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D1.4-1 Case description document and new unit model specifications for Apros

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Summary

This document present work done in FLEX^e WP1's task 1.4. The work was case-based simulations done mainly with the Apros® process simulator in the context of a district heating system. The studies were divided into two tracks. Firstly, advanced control strategies of the district heating were studied. More specifically, these included adaptive pumping station control and predicitive supply temperature control. Secondly, a joint undertaking with other tasks of WP1 was initiated. In this task WILMAR, EnergyPRO and Apros tools were used together to evaluate a future scenario.

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1 Executive summary

This document present work done in FLEX^{e} WP1's task 1.4. The work was case-based simulations done mainly with the Apros® process simulator in the context of a district heating system. The studies were divided into two tracks. Firstly, advanced control strategies of the district heating were studied. More specifically, these included adaptive pumping station control and predicitive supply temperature control. Secondly, a joint undertaking with other tasks of WP1 was initiated. In this task WILMAR, EnergyPRO and Apros tools were used together to evaluate a future scenario.

2 Introduction

2.1 Purpose and target group

This deliverable is intended to document the comparative simulation work done in Task 1.4. The target group are the partners for FLEXe program interested in detailed simulation of district heating grids and their control development.

2.2 Partner contributions and initial data gathering

The partners involved and their roles in this work were

- VTT: Model configuration, simulations with Apros.
- Aalto University: heat production boundary condition data with EnergyPro
- Fortum: Provider of baseline Apros model, district heating expertise, definition of KPIs, commentary of intermediate results and support
- Valmet: expertise on district heating system requirements, definition of KPIs
- Wärtsilä: experise on heat only boilers, definition of KPIs

2.3 Relations to other activities in the project

The simulations on Task 1.4. were two-fold. Firstly, rather independent work was conducted on district heating grid control development. This work linked to CLIC's EFEU program in the sense that the model utilized here was an extension of a model originally made in EFEU.

Secondly, a joint undertaking with other tasks of WP1 was conducted. This study started with WILMAR simulations of Task 1.3. These results were used as boundary conditions to EnergyPRO optimizations by Aalto University in Task 1.4. Finally, the optimization results of Aalto were used as boundary conditions to VTT's Apros simulations in Task 1.4

3 Description of the case system

3.1 Overall

The case system under analysis was the Järvenpää DH network which is a middle sized DH network in Southern Finland with about 38 km piping. The case DH network's main components are heat sources, pumping stations, network pipes and consumers. The case system was used to investigate effects of advanced control strategies and also as a common target of analysis with other WP1 groups.

An overall schematic of the case system under study is depicted below in Figure 1.

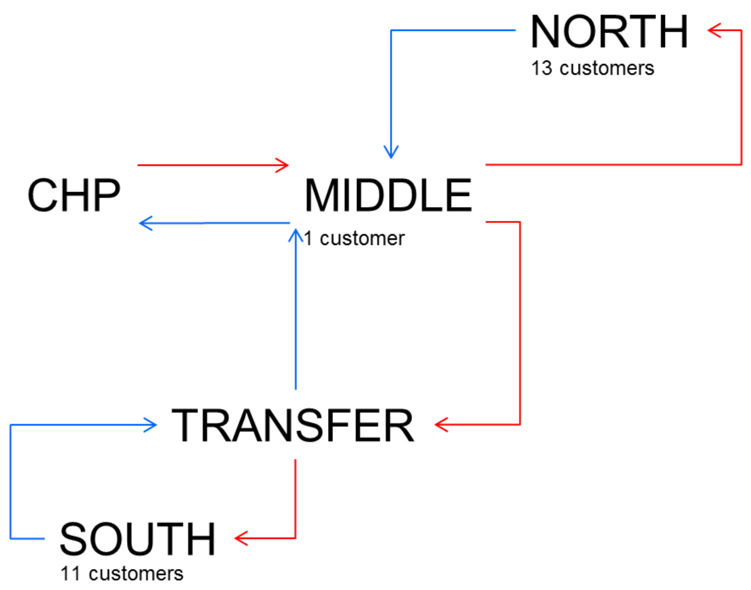

Figure 1 Schematic figure of the DH grid under analysis

3.2 Apros Simulation model

The first principles Apros simulation model of a district heating grid is based on a case study of the EFEU project and orignated from Fortum. It is a description of the the Järvenpää area district heating network. The model includes one central heat source, the Järvenpää CHP plant, which in this case was modelled in a simplified way. The reason for this was that the investigation focused on the network and not the plant as such. Also included in the more is a heat storage, pumping stations and 25 consumption blocks in 3 regions: north, middle and south. In each region there are consumers which were classified and lumped into three categories according to their average heat consumption: 1MW, 2MW, 5MW and 10MW. Water flow between the plant and the consumers was modelled in more detail. The district heating pipes were modelled with Apros pressure-flow solution with also heat losses to the ground. Realistic dimensions (diameter and length) were given to the pipe lines. Furthermore the model included intermediate pumping stations. The maximum heat consumption of the grid is at about 125MW. Electricity generation is also calculated as a fixed percentage of the produced heat power of the plant. A screenshot of the model is shown in Figure 2.

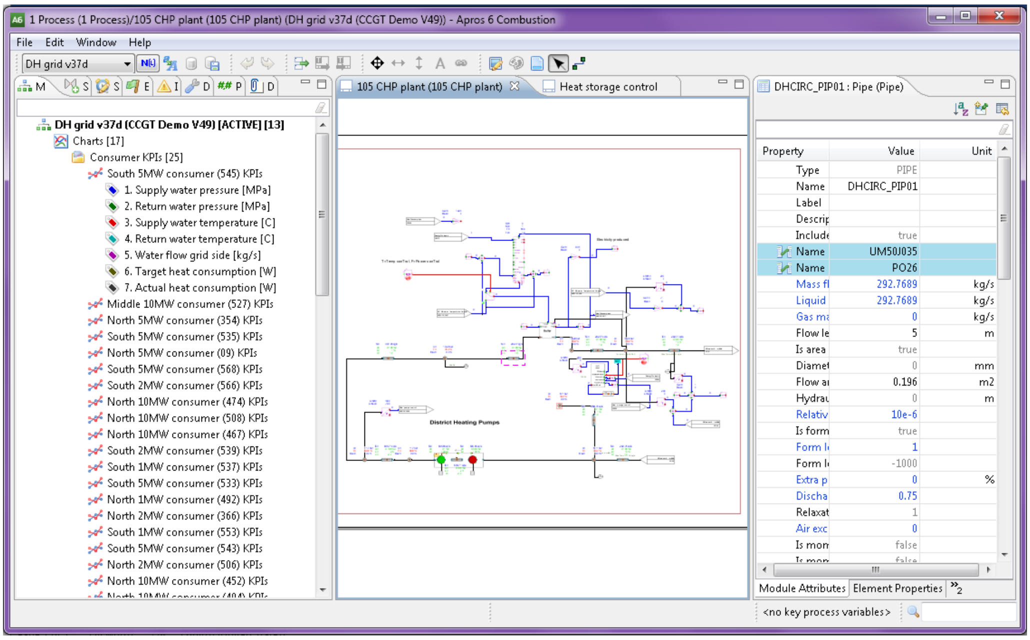

Figure 2 Screenshot of the Apros model.

The simulations in Apros were run for a full year (simulator time) in order to account for seasonal variations. The time resolution of the simulations was one minute. This resulted in large set of data which required specialized tools for analysis which are described in chapter 3.5.1. The model has been optimized to the point it can simulated within a few hours' real time on a common computer. The logged signals were exported at an hourly resolution in order to reduce file sizes.

In the FLEXe program the model was extended with several features which included:

- new pumping stations and their control logics
- consumer DH-grid connection modification
- heat consumption model modification
- heat storage

3.3 KPIs

In order to compare two simulations a set of key performance indicator (KPIs) were defined with the help of partners. Key performance indicators are monitored for all consumers (supply/return heat grid line pressures and temperatures, water flow and target/actual heat consumption). The target consumption for each consumer is read from a generated consumption profile text file (see section 3.4.3). Every consumer interfaces with the heating grid using a heat exchanger with control loops so that the target power is extracted from the grid. An example of the grid interface block is shown in Figure 5.

The KPIs used were:

1. Heat losses of the DH grid (average) (kWh)
2. Total pumping energy (average) (kWh)
3. Minimum observed consumer pressure difference (ΔP_c = supply – return line) (average) (MPa)
4. Minimum consumer ΔP_c, times below 0.06MPa
5. Minimum consumer ΔP_c, times below 0.03MPa

3.4 New unit model specifications

3.4.1 Pumping stations and their control logics

The intermediate pumping stations were modelled with Apros pump unit model as shown below in Figure 3.

