SIMULATION OF DISTRICT HEATING SYSTEMS FOR EVALUATION OF REAL-TIME CONTROL STRATEGIES

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ABSTRACT

This paper describes a general simulation tool for district heating systems. The purpose is to study the performance of different real-time control strategies for district heating management. A short description of the basic principles of district heating systems as well as some of the managerial considerations is given. Simulation is commonly used within the domain of district heating, both as a strategical decision support tool and as a operational optimisation tool. However, since approaches to distributed real-time control strategies are very rare within the domain of district heating, current simulation tools lack support for such studies. To improve this situation a simulation tool has been developed which integrates existing models of the various entities in a district heating system in a novel way.

1 INTRODUCTION

The optimal operation of District Heating and Cooling (DHC) Systems has for a long time been a important issue for operators of DHC systems. The optimal operation usually refers to the determination of the optimal supply temperature for the nearby future, i.e., from a couple of hours to a few days, depending on the type of production sources and the size and the topology of the supply network. However, we believe that optimisation efforts regarding the production, e.g., (Bøhm et al. 2002, Aringhieri et al. 2003, Arvastson 2001), might loose some of the potential impact because of the stochastic nature of the consumption and the fact that the optimisation models assume a fixed and given demand. The purpose of the ABSINTHE (Agent-based monitoring and control of district heating systems) project [ABSINTHE-WWW] is to deal with this uncertainty by investigating the possibility of using distributed software agents to perform load balancing and local regulation of consumption. The goal could be seen as trying to prolong the validity of a computed optimisation schema despite discrepancies between predicted and actual consumption. This will result in both energy saving and the possibility of delivering a higher quality of service to the customers.

As there are large risks involved in making experiments in a real DHC system, we have developed a district heating simulator in order to evaluate different management strategies. In fact, simulation is a commonly used decision support tool for design of district heating networks as well as for determination of supply temperatures. However, since approaches to distributed real-time load balancing and regulation of individual customers are very rare, current simulation tools lacks the ability to provide environments for controlled experiment of such strategies. This paper describes such a dynamic simulation tool which integrates existing models of the various entities in a district heating system in a novel way.

In the next section, we give a brief description of district heating and the current approaches to management of such systems. The parameters to consider in a simulation model are presented in section 2, and in section 3, we describe the novel simulation approach. Finally, we conclude and discuss future work in section 4.

2 DISTRICT HEATING SYSTEMS

The basic idea behind district heating is to use cheap local heat production plants to produce hot water (in some countries steam is used instead of water). The customers use heat to heat buildings and to produce domestic hot tap water. In most cases, warm water is produced in conversion plants (CHP) that in excess to fossil fuels, may use alternative energy sources, e.g., biomass, biogas or geothermal reservoirs. To fully utilize the conversion plant during all seasons of the year, the system often also includes a power generator. This way, excessive heat can be used to generate electricity.

The heat is distributed to consumers through a closed loop network where the hot water is transported to consumers in the supply network, cooled down by the consumer through a heat exchanger, and transported back to the heat plant where it is heated again. A major benefit of this method of distribution is the possibility of centralized heat generation outside of the city, which contributes to the decongesting of the often polluted air of the cities (Aringhieri 2003). However, due to the large distances the distribution of heat is also the largest managerial planning problem, the distribution time can get quite large, typically ranging from 3 to 24 hours.

Factors that have an effect on the heat load can be classified into three groups: human factors, weather conditions, and physical factors of the distribution network. Approximately 70 percent of the total heat load can be attributed to ambient temperature (Lehtoranta et al. 2000), other weather conditions affecting the heat load are for example, humidity, solar radiation, wind velocity and direction.

2.1 District Heating System Management

Today, the operation of most district heating systems are based on a simple mapping between the outside (ambient) temperature and the temperature of the water in the supply network. When engineers refer to operational optimisation of district heating systems, they usually refer to deciding the optimal operation of the heat supplies and the optimal supply temperature for the nearby future (a couple of hours to a few days). In a general optimisation model for the supply temperature the network appears as a set of constraints (where consumers have fixed and given demand), and the objective function is composed of cost for production. Combinatorial optimisation problems are difficult because there is no formula for solving them exactly. Every possibility has to be examined in order to find the best solution and the number of possibilities increases exponentially as the size of the problem increases. It is obvious that an optimisation model of a large district heating system with many loops and more than one heat production plant is extremely computationally demanding. (Bøhm et al. 2002, Aringhieri et al. 2003). When the complexity of an DHC system reaches approximately 100 components and restrictions, the present computer and software technology is insufficient to find an optimum operational strategy (Bøhm et al. 2002).

