7). The model parameters *A* and *B* can be estimated from data using the "System Identification Toolbox" of the computational software Matlab. For more information on empirical modelling methods and the ARX model, see for example [21].

$$y(t) = \frac{B(q)}{A(q)}u(t) + \frac{1}{A(q)}e(t) \quad (7)$$

A third-order ARX model is used to model the deviation of the load of the Nyköping district heating network from the diurnal pattern during the last four days. Input to the model is the *diurnal difference* of the outdoor temperature, described by equation (8), and output is the deviation of the load from the "prediction" made by the diurnal load model.

$$P_{diff}(t) = P_{del}(t) - P_{diurnal}(t) \quad (8)$$

The model parameters were estimated with data from September 2008 to May 2009, and can be seen in equation (9).

$$\begin{aligned} y(t) &= \frac{(-0.536 + 0.01361q^{-1} + 0.5132q^{-3})u(t) + e(t)}{1 - 1.033q^{-1} + 0.1221q^{-2} - 0.07039q^{-3}} = \\ &= -0.536u(t) + 0.0136u(t-1) + 0.5132u(t-3) + \\ &\quad + 1.033y(t-1) - 0.1221y(t-2) + 0.07039y(t-3) + e(t) \end{aligned} \quad (9)$$

y	= diurnal difference of the heat load
u	= diurnal difference of the outdoor temperature
e	= error, white noise

In the degree project [1], various model structures and model orders were tested, and the third order ARX model was chosen since the performance of the model did not improve substantially from using higher order or more complex model structure.

3.3 Control strategy

In this section, the suggested model-based control strategy is described. Figure 6 shows a schematic picture of the calculation steps used to find the appropriate supply temperature setpoint.

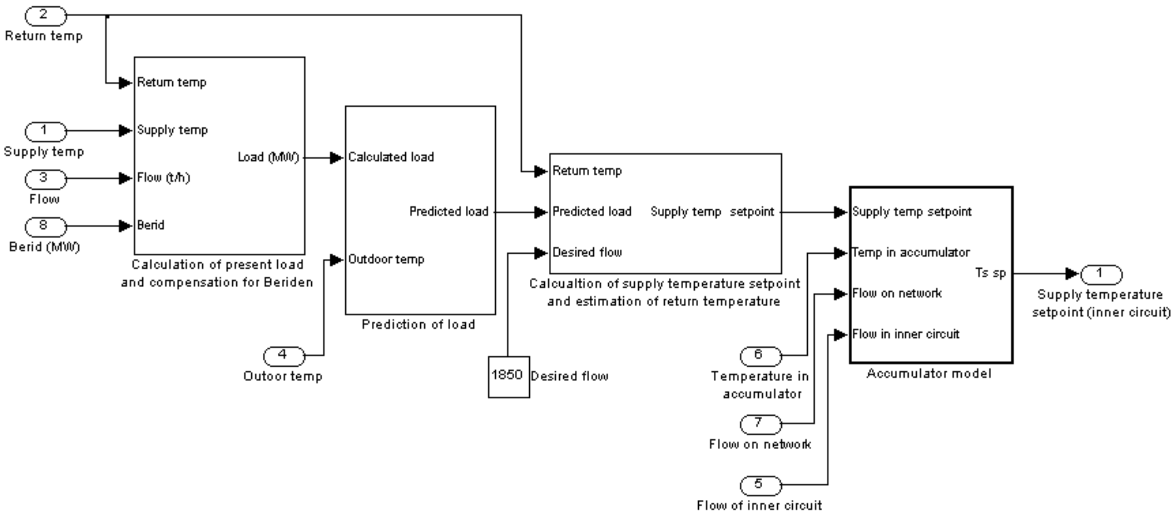


Figure 6. Schematic picture of the calculation of the supply temperature setpoint.

The supply temperature setpoint is updated every 10 minutes, and is determined using the following steps:

1. Calculation of the present load of the district heating network.
2. Compensation for recooler "Beriden".
3. Prediction of load.
4. Estimation of return temperature from the customers.
5. Calculation of supply temperature setpoint.
6. Compensation for accumulator.

1. The present load is calculated according to equation (10). The transport time Δt is approximated to be constantly 3 hours, although in reality it varies with the flow of the network. See discussion on transport time in chapter 3.1.1.

$$P_{del}(t) = c_p Q(t)\left(\frac{1}{\Delta t}\sum_{i=t-\Delta t}^{t} T_s(i) - T_R(t)\right) \tag{10}$$

P_{del} = heat delivered to the consumers

c_p	=	specific heat of water
Q	=	mass flow of water to the network
T_s	=	supply temperature measured at the plant
T_R	=	return temperature measured at the plant
Δt	=	transport time (3 hours)

2. The power cooled away by “Beriden” is subtracted from the calculated load. If “Beriden” has increased or decreased its cooling power with more than 5 MW during the last half-hour, the new value of the load is judged to be unreliable, and its last value is used instead. This is done to eliminate disturbances from “Beriden”. When the recooling is increased, the flow to the network increases momentarily, and the return temperature from the part of the network where “Beriden” is located falls. The transport time of return water from “Beriden” to Idbäcken is approximately 20 minutes and therefore the return temperature will need at least 20 minutes to stabilize to its new value. See Figure 7.

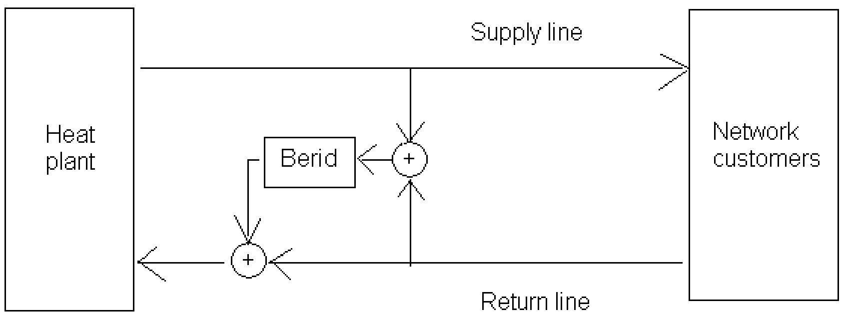


Figure 7. Sketch of the connection of “Beriden” to the network.

3. The load 2 hours into the future is predicted using the diurnal difference model in equation (6) and the ARX model in equation (9). The prediction horizon 2 hours is chosen in order to ensure that this supply temperature should reach half of the network before the predicted load is exerted.

4. The return temperature from the customers of the district heating network changes slowly, and depends on the time of the day and the outdoor temperature. It is measured at the plant, but at times when the recooler “Beriden” is in operation, the measured return temperature does not correspond to the return temperature from the consumers. If the return temperature modified by “Beriden” is used to calculate the appropriate supply temperature, the supply temperature will be too low to provide the demanded power to the consumers. This problem was noticed during the tests, and was solved by using a model to estimate the real return temperature in the simulation study (see chapter 3.3.1).

5. The supply temperature setpoint is calculated from the predicted load, the return temperature (either modelled or measured) and a desired flow value (according to

equation 11). During the first initial test, the desired flow was 1750 tons/h. For the second initial test and the long-term test, it was increased to 1850 tons/h. By adjusting the desired flow, the general supply temperature level is changed.

$$T_{s,sp}(t) = \frac{P_{pred}(t+12)}{c_p Q_{desired}} - T_{r,pred} \tag{11}$$

$T_{s,sp}$ = setpoint for the supply temperature,
P_{pred} = prediction of the load,
$T_{r,pred}$ = predicted return temperature and
$Q_{desired}$ = desired flow
$T_{r,pred}$ = predicted return temperature

6. Compensation for accumulator. In Idbäcken, the control of the supply temperature is executed in the inner circuit, which means that the temperature from the condensers follows the supply temperature setpoint. However, at times when the accumulator tank is unloading, the temperature to the district heating network will not be the same as the temperature from the condensers, if it is not the same as the temperature in the accumulator tank. To be able to set the temperature to the network at the setpoint prescribed by the model, the setpoint for the inner circuit must be adjusted in order to compensate for the water added from the accumulator tank (see equation 12).

$$T_{s,sp,inner}(t) = \frac{T_{s,sp,net}(t)Q_{net}(t) - T_{ack}(t)Q_{ack}(t)}{Q_{inner}(t)} \tag{12}$$

$T_{s,sp,inner}$ = supply temperature setpoint to the inner circuit
$T_{s,sp,net}$ = supply temperature setpoint to the network
T_{ack} = temperature in the accumulator
Q_{net} = mass flow to the network
Q_{ack} = mass flow from the accumulator tank
Q_{inner} = mass flow in the inner circuit

3.3.1 Return temperature model

In the analysis of the tests of the control strategy, it was noticed that the supply temperature was sometimes too low when the recooler “Beriden” was turned off, although the load prediction had been accurate. The reason was that the real return temperature from the customers was underestimated, because the only measurement of the return temperature was affected by the recooling. To avoid this problem, an estimate of the return temperature from the customers must be used instead of the measured return temperature at times when “Beriden” is active.

In Figure 8, return temperature measurements from September 2008 to November 2009 at times when the recooler is shut down or operating at less than 5 MW are plotted together with a linear approximation valid for outdoor temperatures under 5ºC. This approximation was used in the simulation study in the *calcualation of the supply* *temperature setpoint*. However, for the *calculation of the load*, the measured value of the return temperature was used.