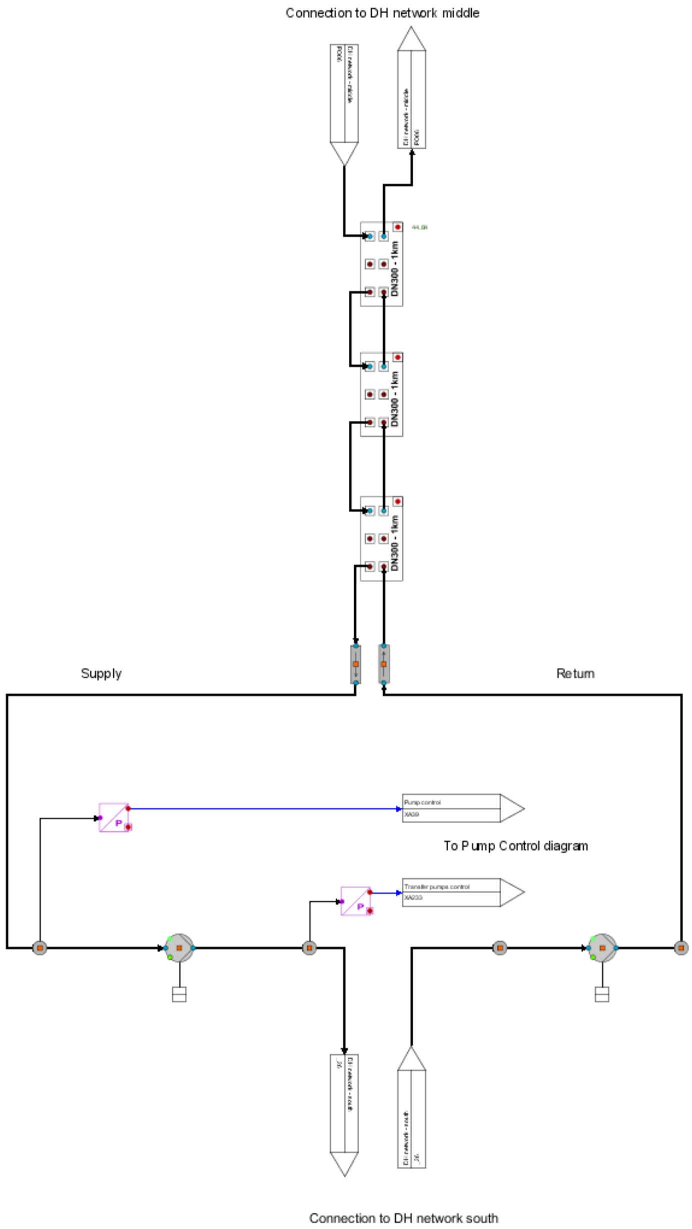

Figure 3 Example of a pumping station and district heating pipes.

The control logics of a pumping station were modelled on a separate diagram. The basic operational logic were obtained from Fortum. The idea is that in long DH pipe lines there may be several pumping stations, some of which are in operation and other which are in reserve. The pumps are controlled based on two possible measurement signals from the network: critical customer pressure difference or pump stations suction pressure. If the pressure difference at the key customer falls too low (e.g. below 0.6bar) then an additional pumping station is started. This station will then be run according to the customer pressure difference and the original station will revert to suction pressure control mode. Such switching logics and continuous control were implemented into the Apros model for all pumping stations.

3.4.2 Consumer DH-grid connection

The consumer model included two parts: its connection to the DH grid and model of its heat consumption. The DH grid connection model was modified to include more configurability in order to gain more realistic pressure drops and controllability.

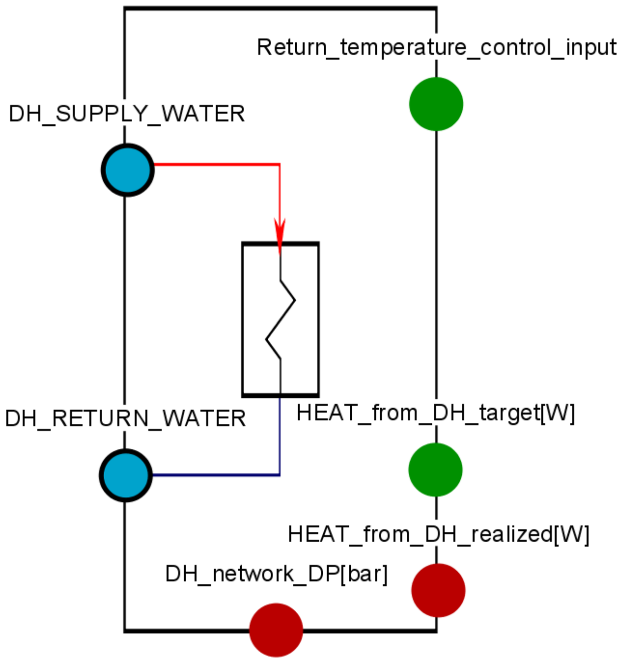

Figure 4 DH Connection module faceplate

Shown in Figure 4, the DH connection model is connected via the blue terminals to the DH grid. The green input terminals are used to input values for the return temperature control and the heat consumption from the heat consumption model. The DH connection module outputs the actual heat transferred and the realised pressure drop in it. Inside the DH connection module is a heat exchanger as well as two flow lines: one for DH water and the other for the building's own circulation. The DH flow is manipulated so that return line temperature reaches a desired value. The building's own flow line is manipulated so that the consumption from heat consumption model is reached. This is depicted in the internal structure of the DH Connection block, see Figure 5.

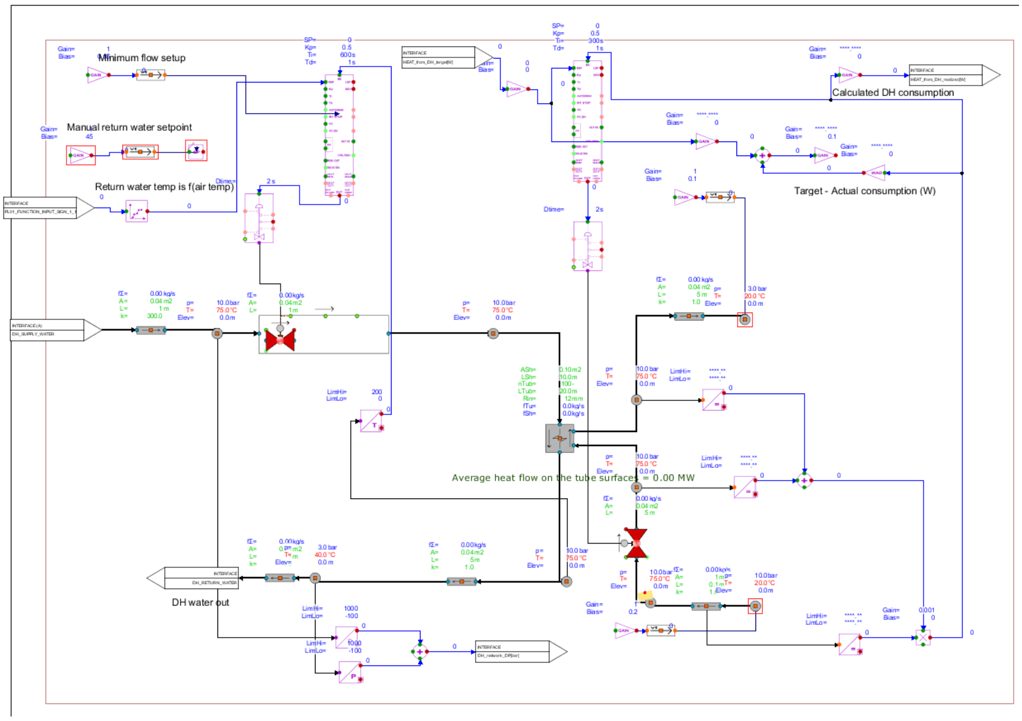

Figure 5 Internal structure of the consumer DH connection block.

3.4.3 Heat consumption model

In order to have meaningful simulations with high resolution (e.g. 60s) detailed consumption profiles were needed for every consumer type. The flowchart in Figure 6 shows this process.

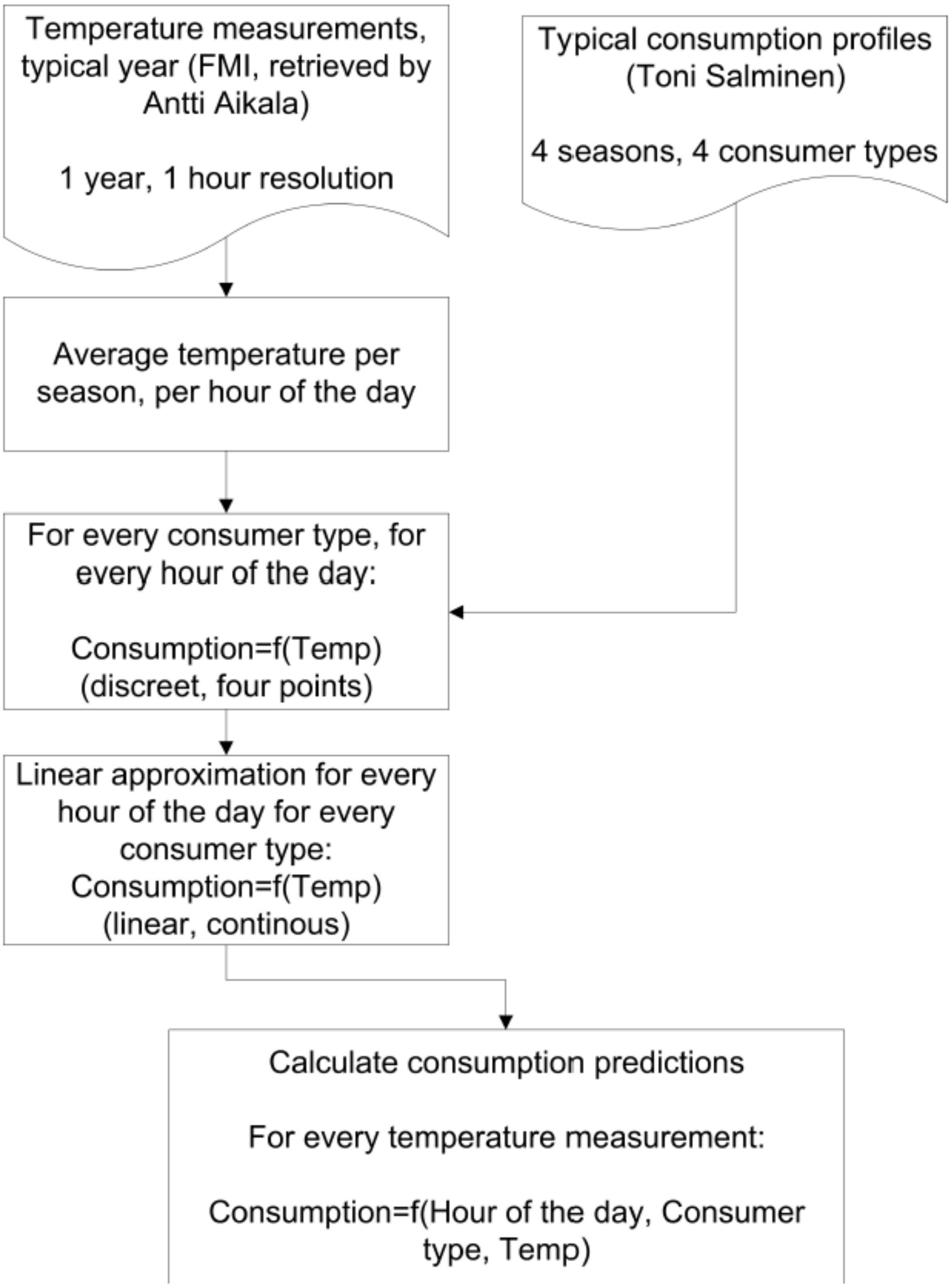

Figure 6 Flowchart of consumption profile generation.