Current approaches to operate district heating systems are performed in a centralised manner without possibilities of regulating the consumption in the distributed network and the behaviour of the network is mainly a consequence of the consumers behaviour. The flow through the network is determined by the collective behaviour of the consumers since every connected building has a valve controlling the flow in the primary distribution pipe.

2.2 Simulation of District Heating Systems

The purpose of simulation models of district heating systems is to capture the time dependent behaviour of the system. As shown in Figure 1, depending on the focus of the study, many different time scales for simulations of district heating systems can be used (Valdimarsson 1993). At one end we have the transient behaviour at the other we have studies of strategical concern.

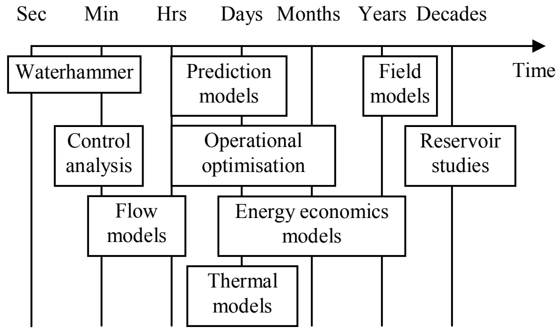


Figure 1: Time considerations depending on the focus of the study.

In addition to differences in time scale, simulation models of district heating systems can be classified in four categories (Valdimarsson 1993):

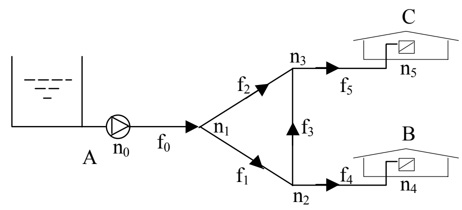
- By *type*, microscopic or macroscopic. *Micro-simulation* generally refers to detailed studies in both time and space of individual entities in the system. *Macro-simulation* refers to studies where the entities of the system are grouped together and modelled as larger entities.
- By *method*, dynamic or steady state. *Dynamic* models calculates current state from previous states, whereas *steady state* models are time-independent or assume steady state conditions.
- By *approach*, physical or black box. *Physical* models uses general priori knowledge of the nature of district heating systems, whereas *black box* models are based on relations determined from measured data.
- By *usage*, design or operation. The purpose of *design* usage is to study different configurations of the physical system. *Operational* usage generally considers improvements of an existing system with respect to its economy or performance.

One of the most important components of a district heating system is the network of distribution pipes. When modelling this structure the work of Kirchhoff (Laws of Closed Electric Circuits, 1845) concerning “electrical circuits” is often used. A common way to represent a complete description of the structure is by graph theory. A graph contains information about flows (branches, edges), nodes (connection points) and the relation between them. For electrical networks graph theory is the mathematical basis (Christofides 1975). The first law (the current law) means, that the sum of all mass flows in a node is zero. The second law (the voltage law) says, that the sum of the pressure losses in a closed path (loop) is zero.

Consider a simplified network with 2 loops, and suppose that we want to calculate the steady state. If the current law is fulfilled but the sum of the pressure losses in one of the loops is not zero, a loop correction has to be carried out. This loop correction affects the adjacent loop resulting in yet another loop correction, since this correction also affects the adjacent loops, resulting in yet another correction and so on. One can easily see that the calculation of the steady state of a large system with numerous loops is not easily verified.

A number of techniques based on Kirchhoff's laws has been used for flow calculations of pipe networks. The classical method is the iterative Hardy-Cross method for determination of steady state, or to be used as input for methods such as the Newton-Raphson method. However, this method has drawbacks when it comes to district heating networks. It requires the network to have at least one loop and therefore it can not be used for the most common case, i.e., when there is no loop at all in the system or in the part of the system under study. Valdimarsson has developed a method that solves a matrix equation based on the laws of Kirchoff directly. The approach by Valdimarsson will be described briefly here, more details are found in (Valdimarsson 1993, 1995, 1997).

The general network analysis of Valdimarsson follows the analysis of electrical circuits made by Chua and Lin (Chua et al.1975). An *connectivity* matrix is used to describe the relations between nodes and flows. The matrix has one column for each flow and one row for each node. A starting (1) and a ending (-1) location (node) is indicated for the flow direction in each column. However, it is normally not feasible to describe the network only in terms of pipes and their relations. There are inflows and outflows to the system, or in the part of the system to be studied. These points are considered as boundary conditions of the system (Athans et al. 1974). These locations are places where one know the condition before calculation of the network state, i.e., one knows the flow and pressure. A simple example of a district heating system and the relating connectivity matrix is shown in figure 2.