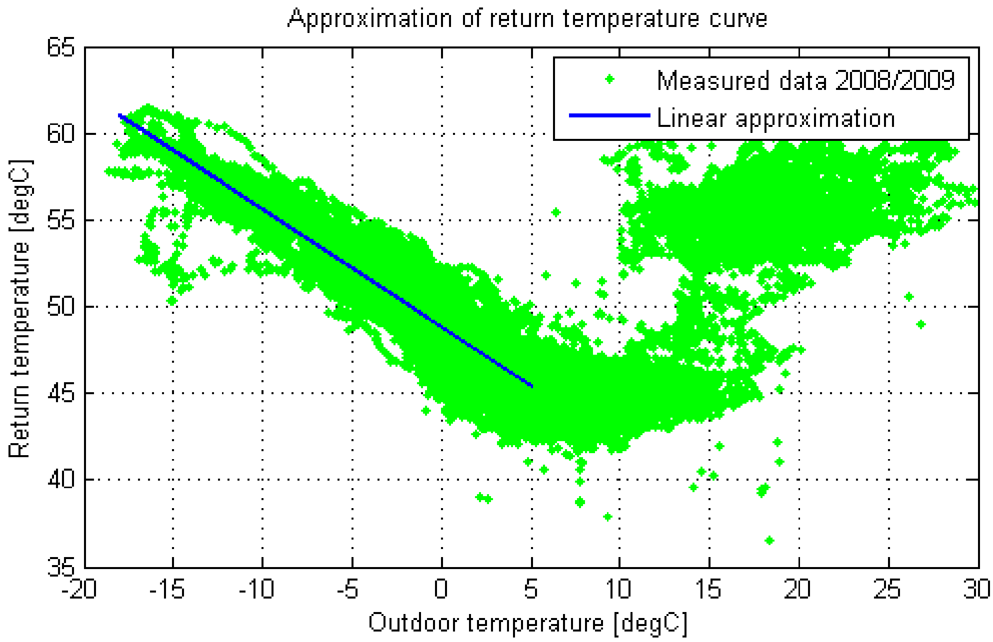


Figure 8. The outdoor temperature dependence of the return temperature.

4 Experiments

The model-based control strategy was tested at Idbäcken's CHP plant during the autumn 2009. The initial 24-hour tests aimed at determining if the transport time of the model was correct. Three such tests were made, of which the first yielded no information about the transport time since the supply temperature was constant during the whole test. The result of the other two initial tests is presented in chapter 4.1.

After the initial tests, a long-term test began. The aim of the long-term test was to generally test the performance of the control strategy at different load levels and conditions, and also to see how the model would perform working on data created by the new control strategy. Supply temperature reduction, flow stability, alpha value improvement and differential pressure on the network were the parameters most interesting to evaluate.

As a precaution from the plant owner, the supply temperature was not allowed to diverge from the old control setpoint by more than 5ºC, or to go below 75ºC, during the tests. Data sampling time was 10 minutes.

4.1 Initial tests

The initial tests were carried out the 12th to 13th of November and 2nd to 3rd of December 2009 at Idbäcken's CHP plant. The main purpose was to test the network model, particularly the estimated transport delay time from heat plant to load point-of-balance. For both the initial tests, the model was set to counteract the effect of the recooler "Beriden". The control was attempting to keep the flow to the network constant regardless of if "Beriden" was running or not. This control strategy was changed before the long-term test, so that the supply temperature would only follow the load of the real customers, and not be increased just because the recooling was increased. In all the plots, the supply temperature setpoint given by the long-term test model is showed as well as the actual supply temperature setpoint (given in the initial tests by the initial model, and always kept within 5°C from the old control setpoint).

In Figure 9 and Figure 10, the result of the first initial test is shown. For this test, the desired flow was set to 1 750 ton/h. The supply temperature was lower than it would have been with the old control during the afternoon and night, but higher during the morning, when the load was high (top pictures in Figure 9). The flow to the network was rather constant during the experiment (Figure 10), except for small disturbances when the recooling was changed. The frequency of the district heating pump was stable and below its limit 50 Hz, and the differential pressure in the peripheral point of the network used to control the pump, was stable except for short disturbances due to changes of the recooling (Figure 9).

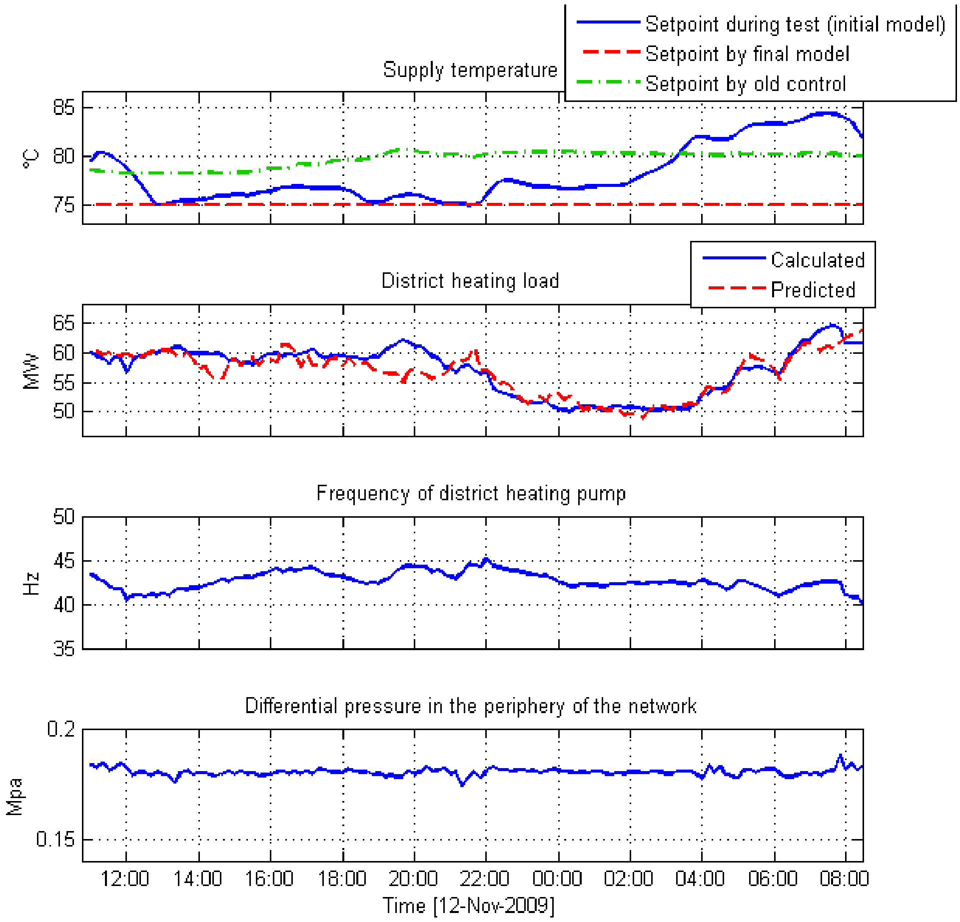


Figure 9. First initial test.

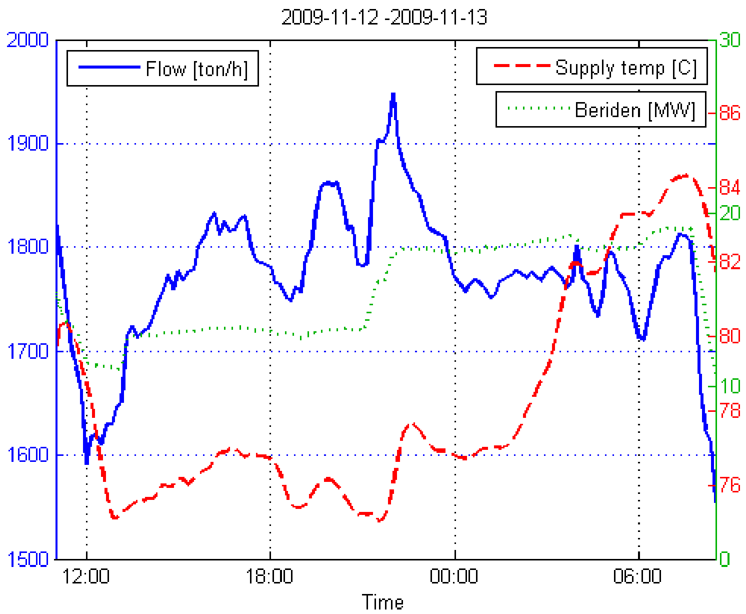


Figure 10. First initial test.

The load increase in the morning is accurately predicted by the load model. The supply temperature is increased accordingly. The fact that the flow stays relatively constant (until “Beriden” is turned off) shows that the transport time of the network model is correct – the consumers get a higher supply temperature in time for their load peak and does not have to increase the flow on the network to get their required heat.