The starting point was one consumption profile chart per consumer type with hourly resolution per season (please refer to Toni Salminen's master thesis (Salminen, 2013)). The typical year weather data from FMI was used as a source to extrapolate the consumption profiles to an hourly resolution. A software tool was built to support this task (see Figure 7).

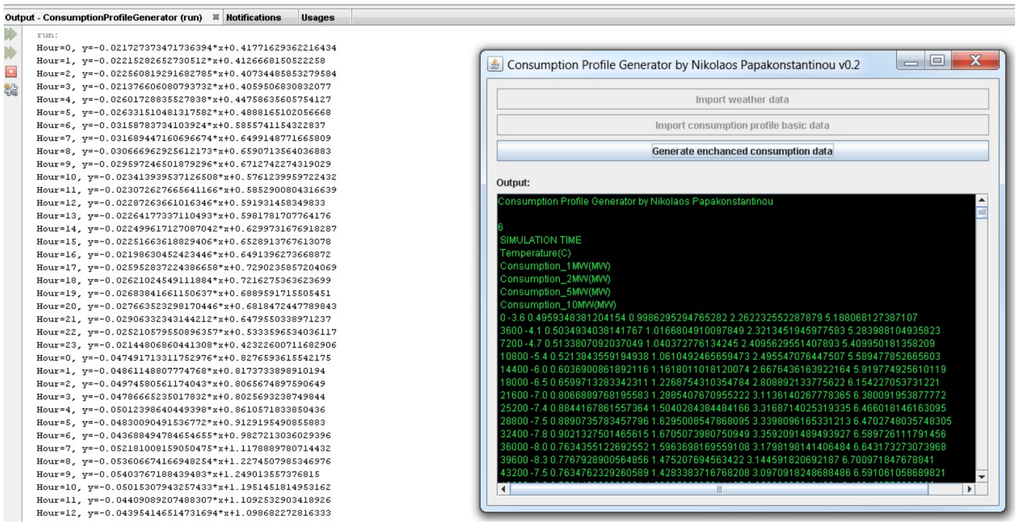

Figure 7 Screenshot from the consumption profile generator tool.

3.4.4 Simple heat storage

A simplified heat storage was implemented into Apros. The model includes an ideally mixed water volume from/to which heat is transferred from the DH grid. In addition the model allows for local heat generation to be added into it. The internal structure of the storage model is shown in Figure 8.

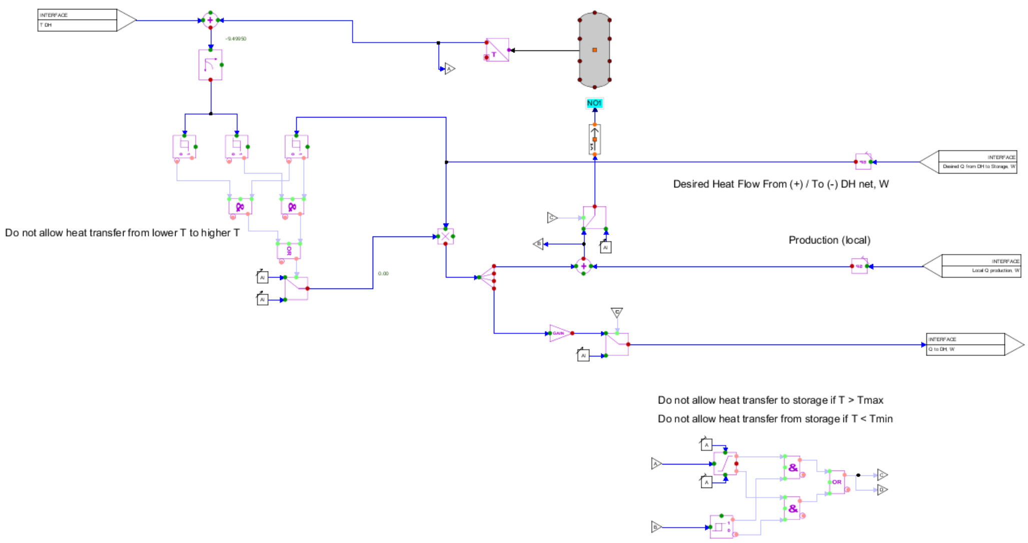

Figure 8 Internal structure of a simple heat storage model.

The storage water volume is in the middle of the figure. The user can define the size (m^3) of the volume. Below the volume is the heat transfer to/from the volume. This heat flow is a sum of two terms: the heat transfer between the storage and the DH grid and local production. Heat transfer to/from the grid is calculated so that a desired heat flow is an input from outside the model. This heat transfer is allowed if a) temperatures in the storage and grid allow it (i.e. no heat transfer from lower to higher temperature) and b) temperature of the storage is between user given minimum and maximum temperatures. The storage temperature is calculated by Apros. The storage module can be connected to a DH grid flow line as shown in Figure 9. This figure also shows a simple charging/discharging logic for the storage.

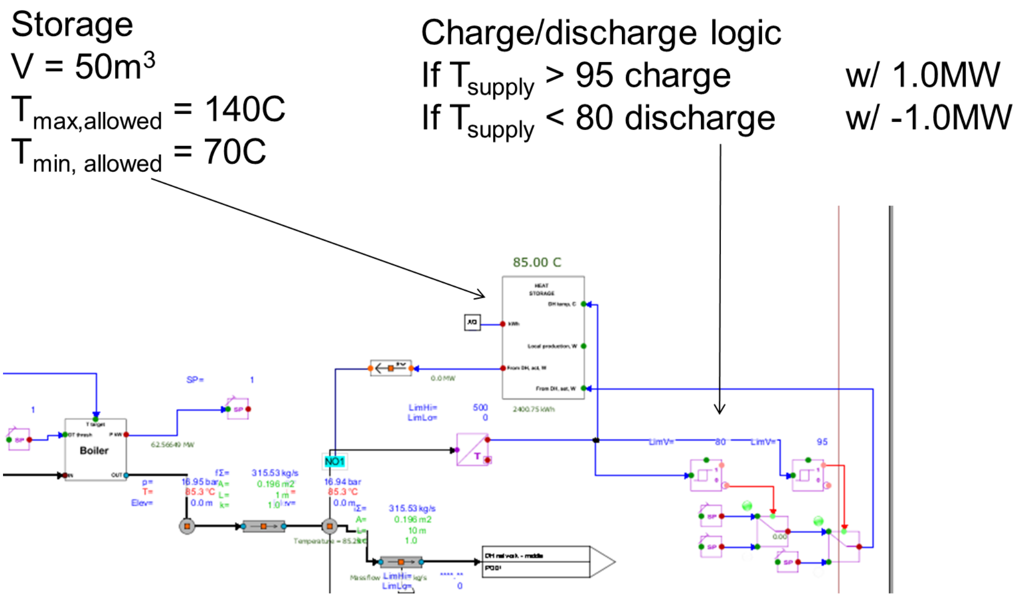

Figure 9 Example connection of the simple heat storage.

3.5 External models and tools

3.5.1 Data comparison tool

A software tool was developed to automatically compare Apros simulation results from two simulations. The input for this tool are the so called Apros subscription data time series of the simulation runs (typically one year, 3600s resolution). The output from the tool is a set of pre-defined Excel files with signal comparisons and possibly additional comparisons selected by the user. The tool was developed to handle the large amounts of raw data originating from the simulations. A screenshot of the tool is shown Figure 10.