Flow

$$
\text{Node}\quad
\begin{array}{c}
 \\ n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5
\end{array}
\begin{array}{c}
\begin{array}{cccccc|ccc}
f_0 & f_1 & f_2 & f_3 & f_4 & f_5 & A & B & C
\end{array} \\
\left[\begin{array}{cccccc|ccc}
1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
-1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & -1 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1
\end{array}\right.
\end{array}
$$

Figure 2: Connectivity matrix for a simple network. The shaded area indicate boundary areas.

The connectivity matrix is then rearranged with respect to a spanning tree by splitting it into two submatrices. The choice of spanning tree is based on a certain order of preferences regarding the flow branches. The flow branches are to be sorted according to the following order; head sources, storage tanks, pumps and valves, pipes, and flow sources. One of the submatrices will then contain the flows in the spanning tree and the other will contain the link flows, i.e., the flows outside of the spanning tree. The cutset matrix is then generated from the submatrix containing the spanning tree. A set of branches of a connected graph is a cutset if (see Figure 3):

- The removal of the set of branches (but not their endpoints) results in a graph that is not connected.
- After the removal of the set of branches, the restoration of any one branch from the set will result in a connected graph again.

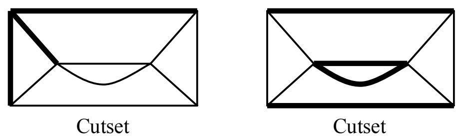


Figure 3: The bold lines indicate the branches of the cutset.

The cutset can be seen as a border that divides the network into two components, that are not connected. Each row in the cutset matrix (see Figure 4) corresponds to a set of flow elements.

$$
\begin{array}{c}
\begin{array}{ccccccccc} A & f_0 & f_1 & f_2 & f_4 & f_5 & B & C & f_3 \end{array} \\
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & -1 & -1 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & -1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0
\end{bmatrix}
\end{array}
$$

Figure 4: Cutset matrix

According to Kirchhoff's current law the sum of the flow in the flow elements, in each of the cutsets is zero. The cutset matrix is partitioned into submatrices according to the various flow groups, i.e., head sources, storage tanks, pumps and valves, pipes and flow sources. The flow can now be calculated for the network by integrating a state differential equation. Finally, Valdimarsson also shows that a linear theory (Wood et al. 1972) is an effective way of finding the solution of the non-linear steady state by iteration (only necessary for networks containing loops).

3 THE ABSINTHE SIMULATOR

In the following sections the simulation program and its different modules are described. For some algorithms only a brief description is given, more details are provided in the referred articles. We start by describing the requirements, which is followed by an analysis of these requirements. Then the design and implementation of the simulator are presented. Finally, the validation of the simulator is described.

3.1 Requirements

Since the purpose of the simulation software is to evaluate different real-time control strategies in different situations, we identified the following requirements:

- The possibility to simulate arbitrary network configurations.
- The possibility to simulate arbitrary consumer patterns.
- The possibility to simulate arbitrary production strategies.
- The possibility to calculate the flow, pressure and the temperature in all elements of the system as a function of time and the state of the environment.
- The possibility to control parameters during run-time, e.g., possibility to control the consumption and the production during a simulation.
- Recording of the most important output parameters, e.g., mass flow, temperatures, wanted consumption, actual consumption, and pressure of all components.

3.2 Analysis

The focus of the project is to study optimisation of control strategies, hence the time scale of the simulator had to be granular enough to encompass the control analysis time scale (Figure 1). The chosen simulator model is of the microscopic type. The time model was selected in order to fully capture the dynamics of the time dependant behaviour within the individual components.

Components of importance to model are those who may have an active impact on the state of the environment within the district heating system, i.e., those who can be said to control the state. The following control devices need to be simulated:

- Pump stations.
- Heat exchangers.
- Heat producers.
- Storage tanks.
- Valves

The system is based on previously validated models and can thus be said to adhere the physical approach to simulation. Furthermore, the purpose of the simulation is to evaluate different operation strategies, making its usage concentrate on operational considerations rather than design.

3.3 Design and Implementation

In order to achieve a high level of modularity, thus easing future development, the simulator software has been divided into three separate parts:

- Editor, provides the possibility to create a representation of an arbitrary district heating system. The editor also provides an interface for setting all initial values and operational parameters of the simulation.
- Simulator kernel, calculates the dynamic behavior of the system, based on input given from historical states as well as input provided at run time.
- Analyzer, provides the possibility for detailed analyses of output from the simulation.

The simulation program (see Figure 5) comprises approximately 35000 rows of code (approximately 15000 for the simulator kernel) and is written in the Java programming language in order to achieve platform independence. Furthermore, all simulation parameters, component attributes, district heating network configurations as well as the output, are represented in XML, making it easy to add, delete or customize the environment.