In Figure 11 and Figure 12, the result of the second initial test is shown. For this test, the desired flow was set to 1 850 ton/h. The supply temperature was lower than it would have been with the old control except for a couple of hours in the early morning when the recooling was high (Figure 11). From approximately 18:00 to 03:00, the recooler “Beriden” was turned off. The reason why the setpoint did not follow the “setpoint by model”-curve at that time is the restriction on the deviation from the old control setpoint. The setpoint is forced to follow 5ºC below the old control setpoint, which is increasing due to sinking outdoor temperatures. This supply temperature is actually too high, as can be seen on the flow to the network, which starts to decrease at 18:00, and stays low until “Beriden” is started at 03:00 (Figure 12). The rapid load increase causes a disturbance in the differential pressure on the network, which makes the pump run up. It also causes an increase in supply temperature, since the model during this experiment was set to respond on the recooling. Once “Beriden” stabilizes and the supply temperature is adjusted to the new load, the flow stabilizes around the desired flow level.

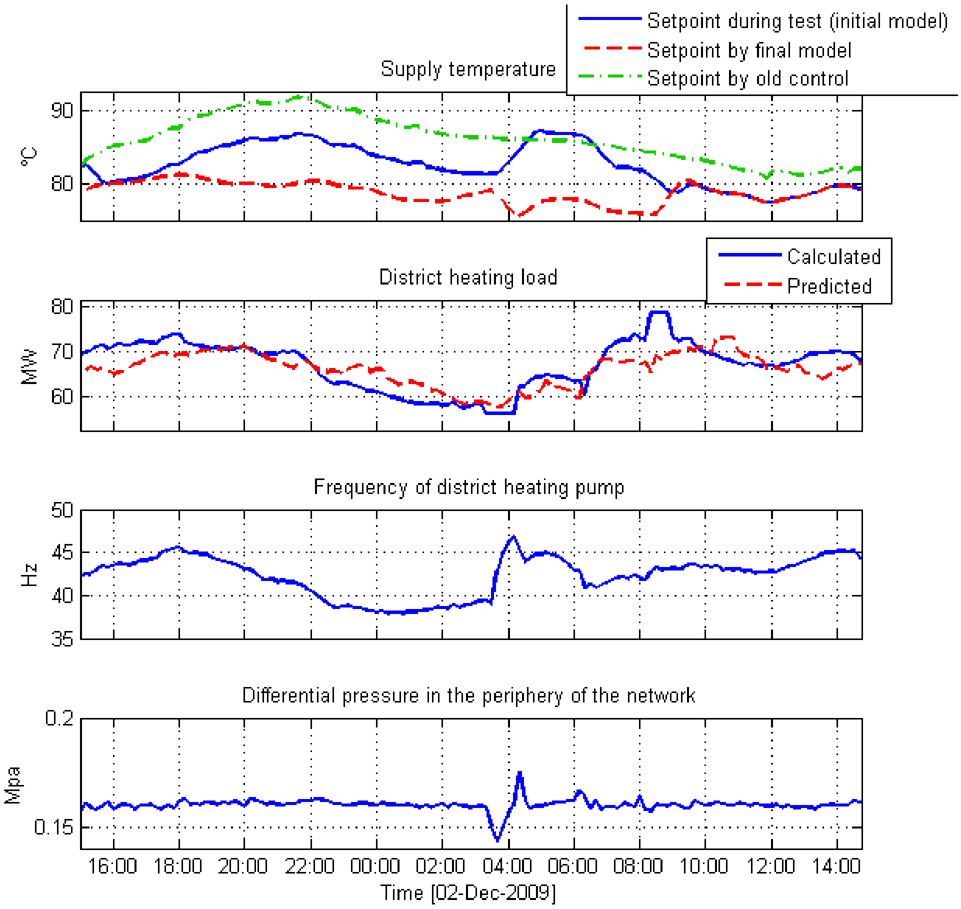


Figure 11. Second initial test.

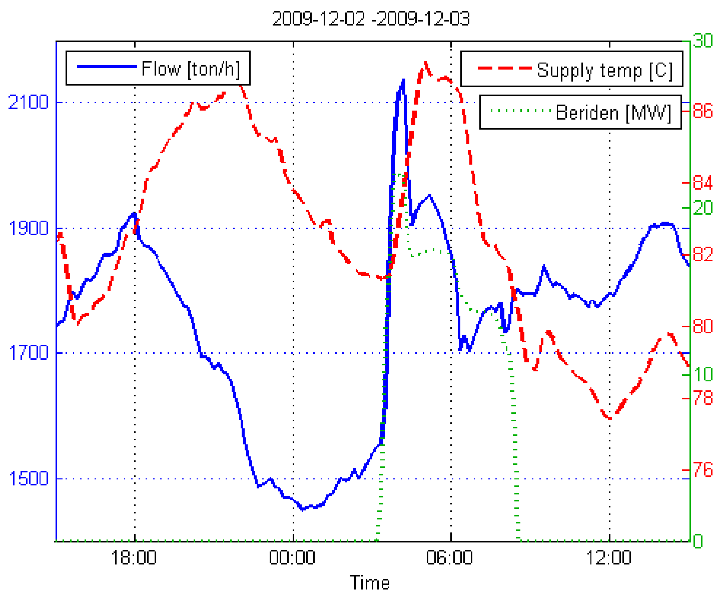


Figure 12. Second initial test.

4.2 Long-term test

The long-term test was carried out from December 3rd to December 15th 2009 and January 18th to January 24th 2010. The result of the test is plotted in Figure 13-Figure 21.

During the first part of the test, December 3rd to December 10th, Figure 13 and Figure 14, the load was not sufficient to get any variation in the supply temperature. Although the old control would have asked for a higher supply temperature the 6th and the 9th-10th of December, the model-based control did not deem it necessary. The flow was high from time to time during this period, but this was correlated to the recooling by “Beriden”. As can be seen in the bottom picture in Figure 13, the differential pressure on the network was either 0.16 or 0.18. Generally the district heating pump is run with a setpoint of 0.18 MPa network differential pressure when the recooler “Beriden” is in operation, and 0.16 MPa at other times.

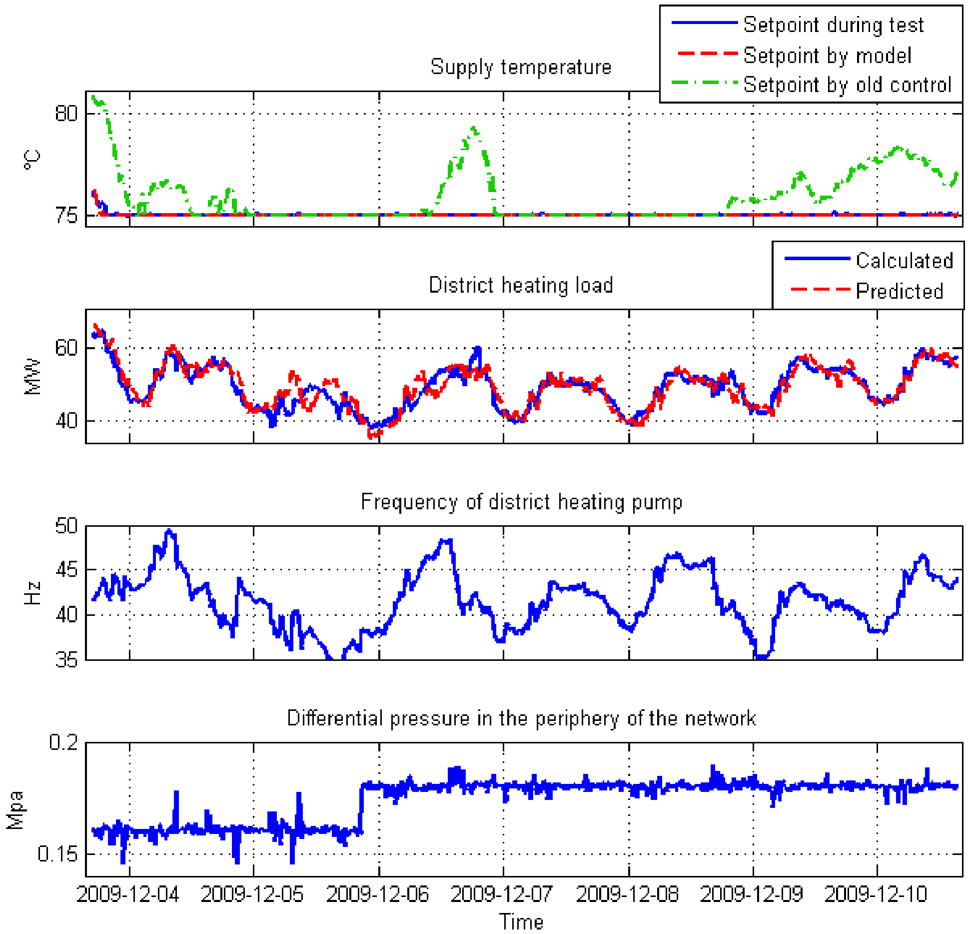


Figure 13. First part of long-term test.