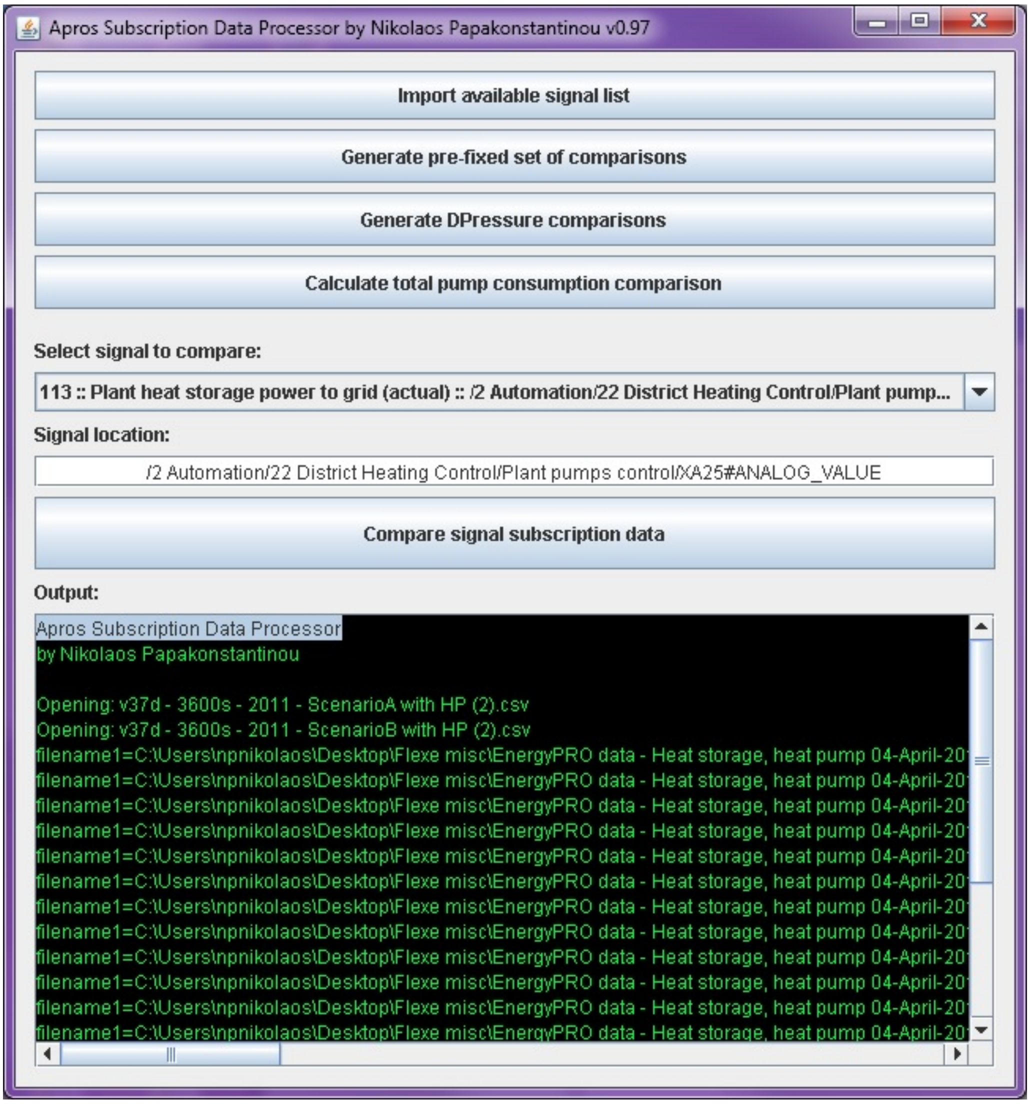

Figure 10 Screenshot from the Apros Subscription Data Processor tool

3.5.2 External calculation machine – the Beast

As mentioned in chapter 3.2 the simulations' time span was one year with one minute time step. This resulted in a considerable amount of data and computational load. To alleviate this, a dedicated simulation computer was purchased at VTT's own expense. A majority of the simulations were conducted on this machine.

4 Simulation experiments and results

4.1 Pump control strategies

The model contains four pumping station locations, one at the plant, one at the middle of the grid, one at north and one at the south. The key performance indicator for the pumping strategy is the consumer supply-return line pressure difference (ΔP_c). The minimum value of that ΔP_c should be above a certain set point (e.g. 0.6bar with 0.3bar absolute minimum) for all consumers in order for their equipment to function correctly. To evaluate the pump control strategies, the simulation results were processed and the worst case pressure difference (min ΔP_c) was logged for the whole grid at any given moment.

Two pump control strategies which were evaluated. In “Pump control strategy A” all pump stations are always enabled and the target was that the worst case minimum ΔP_c was never bellow 0.6bar (but can climb much higher). Stations upstream never stop controlling the pressure at the suction end of the pump stations. The “Pump control strategy B” involved the adaptive enabling of pump stations so that the worst case minimum ΔP_c is at 0.6bar (with a chance to drop below that for short transients) and the control of the minimum ΔP_c can be passed on to stations upstream.

Two variations of the “Pump control strategy A” were used. In the first variation the pressure at the suction end of the pump stations is kept steady for the whole year at the maximum allowed level of 16bars (limit of the grid). The second variation (adaptive pressure) uses different pressure set points (factors x-y-z%, e.g. 100-70-50%) for low (-26°C), medium (6°C) and high (25°C) outside air temperatures. Interpolation is used to get the pressure set point values at the suction end of the pump stations for temperatures between these points.

4.2 Supply water temperature set point control strategies

Two alternatives were used to control the DH grid supply water temperature set points. For the “Supply water temperature control strategy A” the supply water temperature is a function of the air temperature at the heat plant. The maximum supply water temperature of 115°C is mapped to the -26°C air temp and lower while the minimum supply water temperature of 76°C is mapped to +6°C air temp and higher. The function is linear for values between -26°C and +6°C air temp. This is shown in Figure 11.

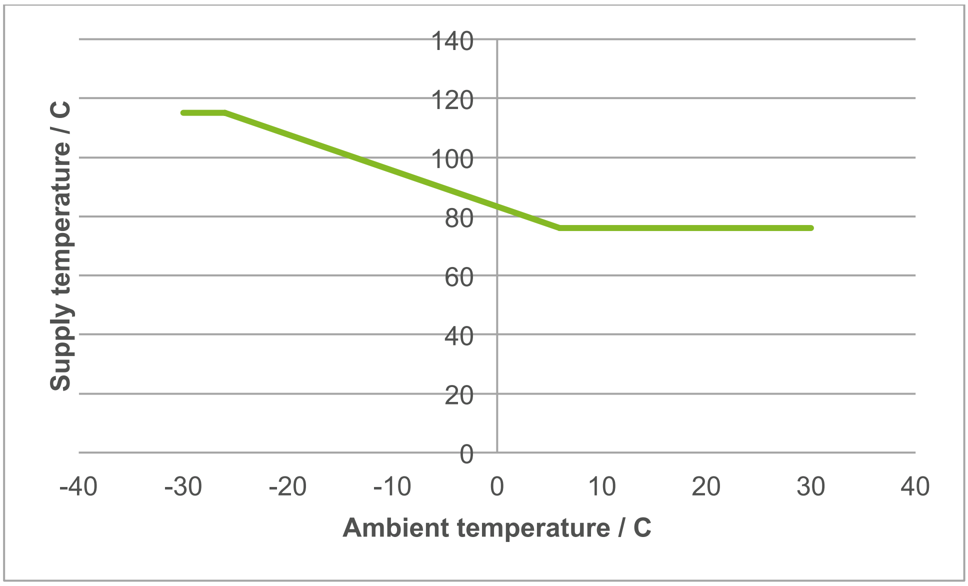

Figure 11 Traditional district heating supply temperature control scheme.

This way of controlling the supply temperature has the drawbacks that it is reactive (i.e. takes into account only current ambient temperature) and does not account for the temperature propagation delays in the pipes. To alleviate this the “Supply water temperature control strategy B” targets to deliver hotter water to the consumers when it is predicted that they will need it the most. This prediction is based on short term weather forecast and water temperature propagation delays in the grid. This method is presented in detail in (Papakonstantinou et al., 2016).

4.3 Summary of experiments

Altogether 8 simulation runs with all the combinations of pumping controls and supply temperature control strategies were performed. These are summarized in Table 1.

Table 1 Summary of control strategy simulation runs.

Simulation run	Pumping station suction pressure	DH grid supply temperature
A1	fixed 16bar	traditional
A2	adaptive	traditional
A3	fixed 16bar	predictive
A4	adaptive	predictive
B1	fixed 16bar	traditional
B2	adaptive	traditional

B3	fixed 16bar	predictive
B4	adaptive	predictive

4.4 Joint simulation undertaking with WILMAR, EnergyPRO and Apros

Aside from the above control strategy simulation runs, also a simulation experiment with three tools of different detail levels was conducted. The three tools used were the high level unit commitment and economic dispatch model WILMAR, energy system optimizer EnergyPRO and process simulator Apros. In the experiment WILMAR was used to derive hourly power price time series over a one year period in a year 2020 scenario. The modelled area consisted of Nordic and Baltic countries as well as Germany and Poland. Each country included one or more price regions and each price region included one or more heat areas. Finland was modelled with three heat areas: one for capital region district heating, one for rural district heating and one for industrial heat consumption. These regions are shown in Figure 12.

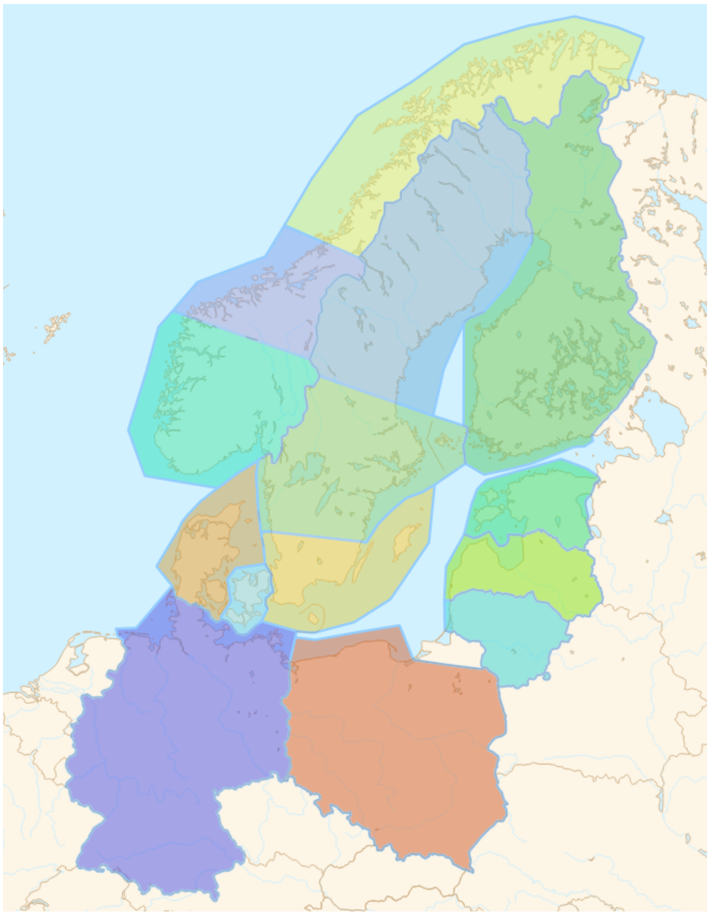

Figure 12 Price regions in the WILMAR model.

Electricity consumption, wind power production and PV production profiles used as input were based on 2011 data available mainly on Nord Pool and

ENTSO-E. Fuel and CO_2 price assumptions were according to IEA New Policies Scenario. Power price time series produced by WILMAR were used by EnergyPRO to calculate the optimal running schedule for production units in the Järvenpää area. Price date for two example weeks from WILMAR are shown in Figure 13.

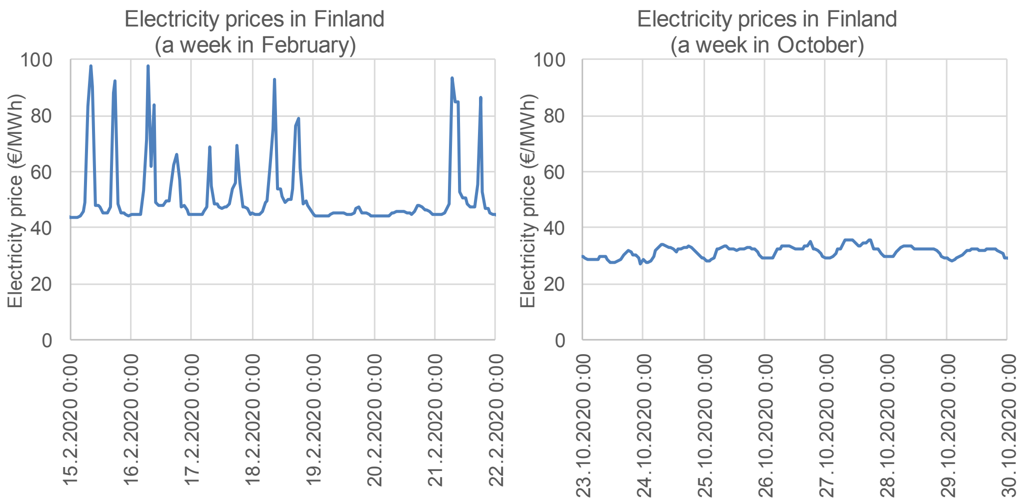

Figure 13 Electricity prices from two example weeks produced by WILMAR.

The optimal dimensioning of a heat storage, heat pump and solar collectors was studied in three future electricity price scenarios and the most cost effective combinations of these components were also searched. EnergyPRO software was used in the analysis, and inputs of the model were for example hourly heat demand, the capacities of the production units and electricity and fuel prices. The power price time series used in the simulations were produced by WILMAR. The current national fuel prices, taxes (excluding VAT) and subsidies were used in the energyPRO model. In addition, other variable costs and revenues from the electricity sales were taken into account in the optimization. The optimal hourly heat and electricity production schedule was determined by minimizing the total variable costs so that the assumed hourly heat demand is met. Yet, the investment costs of the different components can also have a large impact on the profitability of including the DH technologies in the system. The investment costs have therefore also been considered in the profitability calculations and these costs have been estimated based on literature ((Hast et al., 2016) and the references therein) and expert opinions. The effects of the studied components were first studied separately and the results suggest that a rather large heat storage (100,000 – 110,000 m^3) is profitable. A heat storage of around 20 – 25 MW was most profitable investment but the most economical solution was to include both a heat storage (110,000 m^3) and a heat pump (20 MW) in the DH system. The optimal running schedules for production units with these DH components in different electricity price scenarios were calculated with energyPRO.Finally this data was fed to Apros to evaluate the schedule's effect on the grid. This entire data flow is shown in Figure 14.

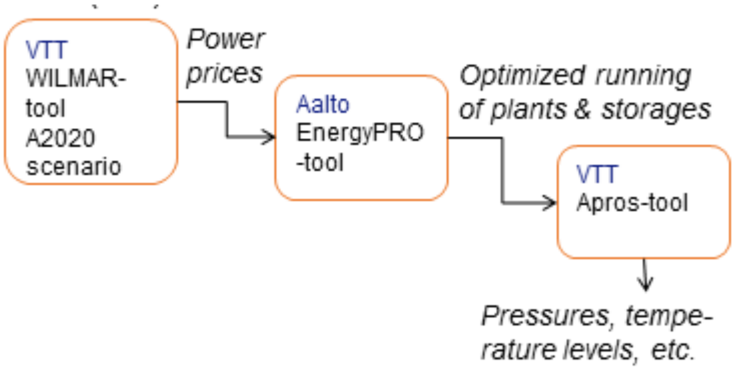

Figure 14 Data flow in three-simulator case.

In Figure 14 the data flow is depicted to be one-way only. While this may be true in some cases, it should be noted that bi-directional data flow is likely to happen in general. In this work, for example, heat demand data were used as one input to the WILMAR-calculations. This data came from the heat consumption models described in 3.4.3. Here, it should be clarified, that the data did not come from Apros itself but from the consumption models, which can be used also without Apros.

5 Results

The following nine sub-chapters present example results from the control strategy simulations. The final chapter gives indicative results from the three-simulator case of chapter 4.4.

5.1 Simulation run A1

In Figure 15 the minimum pressure difference (ΔP_c) of the worst case consumer is shown for *pump control strategy A*. Fixed pressure at the suction end of the pump stations is at 16bars and supply water set point temperature as a function of air temp was used for the whole year of simulation. Although the minimum ΔP_c never falls below 0.6bars, it is obvious that especially in the summer time it is consistently very high.

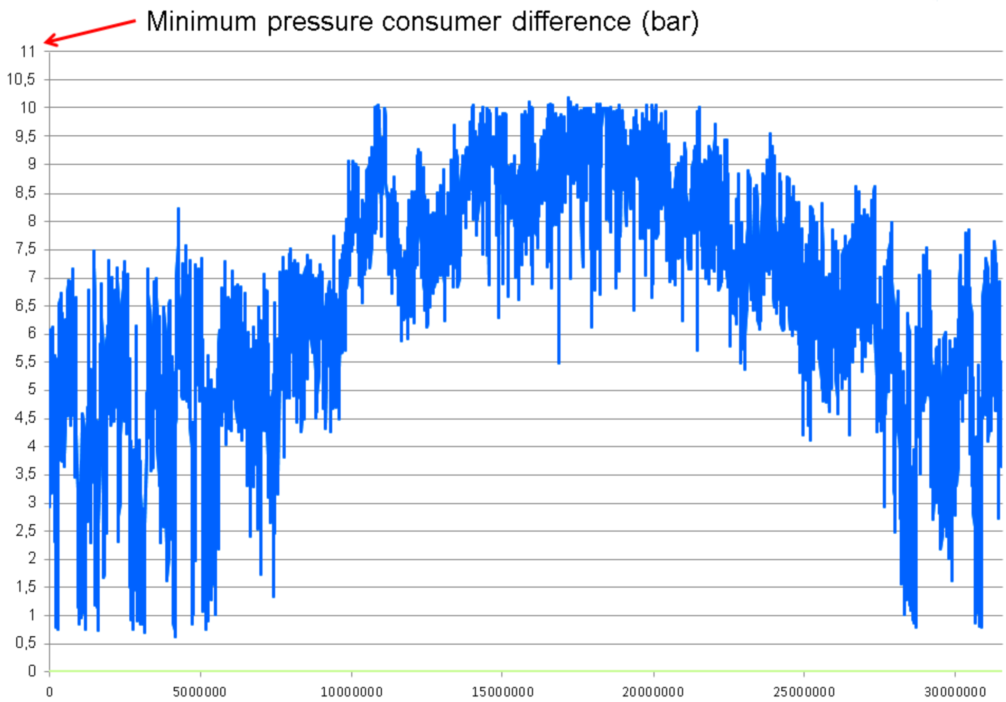

Figure 15 Pressure difference of the worst case consumer in pump control strategy A.

5.2 Simulation run A2

In Figure 16 the minimum pressure difference of the worst case consumer is shown for *pump control strategy A*. In this case the pressure at the suction end of the pump stations is adaptive at 100-70-50% for low (-26°C), medium (6°C) and high (25°C) outside air temperatures (see chapter 4.1). The supply water set point temperature is a function of air temperature for the whole year of simulation. In this case the minimum ΔP_c sometimes falls below 0.6bars, but in the summer time it is much lower than the previous simulation run (run A1).

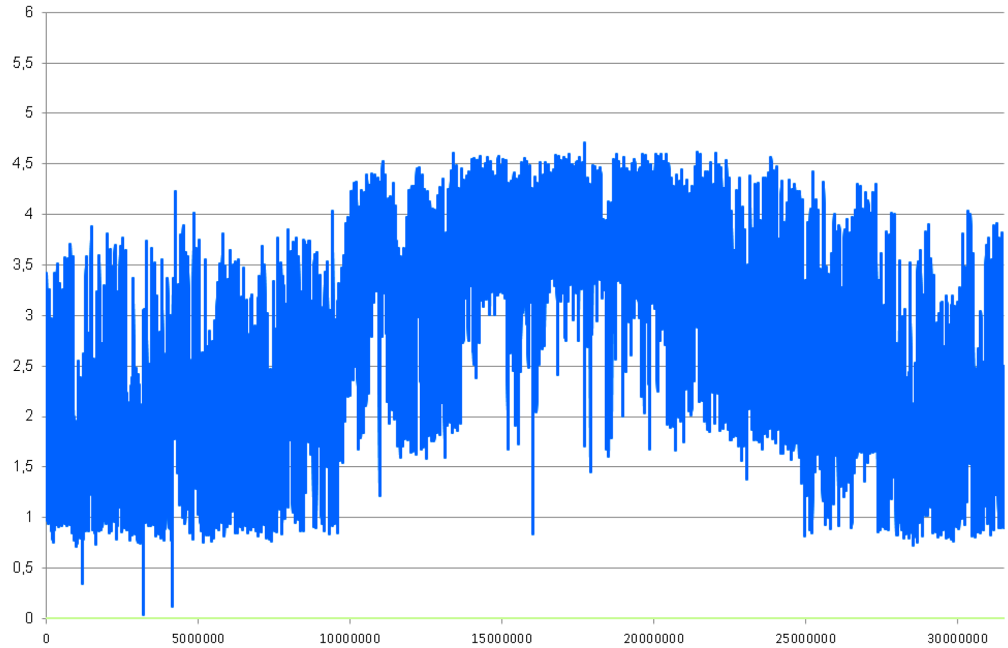

Figure 16 Minimum pressure difference of the worst case consumer

5.3 Simulation run A3

In fig. Figure 17 the minimum pressure difference of the worst case consumer is shown for *pump control strategy A*, fixed pressure at the suction end of the pump stations at 16bars. In this case the predictive supply water set point temperature control (see chapter 4.2) for the whole year. Compared to the first simulation run (run A1) the minimum ΔP_cs are higher while in the summer time the minimum ΔP_cs are at a similar level.