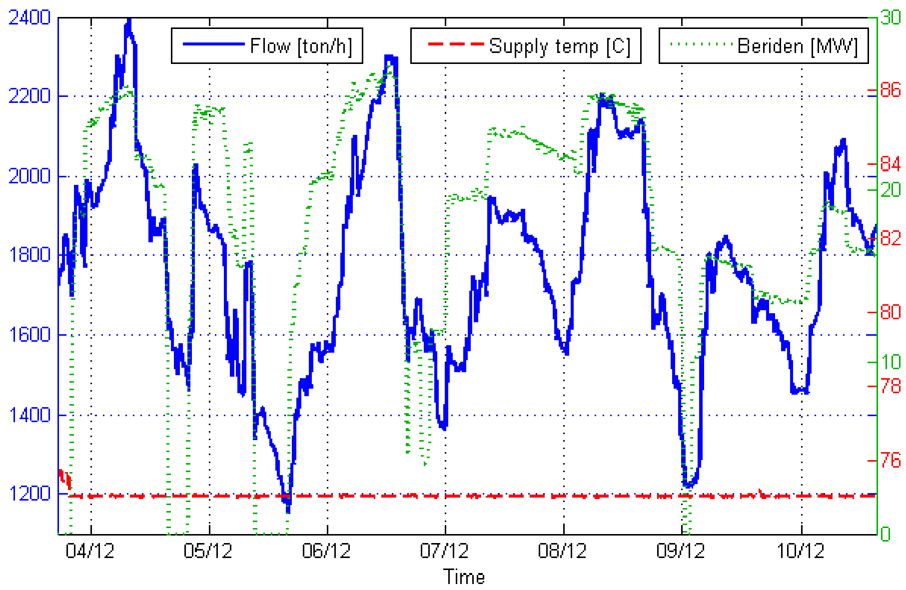


Figure 14. First part of long-term test.

Data from the second part of the long-term test, December 10th-15th, can be seen in Figure 15 and Figure 16. The 12th of December, the supply temperature setpoint exceeds 75ºC for the first time. At first it is forced up because the old control setpoint exceeds 80ºC, but shortly after this, the model also prescribes an increase. The flow is kept on an appropriate level, except for peaks due to the recooling.

The next noteworthy thing happens in the morning the 14th of December. The load increases rapidly, and so does the supply temperature setpoint. The recooling is turned off (probably because the load peak has been observed in the control room). However, the flow continues to increase slightly for a couple of hours, until the load decreases again. The high flow at this time is caused by the underestimation of the load predicted by the model, which can be seen in the second picture from the top in Figure 15.

Another interesting thing happens the 15th of December. The supply temperature setpoint by the model makes two dips. The first one is due to the dip in the load at this time. Since the supply temperature is not allowed to follow the load down, the flow is rather low during this period. The second dip, however, is not connected to a load decrease. In fact, this dip is caused by a dip in the measured return temperature, caused by the turning on of the recooling. The return temperature from the customers is higher than the measurement at this time, since the recooling lowers the measured return temperature. But the model interprets the measured return temperature as coming from the customers, and therefore sets a supply temperature that is too low. The peak in the flow at this time is due both to the return temperature problem and to underestimation of the load by the predictor.

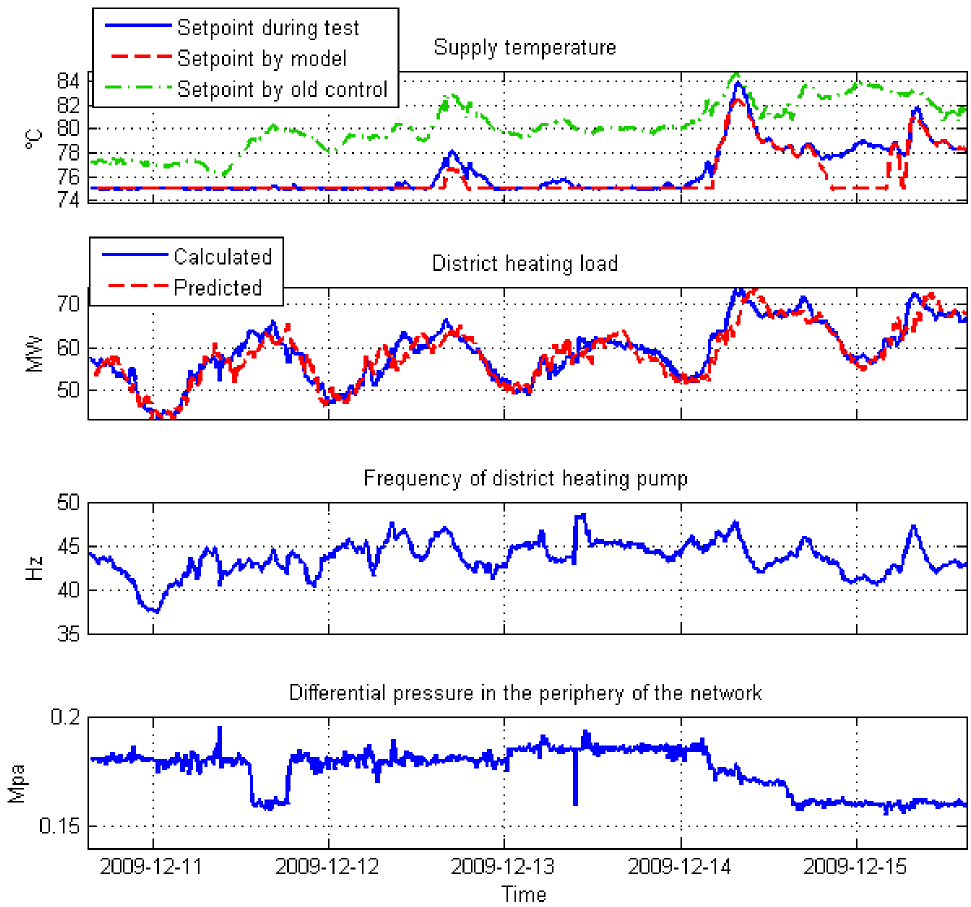


Figure 15. Second part of long-term test.

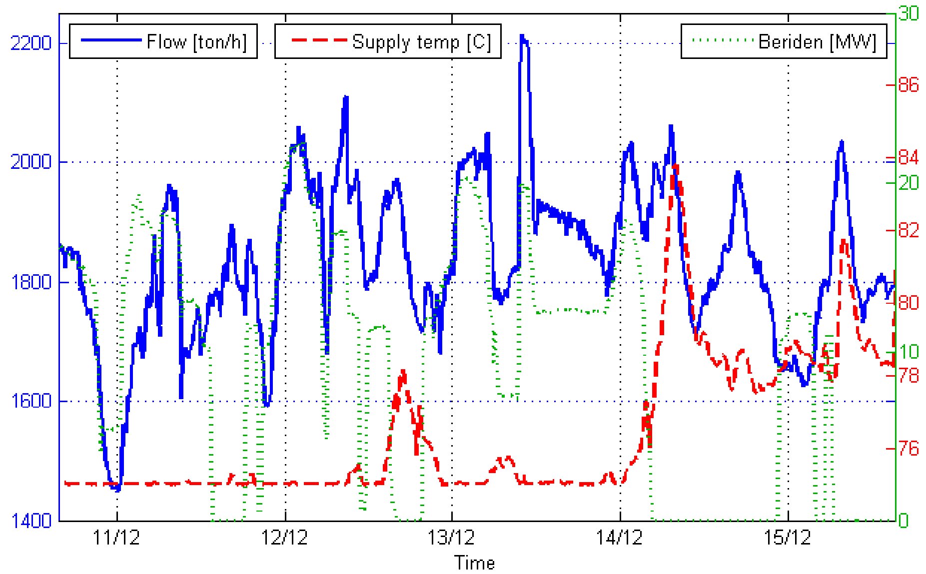


Figure 16. Second part of long-term test.

Data from the third part of the long-term test, January 18th to 24th, is plotted in Figure 17 and Figure 18. The outdoor temperature was between +1ºC and –2ºC during most of this test period. However, during the night the 23rd and 24th, the temperature fell to –13ºC and –15ºC respectively. The recooler "Beriden" was turned off during the whole period. The supply temperature was approximately the same as the old control setpoint during the days and 5ºC below evenings, nights and early mornings. The variations in the flow to the network and the frequency of the district heating pump were small, and the differential pressure on the network was kept at setpoint. The sharp outdoor temperature drop the 23rd of January forced the supply temperature setpoint to rise more than the model prescribed. This caused the flow to drop on the network, which indicates that the supply temperature prescribed by the model would have actually been sufficient. The next morning, the outdoor temperature dropped even sharper, and this time the model was not able to keep up, resulting in a peak in the flow. After this, the tests unfortunately had to be aborted due to operational problems of the plant.