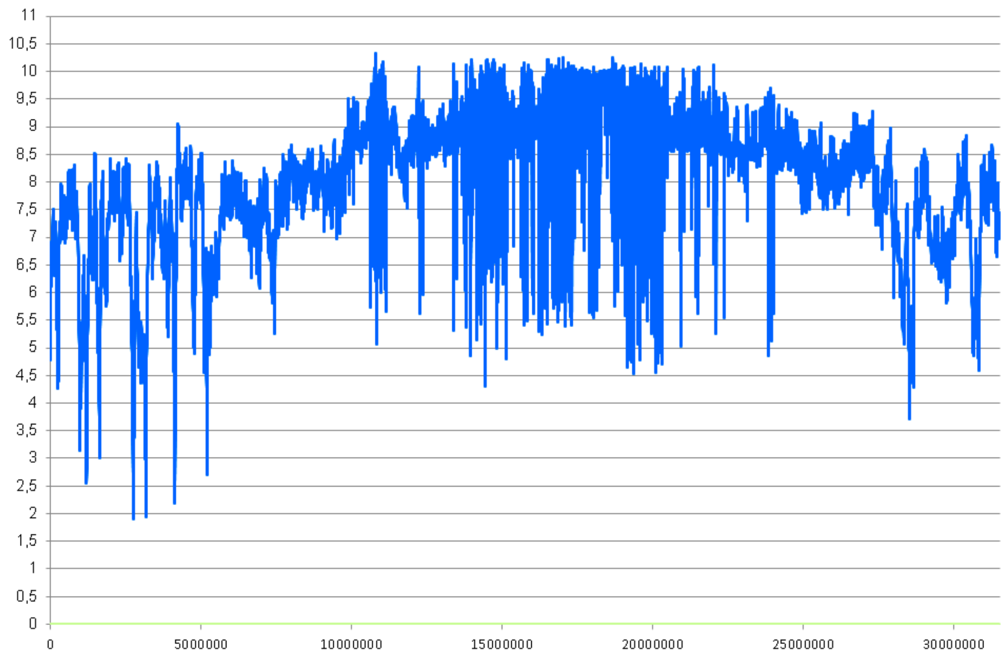

Figure 17 Minimum ΔP_c for run A3.

5.4 Simulation run A4

In fig. Figure 18 the minimum pressure difference of the worst case consumer is shown for *pump control strategy A*. Pressure at the suction end of the pump stations is adaptive and predictive supply water set point temperature control is. In this case the minimum ΔP_c never falls below 1bars and never rises above 5.5bar.

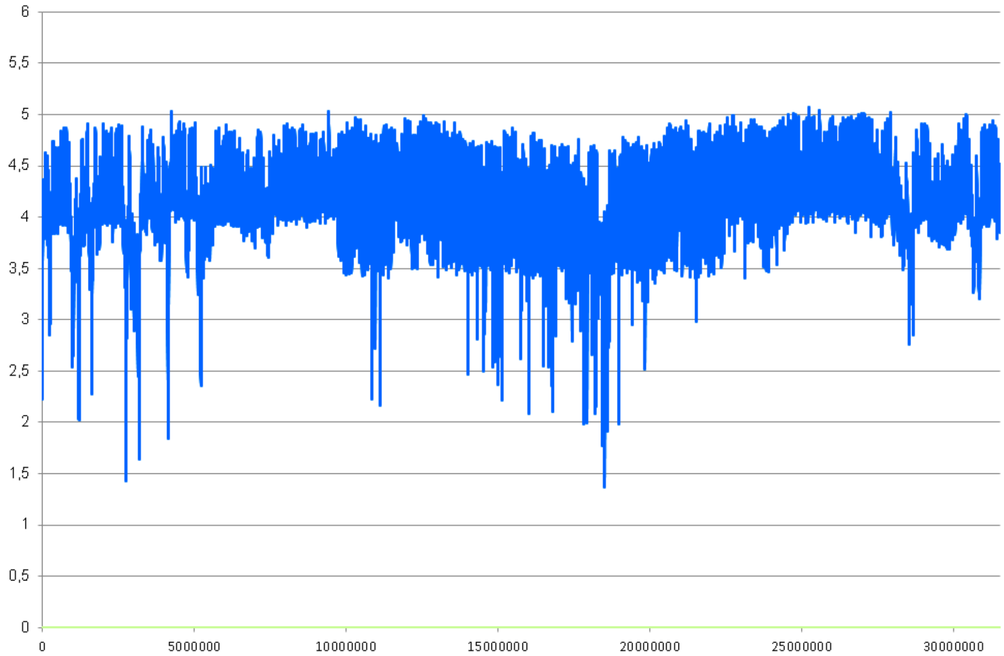

Figure 18 Min DPc with adaptive pressure control and predictive supply temperature control.

5.5 Simulation run B1

In Figure 19 the minimum pressure difference of the worst case consumer is shown for *pump control strategy B*. Fixed pressure at the suction end of the pump stations was at 16bars and the supply water set point temperature was a function of air temp for the whole year of simulation.

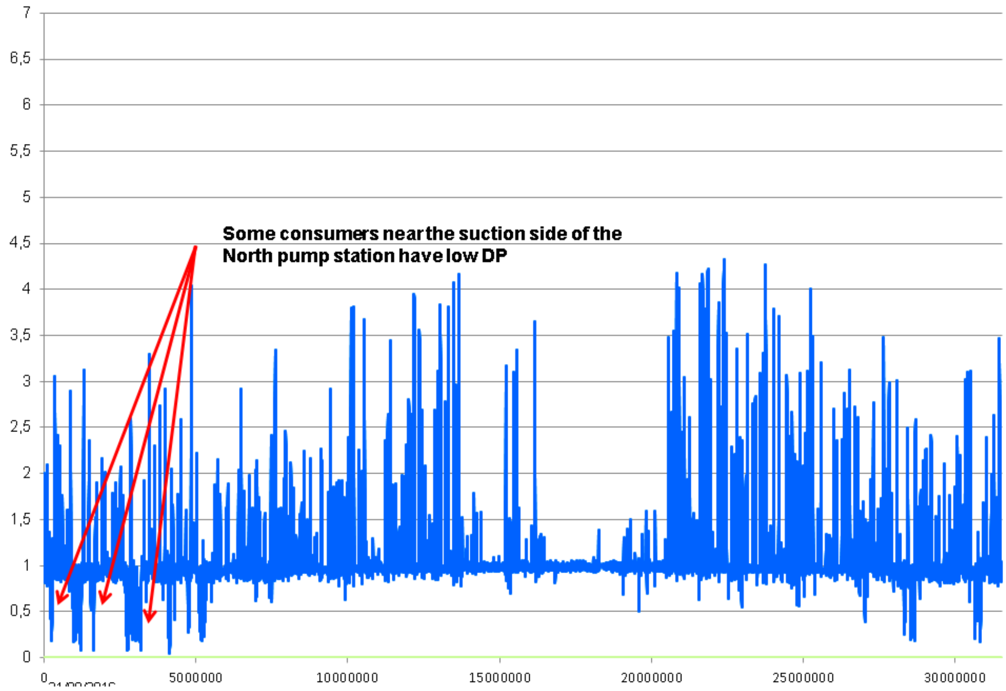

Figure 19 Fixed suction pressure and traditional supply water temperature control.

An example of the pump station activations during the simulation run is shown in Figure 20.

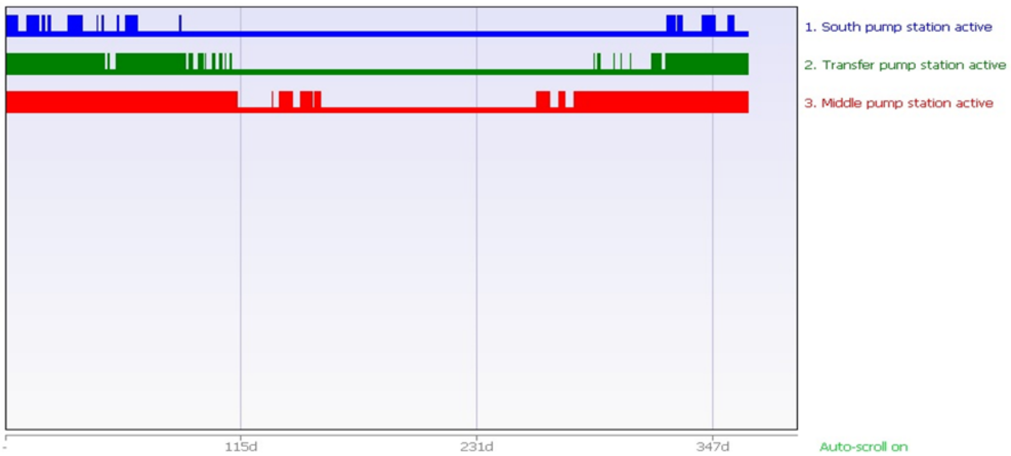

Figure 20 State (on / off) of three pumping stations.