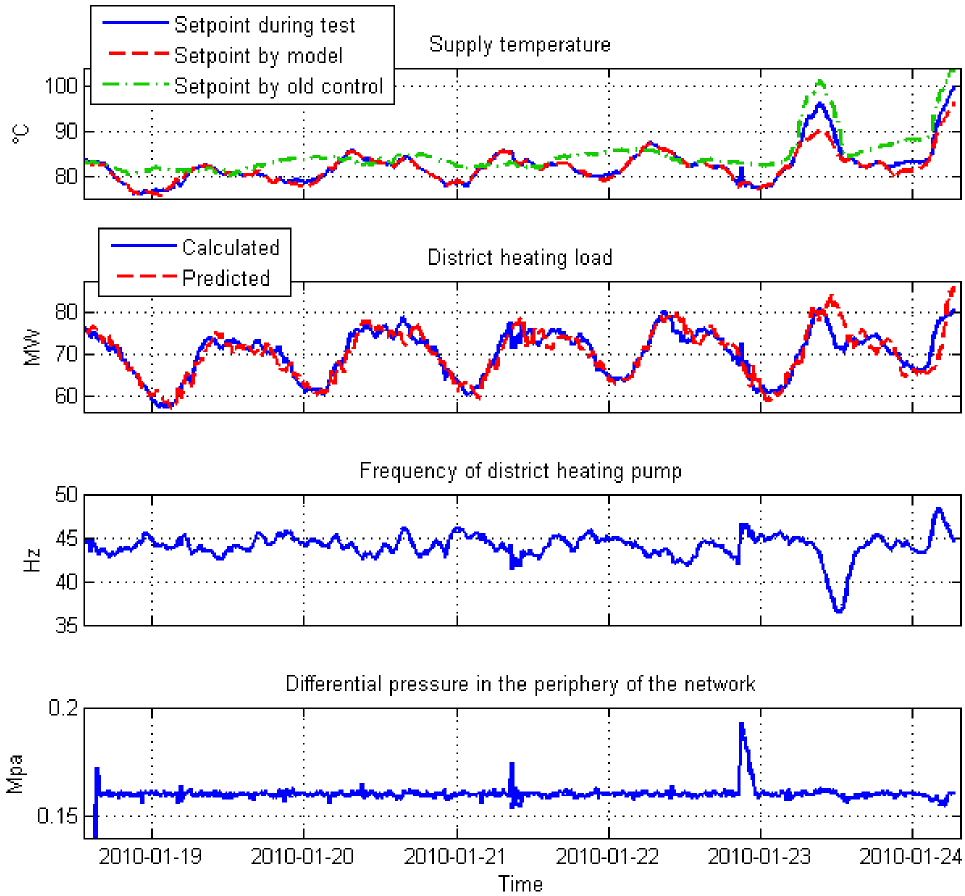


Figure 17. Third part of long-term test.

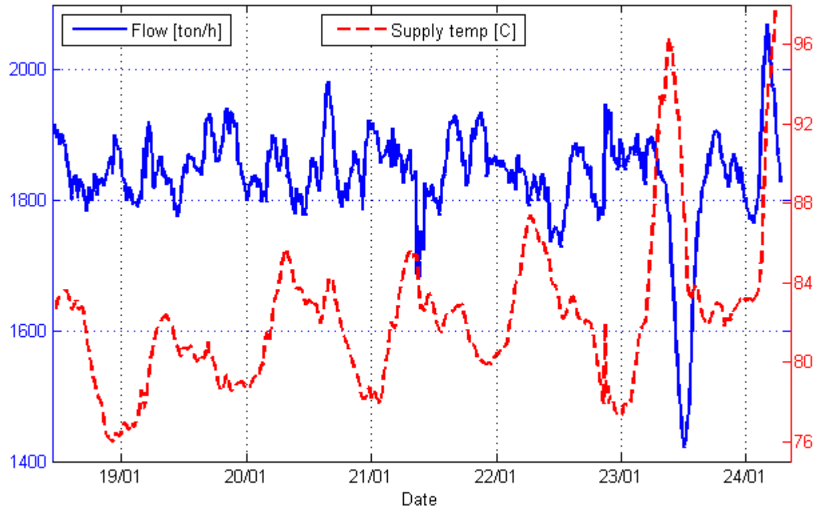


Figure 18. Third part of long-term test.

In Figure 19-Figure 21, the data from the tests of model-based supply temperature control is compared to data from the ordinary control. In Figure 19, the flow variations with the old control and the model-based control are compared. The shift from the ordinary control to the model-based control the 18th of January can be seen clearly. The flow variations diminish and the supply temperature starts to follow the diurnal load variation. From the 12th to the 14th, the weather was cold and the supply temperature was therefore high. From the 16th to the 22nd, the outdoor temperature was rather constant.

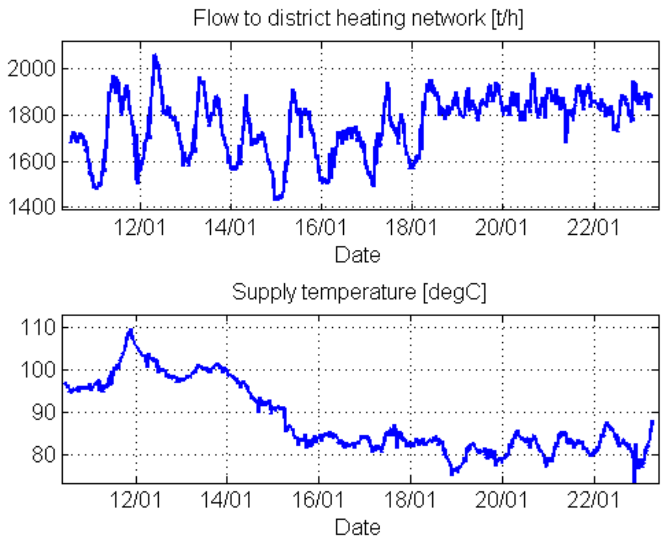


Figure 19. Comparison of flow and supply temperature with old and new control. At noon the 18th of January, the control switched from the ordinary control curve to model-based control.

In Figure 20, the supply temperature is plotted against the outdoor temperature for old control 1st of November 2009 to 18th of January 2010 (green) and for the tests of model-based control (blue). Included in the old control data are situations when a higher supply temperature was chosen manually. The alpha value during the same time period is plotted against the outdoor temperature in Figure 21. There is a wide distribution of the alpha value, but for the experiments it has clearly been in its upper range.

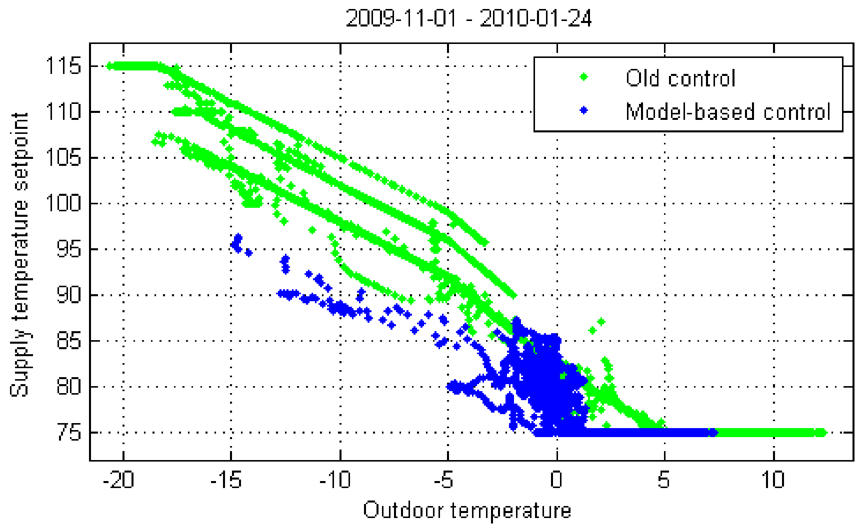


Figure 20. Supply temperature to the district heating network in November and December 2009, with and without model-based control.

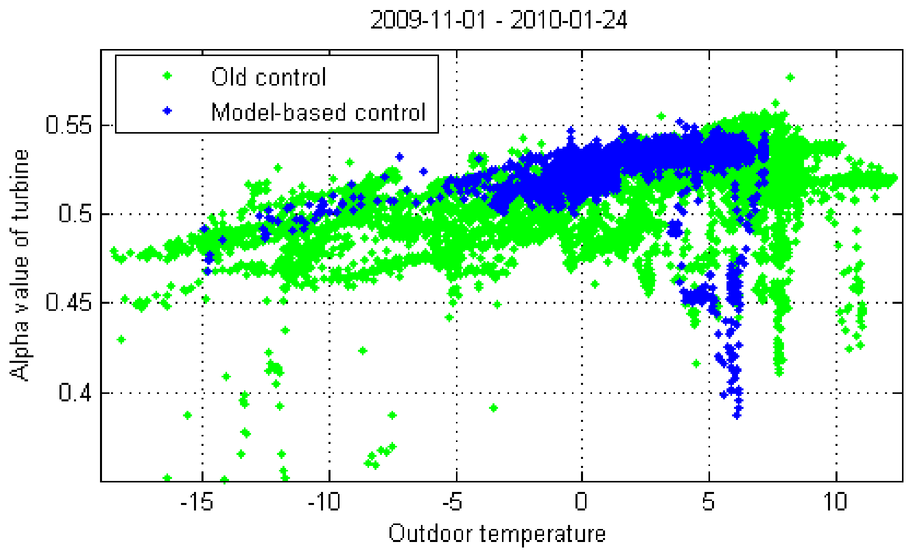


Figure 21. Alpha value in November and December 2009, with and without model-based control.

4.3 Simulation of a year with model-based control

In order to get a more thorough picture of the benefits of the model-based control, a year was simulated using input data from September 2008 to May 2009. Before the simulations, the model was adjusted to include the return temperature model in the calculation of the supply temperature setpoint. This should lead to a slightly higher supply temperature than the model used for the tests would have given. The alpha value was simulated using the relation in equation (2) in Chapter 2.

The results of the simulation study are presented in Figure 22-Figure 26. In Figure 22, the mean value of supply temperature reduction and increase of alpha value and electricity production for different outdoor temperatures are listed. The best results are obtained for outdoor temperatures around –5ºC.