The minimum ΔP_c falls below 0.6bars at multiple instances, but overall the ΔP_c is closer to 0.6bars than the simulation runs using the "Pump control strategy A".

5.6 Simulation run B2

In Figure 21 the minimum pressure difference of the worst case consumer is shown for *pump control strategy B* with the pressure at the suction end of the pump stations is adaptive at 100-80-60% for low (-26°C), medium (6°C) and high (25°C) outside air temperatures. The supply water set point temperature is a function of air temperature for the whole year of simulation. Compared to run B1 the minimum ΔP_c also falls below 0.6bars frequently, but overall the ΔP_c is much closer to the target level of 0.6bars.

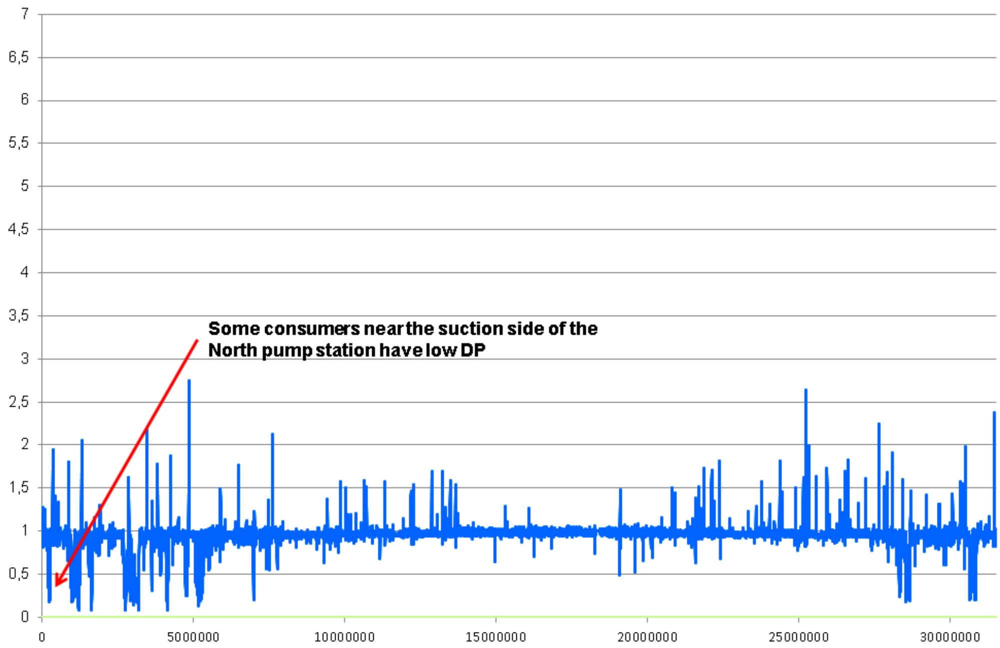

Figure 21 Adaptive pumping control and traditional supply water temperature control.

5.7 Simulation run B3

In Figure 22 *pump control strategy B* was used with fixed pressure at the suction end of the pump stations at 16bars and predictive supply water setpoint temperature control. Compared to the simulation run B1 the minimum ΔP_cs are higher and more stable.

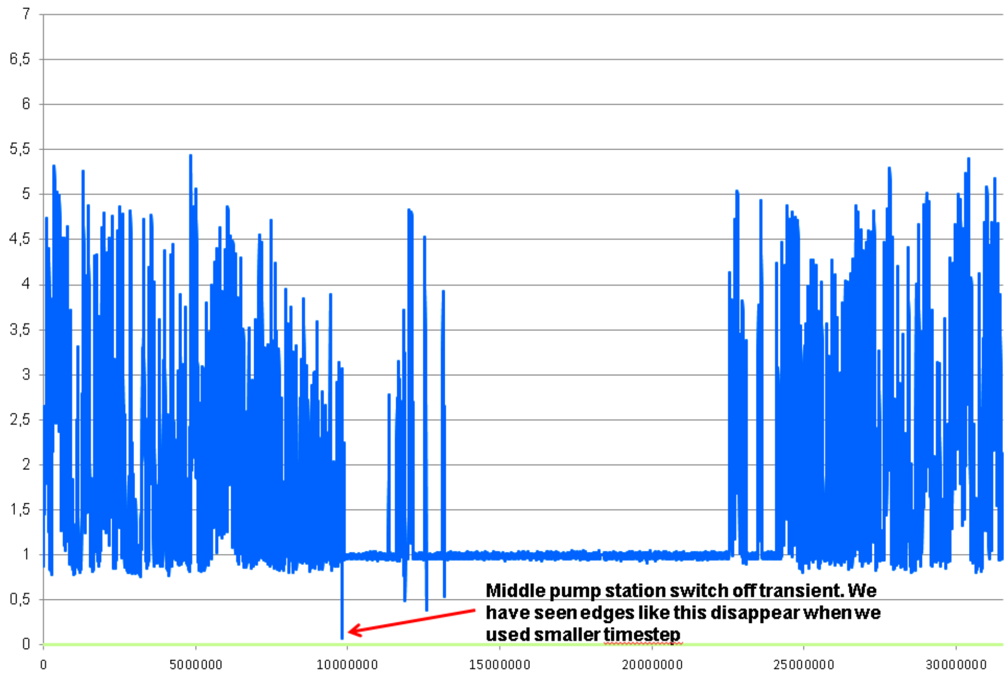

Figure 22 Fixed suction pressure and predictive supply temperature control.

5.8 Simulation run B4

In Figure 23 pump control strategy B, with pressure at the suction end of the pump stations as adaptive at 100-80-60% for low (-26°C), medium (6°C) and high (25°C) outside air temperatures and predictive supply water setpoint temperature control was used. This simulation run gave the best performance.

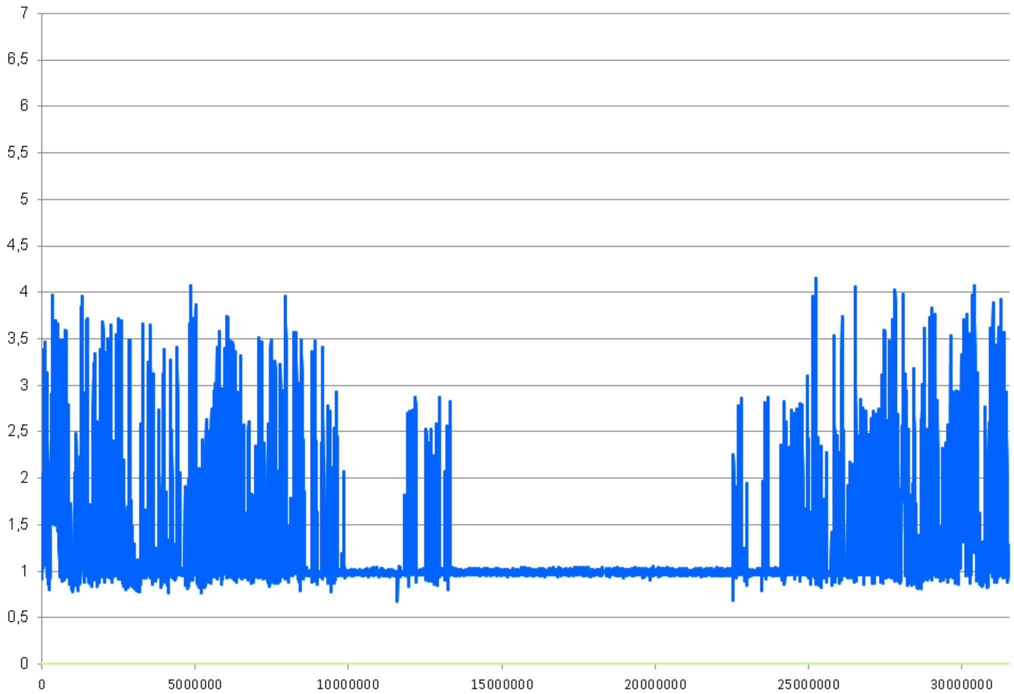

Figure 23 Adaptive pressure and predictive temperature controls.

5.9 Pump power consumption, pump control method A vs B

The following figures (Figure 24 and Figure 25) display the total pump power consumed for the whole simulation year for the pump control strategies A and B and the different simulation runs.

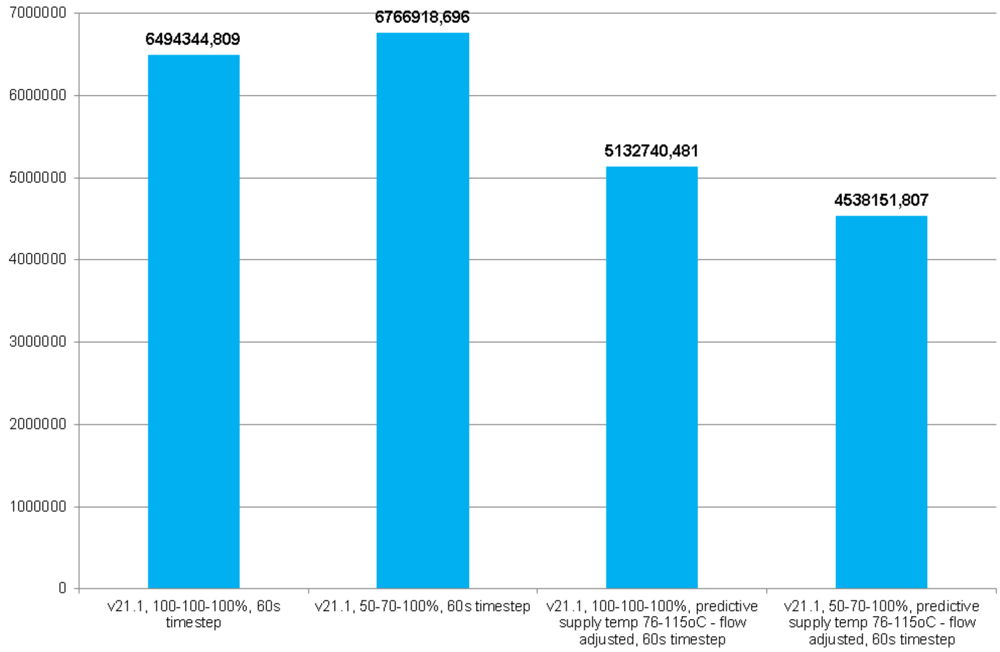

Figure 24 Pumping power consumption, strategy A.