Figure 22. Table of results for different outdoor temperatures.

Outdoor tempeature [ºC]	*-10*	*-8*	*-6*	*-4*	*-2*	*0*	*2*	*4*	*6*
Reduction of supply temperature [ºC]	5,4	5,6	6,2	6,1	5,0	5,4	4,7	2,8	0,4
Increase of alpha value	0,016	0,016	0,018	0,018	0,014	0,016	0,014	0,008	0,001
Increase of el. prod. [MW]	0,8	0,8	1,0	0,9	0,7	0,7	0,5	0,3	0,0

Although the alpha value is increased more for lower outdoor temperatures, the gain from using the model-based control strategy is highest around +2ºC, since that temperature is more common. This can be seen in Figure 23. The additional electricity production during one year is divided into outdoor temperature bins, and clearly peaks at +2ºC.

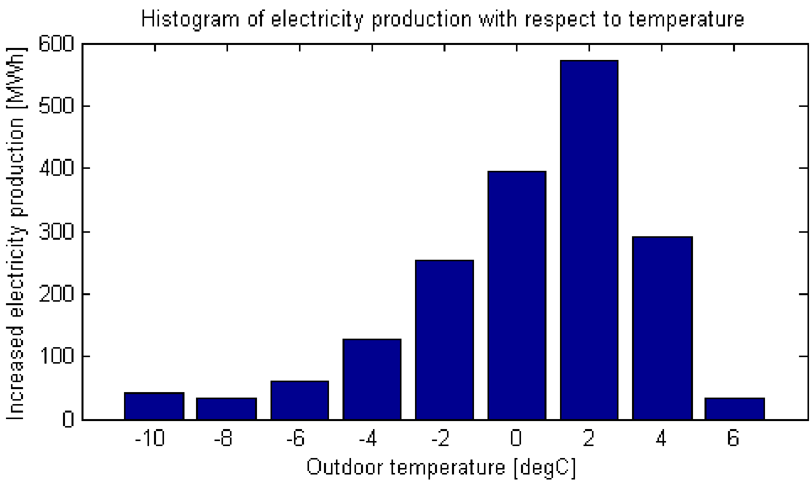


Figure 23. Simulation results. Increase in electricity production with one year of model-based control for different outdoor temperatures.

In Figure 24, the supply temperature setpoint with model-based control for different outdoor temperatures is compared to the old control and to an "optimal" supply temperature. The optimal supply temperature is here the temperature that would ensure a constant flow of 1 850 ton/h to the district heating network. The figure shows that the mean supply temperature would be approximately 5°C lower for all outdoor temperatures below +2°C with the model-based control.

Another interesting thing can be seen for outdoor temperatures from 2ºC to 6ºC. The supply temperature by the model is limited downwards to 75ºC. The discrepancy between the optimal supply temperature and the temperature by the model shows that much could be gained if the lower supply temperatures were allowed. Although the mean supply temperature of the model is above 75ºC for outdoor temperature below 4ºC, there are times with outdoor temperatures down to 0ºC when the load is low enough for actually going below 75ºC. The reason for not allowing lower supply temperatures is that customers in the periphery of the network might not get the prescribed temperature. Improvements in the outer part of the network could open the possibility to allow lower supply temperatures.

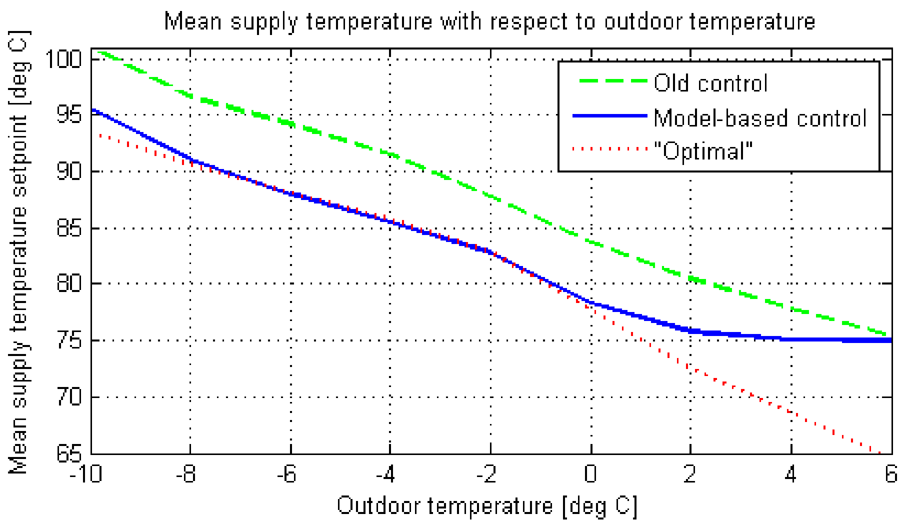


Figure 24. Simulation results. Mean supply temperature setpoint with respect to outdoor temperature.

In Figure 25, the mean supply temperature with respect to the hour of the day is plotted. One can see that the old control generally gives high temperatures during the night and lower during the day (following the variations of the outdoor temperature). The model-based control instead reduces the supply temperature during the night, and peaks in the morning hours. The main reduction of the supply temperature with the model-based control strategy takes place from 19:00 to 07:00.

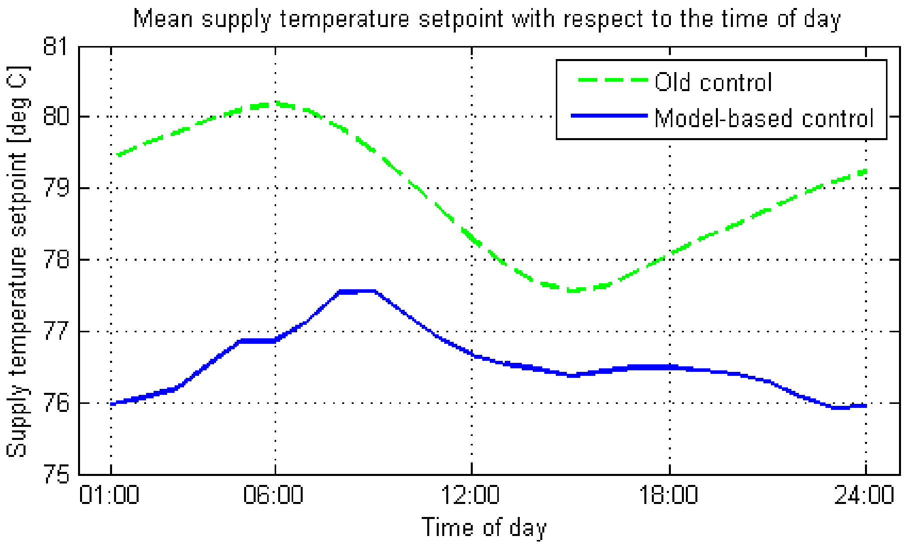


Figure 25. Simulation results. Mean supply temperature setpoint with respect to the time of day.

Another parameter of interest is the flow to the network. A high flow corresponds to a low supply temperature. With too high flow, however, there is a risk for heat deficit and low differential pressure the on the network. Flows over 2000 tons/h should be avoided on the Nyköping network. Figure 26 shows a duration graph of the flow to the network with model-based control and with the old control. The model-based-control results in a flow higher than 2000 tons/h for about 400 hours. However, if the effect of the recooler is withdrawn (see the dashed line), most of these high flows disappear, and the model-based control gives approximately the same delivery reliability as the old control. At times with high flow and "Beriden" in operation, the operator can easily stabilize a falling differential pressure by reducing the recooling.

A flow higher 1600 tons/h is obtained for 1900 hours with the old control, and for 3100 hours with model-based control.

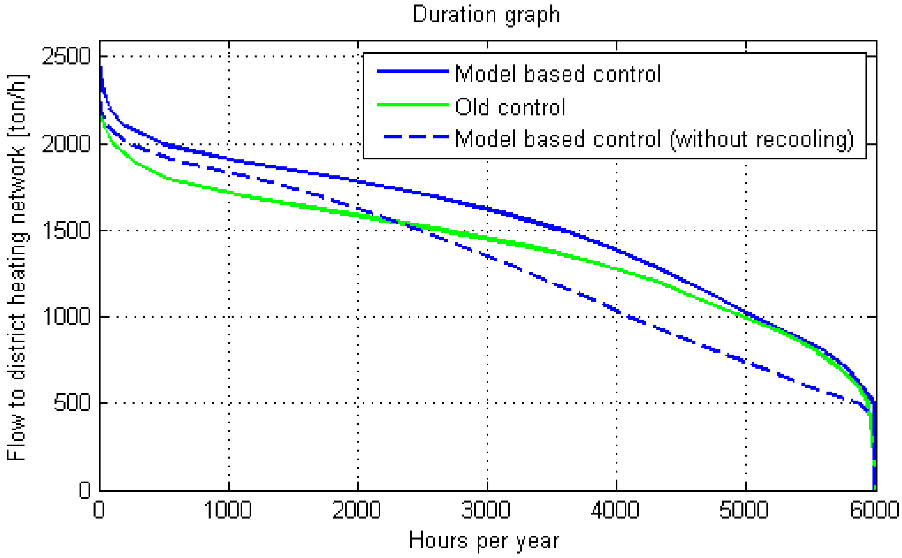


Figure 26. Simulation results. Duration graph of the flow to the district heating network.

In Figure 27, the flow to the network in average for different outdoor temperatures is plotted. In the graph, the mean values are plotted with a solid line, and the standard deviation is plotted with a dashed line. It can be seen that the flow is higher and more stable with model-based control.

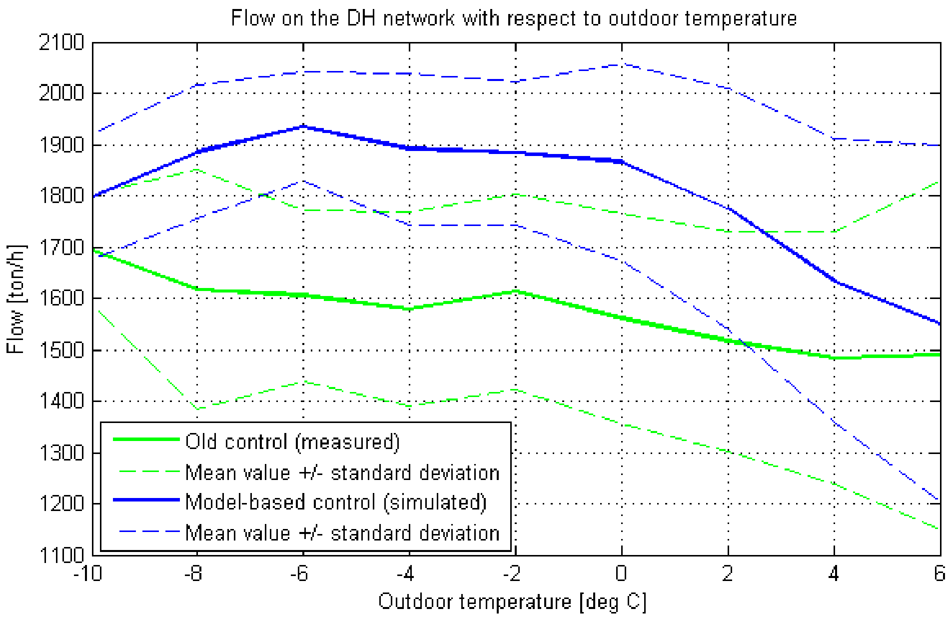


Figure 27. Flow to the district heating network with respect to outdoor temperature, 2008-2009.

4.3.1 Model reliability

One way to quantify the reliability of the model is the root mean square of the prediction error (RMSE). The RMSE is calculated according to equation (13). For the simulation of the production year 2008/2009, the RMSE of the load predictions is 3.3 MW. This can be compared to the standard deviation of the load, which was 17.4 MW for the same period.

$$RMSE = \sqrt{\frac{\sum_i \left(P_{predicted}(i) - P_{measured}(i)\right)^2}{i}} \tag{13}$$

The model does not model the difference between weekdays and weekends. The reason for this was that attempts to include it in the model did not improve the model performance. The model structure uses data from the 4 last days to predict the load. Therefore, it can be expected that the predictions for Thursdays and Fridays should be best, and the predictions for Saturdays worst. In Figure 28, the RMSE for each day in the week is plotted. One can see that the difference of the prediction error between the days is moderate. Saturdays and Mondays are most difficult to predict, but there is no noticeable difference between the prediction error for Tuesdays, Thursdays and Wednesdays. It can be concluded that it was reasonable not to model the difference between weekends and weekdays explicitly.

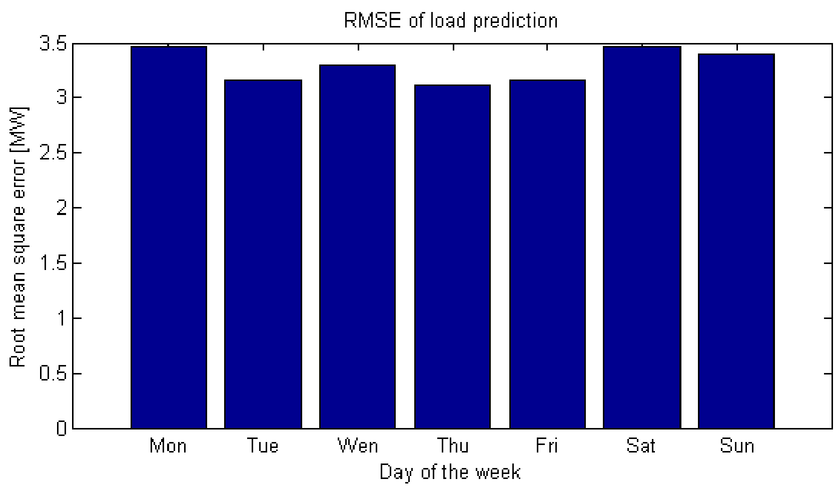


Figure 28. Root mean square error of the load predictions with respect to the day of week.

It should be noted that the performance of the model-based control strategy does not only depend on the prediction error of the load model, but on estimation of the return temperature and the network model as well. The RMSE of the return temperature model is 1.4ºC. The network model does not affect the control strategy directly in the same way as the load and return temperature models, but a bad network model could give an undesired lead or lag on the supply temperature. The experiments showed that the transport model is satisfactory.

5 Results

5.1 Initial tests

The goal of the initial tests was to evaluate and tune the model's transport time from heat plant to consumer. The result showed that the estimated transport time (3 hours to reach the major part of the network, 2 hours prediction horizon for the load model) was valid.

The initial tests brought up the question of whether the supply temperature should increase to counteract the increased flow when the recooler "Beriden" was operating, or if it should just aim to satisfy the real customers of the network. It was decided, after a discussion with the plant owner, that "Beriden" should not affect the supply temperature, and the model was changed accordingly before the long-term test.

5.2 Long-term test

The goal of the long-term test was to evaluate the model-based control strategy with respect to reduction of supply temperature, increase of alpha value and electricity production, effect on flow variations and heat delivery reliability.

Supply temperature
During the tests, the supply temperature setpoint was reduced with 2.7ºC on average.

Alpha value and electricity production
It is rather difficult to determine the alpha value improvement generally from the change of the alpha value and electricity production during the tests, since they are affected by so many parameters other than the supply temperature – fuel, load, steam temperature and pressure before the turbine, return temperature from the district heating network, etc. In Figure 29, the mean alpha value for different outdoor temperatures during the tests and for some time before, after and in between the tests are compared to measurements and simulations from the season before. The alpha value was generally higher in November 2009-January 2010 than it was in the period September 2008-May 2009. Both the simulated data and data from the test however show that the model-based control improves the alpha value compared to the old control.

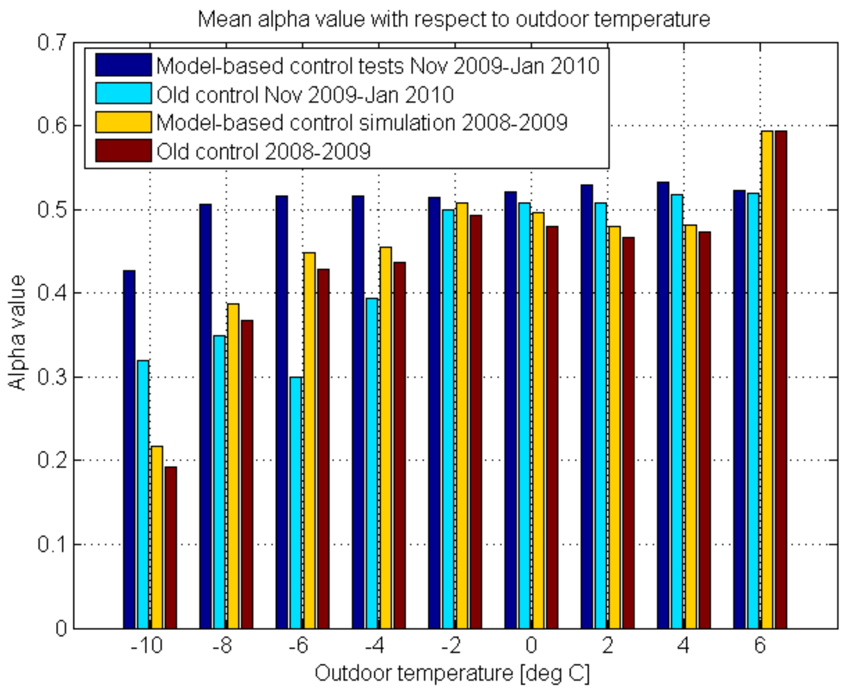


Figure 29. Alpha values for different outdoor temperatures.

Flow variations and delivery reliability

The differential pressure on the network was stable during the test, except for some disturbances connected to the operation of the recooler "Beriden". The frequency of the district heating pump was also well below maximum.

Comparison of flow variations for the test period when there was no recooling with the preceding days of ordinary control (Figure 19) showed that the standard deviation of the flow was almost halved with model-based control.

It is indicated from the test result that the model might not be able to cope with very sharp temperature drops. However, these situations will be problematic with the usual outdoor-temperature control curve as well, since the supply temperature increase will come too late. When sharp temperature drops are expected in the weather prognosis, the operators have to manually increase the supply temperature in advance.