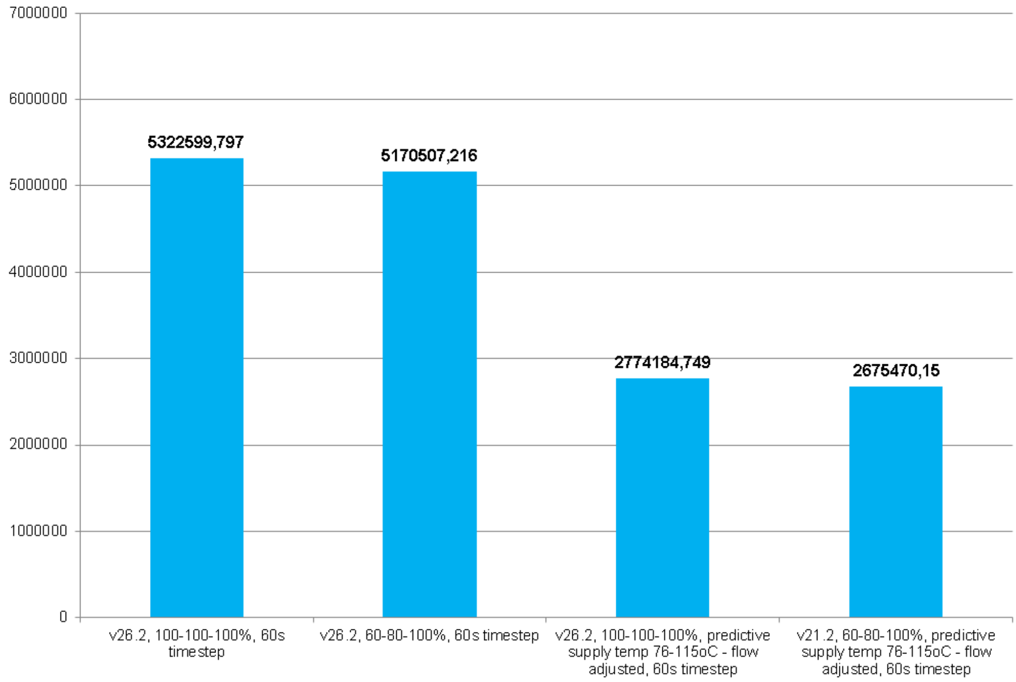

Figure 25 Pumping power consumption, strategy B.

It can be reasoned that the pump control strategy B gave overall lower pump consumption figures. Also, the predictive supply water temperature set point control algorithm had the lowest pump power consumption figures. The predictive temperature control leads to higher supply water temperatures as shown in Figure 26.

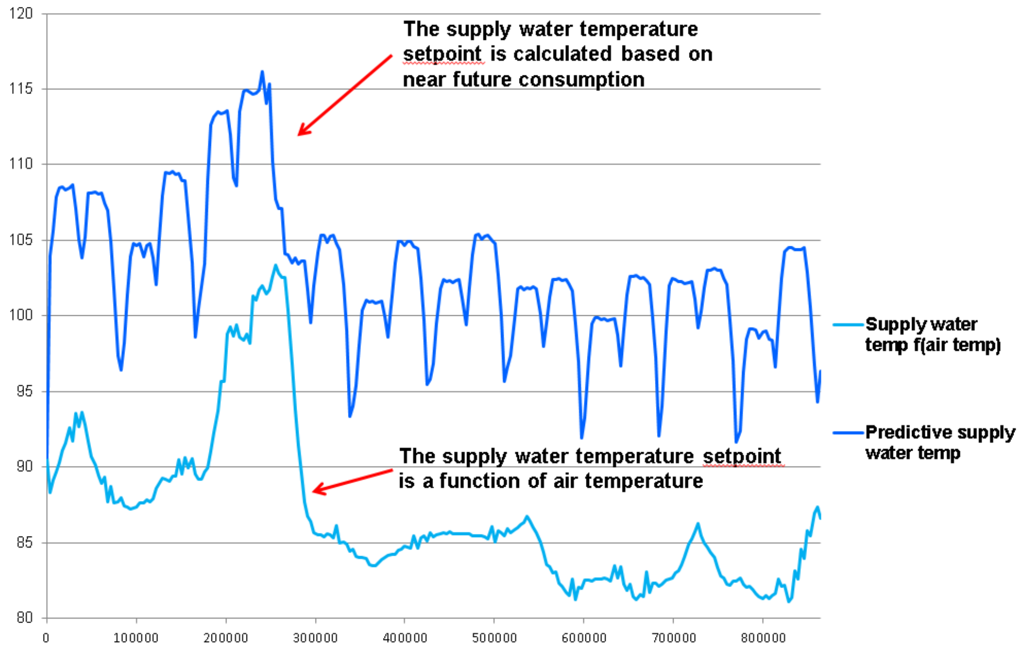

Figure 26 Supply water temperature with traditional and predicitve control.

These higher temperatures will lead to higher heat losses in the grid, which were calculated in the model as the difference between the produced and the total actual consumed heat.

5.10 Joint undertaking

During the experiments, it was found out that the data flow is not as linear as in Figure 14. For example, in order to conduct the WILMAR calculations information on the system structure was needed. This information was obtained from Aalto in this case. Also, when going into more detailed models more information is needed than the upper level tool may be able to provide. For example, the EnergyPRO calculations assumed that the DH grid supply and return temperatures were constants (80°C and 40°C, respectively). At the detail level of Apros, this assumption is not realistic.

The year 2011 weather data was used (compared to FMI's "typical year" weather data used in the previous experiments). We also had multiple production sources, which in our Apros model were all aggregated into one CHP plant production.

The EnergyPRO data contained time-series for heat production for the CHP plant, 4 HOBs (heat-only-boilers) of the optimal operation strategy found by energyPRO and the heat storage:

- Järvenpään voimalaitos, CHP
- Ristinummi, HOB
- Järvenpään lämpölaitos, HOB
- Tuusulan lämpölaitos, HOB

- Electrical Heatpump
- Bio, HOB
- Heat consumption
- Heat rejection
- Storage loss
- Storage

Three scenarios (A, B and C) were simulated in Apros with two variations each (heat storage 110,000m^2 and heat pump 20MW vs. just storage). Those 3x2 scenarios were simulated successfully in Apros and generated 6 large set of results (production data, grid data, consumer KPIs). An example for the results are shown in Figure 27.

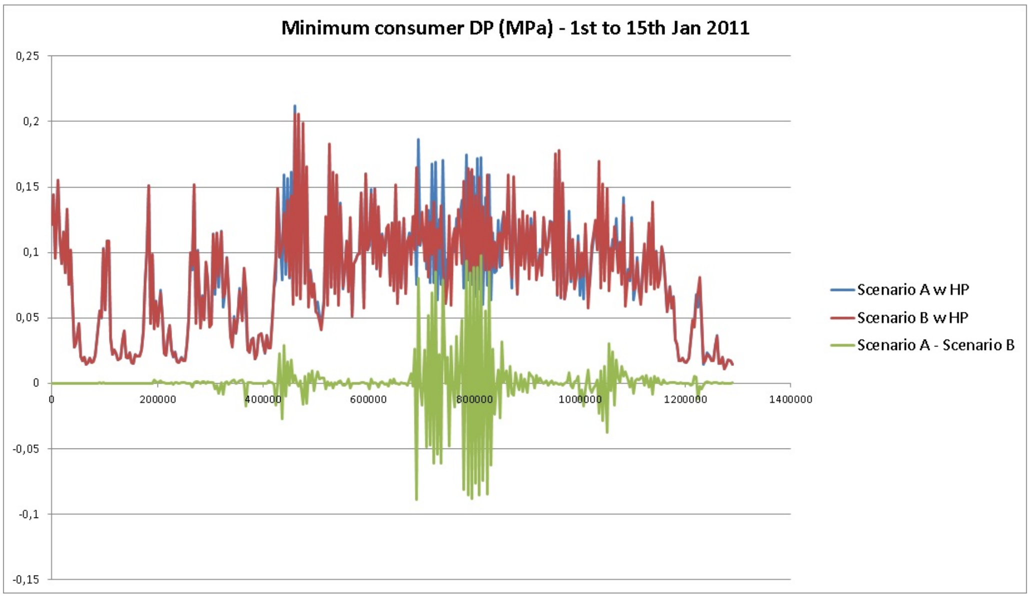

Figure 27 Minimum pressure consumer difference in three scenarios produced from EnergyPRO.

In this chart the minimum ΔP of all the consumers is compared for the first 15 days of 2011 for Scenario A and Scenario B with heat pump. We observe that although the simulation is successful, the minimum ΔP is not kept over the desired limit of 0.06MPa (0.6bars).

6 Conclusions

The model of the case study has shown potential in performing experiments in control methods with the capability to have a high level overview of the system's key performance indicators or a very detailed view if needed. In the experiments presented in this report different pump and supply water temperature set point control methods were tested. These kinds of tests can quantify the parameters needed for decision support in building new grids, planning extensions and introduction of new technologies. Trade-offs can be identified like the one with heat/electricity production vs losses in the grid vs price of heat/electricity. The decision how to run the grid has to also be verified against the regulations (e.g. minimum supply -return line pressure difference at the consumer).

In the three-simulator joint undertaking the conclusions is the feasibility of such multi-level approach was demonstrated although work need to be done in order to make the workflow smooth and cost-efficient. The three-simulator joint undertaking, although limited in scope, was already able to show challenges from the technical (pressure difference) point-of-view.

7 References

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