Modifications of the model

Analysis of the data from the tests showed that there were some problems with high flows when the load was increasing and "Beriden" was taken out of operations. Even though the load model had predicted the load increase, the supply temperature turned out to be too low to cover the heat demand. This could be explained by the fact that the return temperature measurement used for calculation of the supply temperature setpoint was affected by the recooler, and that the return temperature from the network therefore was underestimated when the recooler was in operation. This problem had not occurred earlier, since the model at the earlier tests had been set to compensate the recooling with a higher supply temperature.

Before the simulation study, the model was extended with a return temperature model used to estimate the return temperature from the consumers when the recooler is in operation. This should solve the problem.

5.3 Simulations

The goal of the simulation study was to add more data to the experimental data, in order to make a better estimation of the benefits and drawbacks of the model-based control.

The result of the simulation is summarized in Figure 30. For outdoor temperatures higher than +5ºC, the model-based control strategy does not differ from the old control strategy. For lower outdoor temperatures, the supply temperature can be decreased with in average 4ºC, leading to 1.8 GWh additional electricity production. That corresponds to an increase with 2.5%. Most of the new electricity is produced when the outdoor temperature is around +2ºC, since that temperature is more frequent than lower temperatures.

Figure 30. Simulation results of model-based control compared to the old control for outdoor temperatures below +5ºC.

Reduction of supply temperature	4ºC
Increase of alpha value	0.011
Increase of electricity production	1.8 GWh, 2.5%

If the fuel price is 200 SEK/MWh, the income from produced electricity 350 SEK/MWh plus 300 SEK/MWh for electricity certificates, and the boiler efficiency 85%, the added net income from the improved alpha value would be 750 000 SEK/year.

The simulations also show that much could be gained by allowing lower supply temperatures than 75ºC, which is the lowest value at present. Reducing the lowest allowed temperature to 74ºC would give an additional 0.5 GWh during the simulated period September-May.

6 Analysis of the results

The result from the tests and simulations shows that model-based control can reduce the supply temperature to a district heating network at the same time as the flow is stabilized and the delivery reliability is maintained. The simulation results give a broad picture of the performance of the control strategy at different points of operation, and the test results verifies the simulated results.

The control strategy is simple and robust. The supply temperature setpoint is calculated from the desired value of the flow, the predicted load 2 hours into the future and the measured return temperature (or when this value is not available, the return temperature estimated on basis of the outdoor temperature). The load is predicted from the last measurements of the load and its derivative, the load the same time the last days, and the outdoor temperature and its derivative.

Strengths of the control strategy:

1. Simple model.
2. Self-adjusting. The model is to a great extent self-adjusting, since predictions are made based on recent data of load and outdoor temperature. However, the model parameters are not updated, so it is not an *adaptive* model.
3. Feedback. The model-based control strategy uses feedback (although delayed), while the old control strategy is purely feed-forward.

Model errors and weaknesses of the control strategy:

1. Dependence of operational data. Since the load prediction is based on data operational data from the last 4 days, production disturbances that affect flow, supply or return temperature of the district heating network will affect the load predictions the following days. This can be handled by switching to the old control curve at times when there are major production disturbances.
2. Load predictions. The load prediction has a root mean squared error of 3.2 MW. This is not much compared to the standard deviation of the load, which is 17.4 MW. However, fast changes in the outdoor temperature will give load changes that the model cannot predict in time (for example if the temperature is constant for some time and then falls with ~8°C in 2 hours).
3. Return temperature model. At times when the recooler is operating, the return temperature has to be estimated from the outdoor temperature. The error of this approximation is 1.4ºC, which can be compared to the standard deviation of the measured return temperature which is 3.5ºC. The return temperature problem is associated with the implementation on Idbäcken. On a plant where the return temperature from the consumers could be measured, this type of return temperature model would not be necessary.

The model is estimated from historical data, and will not change although the network might change. Moderate changes of the network, such as connection of new consumers or short-circuits in the periphery of the network, will be handled by the diurnal-difference model which works as an adaptive offset, adjusting to the basic level of the load. However, if major changes are made in the networks, such as adding of new districts or large consumers with different outdoor temperature dependence than the load of today, the model parameters might have to be re-estimated to fit the new conditions.

6.1 Application on larger networks

The Nyköping district heating network is supplied from one location and is not very big. The control strategy presented in this report should be easily transferable to other networks of the same type and size. For a large network supplied from several locations, the simple network model is not applicable.

Larger networks are commonly fed from more than one heat plant. The heat plants might be situated in different parts of the network and have different production costs. This means that there might be several other objectives besides a low supply temperature and a reliable heat delivery. One objective might be to avoid start-up of additional plants at load peaks. This can be achieved by a load-balancing control strategy, where the network is “loaded” with a high supply temperature prior to load peaks. This strategy is at least partially in conflict with the strategy for a low supply temperature described in this report. However, the presented load prediction model could be used for a load-balancing strategy as well.

If the network is supplied from several locations, the supplier of a certain network part will change with the changes in production of the different plants and the load on other parts of the network. Such changes will change the transport times of the network model, and make it more difficult to follow the load with the supply temperature.

Another difficulty in complex networks is the handling of narrow sectors. A narrow sector is a sector where the flow is limited compared to the rest of the network. Often, the flow capacity of these sectors (and the load on the other side of them) will determine the supply temperature of the whole network. The presence of narrow sectors in a network with several suppliers will make the distribution pattern more complex.

If the control strategy presented in this report shall be applicable on a complex network, some development is needed:

1. A more complex network model that takes into account narrow sectors and supply from several plants at different locations.
2. An optimisation with other constraints than reliability of heat delivery and a low supply temperature, if there are such.

The load prediction model is applicable to larger networks, although naturally the parameters need to be re-estimated. For networks where the return temperature can be measured, an ARX model similar to the load prediction model can be used to predict the return temperature from the customers. This can improve the performance of the supply temperature control.

7 Conclusions

The goal of this study was to test and evaluate model-based control of the supply temperature to a district heating system. The tests were carried out during the period November 2009-January 2010. Initial one-day tests showed that the model was valid and that the estimated transport time from the CHP plant to the customers was reasonable. Two longer test periods showed that the control strategy stabilized the flow of the network and that it was possible to substantially reduce the supply temperature without endangering the reliability of heat delivery. After the tests, the model was simulated with process data of nine months, and the simulated results was used for statistical evaluation.

The model-based control strategy presented in this report has shown great potential. The simulated results have been verified by 20 days of operation with the suggested control strategy at Idbäcken's CHP plant. The control strategy serves to both minimize the supply temperature and stabilize the flow to the network.

The conclusion from the tests and simulations is that the supply temperature can be reduced with 4ºC in average at high loads (outdoor temperature below +5ºC). For Idbäcken, the decrease of the supply temperature would improve the alpha value with 0.011 and thereby increase the yearly electricity production with 1.8 GWh. This corresponds to an additional net income of 750 000 SEK/year.

8 Recommendations and applications

The results of this report are generally applicable for combined heat and power plants connected to district heating networks. The potential depends on the load variations on the network, and how well the present control deals with them. Networks in colder climate and with a lot of domestic customers probably have more load variations than networks in warmer climate or with more industrial customers, and would thereby benefit more from a model-based supply temperature control. A simple way to estimate the potential of a network is to check the flow variations with the present control, at times when the supply temperature is increased from its lowest value.

The model structure presented in this report can be applied directly to district heating systems with one main heat producer and a simple network structure such as in the Nyköping case. The parameters of the model have to be estimated from data from the concerned plant and network.

For more complex networks with more than one heat producer, the network model has to be extended and there might be other objectives and restraints besides the aim for lowest possible supply temperature, which have to be taken into account.

Implementation of the model-based control can be made directly into the DCS of the plant, or on an external PC from which the DCS can import the supply temperature setpoint.

9 Suggestions for continued research

The model and control strategy presented in this report is developed for small and medium district heating networks with only one main production site and a simple network structure. For more complex networks, the network model would have to be extended and the control strategy would have to include other objectives than reliable heat distribution and a low supply temperature. Weather prognoses have not been included in the load prediction since they did not improve the predictions significantly. However, in larger networks with longer transport delays from plant to consumer, it might be more beneficial to use weather prognoses in the model. Continued research in the following areas would be of interest:

- **Application on complex networks.** The network model could be extended to take into account narrow sectors, supply from more than one location etc. Methods for modelling of district heating networks have been developed by many researchers, some of them mentioned in Chapter 1.2.
- **Using load predictions to balance load peaks.** In some networks, it is desirable to avoid production peaks, since they demand production by less profitable plants or starts and stops of plants. Production peaks can be avoided by loading the network with a high supply temperature prior to load peaks, evening out the production over time. The load prediction model presented in this report could be used for such a control strategy instead of the presented strategy for lowest supply temperature.
- **Use of temperature and weather prognoses.** For networks with long transport delays, the use of weather prognoses in the load prediction model may be beneficial. Prognoses of outdoor temperature could be used relatively easily in the suggested model structure. The Swedish Meteorological and Hydrological Institute, SMHI, calculates a parameter called “Energy index”, which takes into account solar irradiation, clouds, wind and precipitation as well as the temperature. This index could be used as an input to the load model instead of the outdoor temperature, if it was accessible with the high enough time resolution. Another option is to measure the solar irradiation, wind speed etc at the plant and use those as additional inputs to the load model.

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