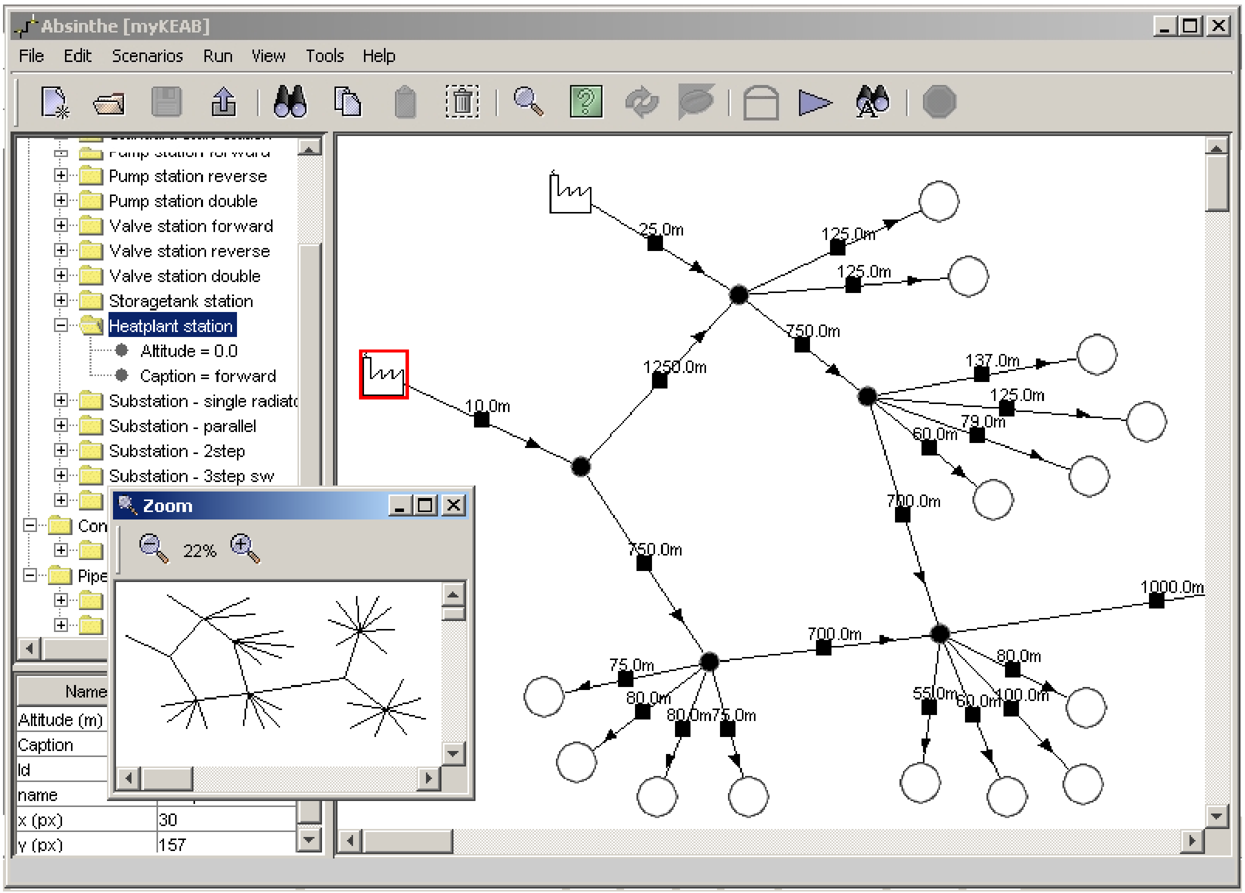


Figure 5. A screen shot of the simulation tool.

We will here focus on the simulator kernel. Before the actual simulation starts, the network produced in the editor is divided into subnets. The construction of these subnets is based on the location of components acting as boundary areas. In a very simple network with a single heat exchanger and a single heat producer there will only be two subnets; one for the outgoing flow, and one for the returning flow. In this case, the heat exchanger and the heat plant will act as boundary areas for the subnets. Then, for each of the subnets the following steps are taken:

1. Sort the components and build the necessary initial data objects representing the tree, links and nodes of the graph.
2. Calculate the available heat production, the wanted heat consumption and, based on these, the actual heat consumption of this cycle. This stage involves considerations of the possible changes during one single time step to the network state. The initial boundary area values are calculated within the components acting as boundary areas.
3. Calculate the mass flow for each component. If the network contains any loops this has to be done iteratively, i.e., until the threshold limit for the difference between two iterations has been reached.
4. Based on the mass flow we make the hydraulic calculations. The flow and hydraulic values are then stored to the actual data objects representing the individual components.
5. After the mass flow and hydraulic values for all components in all subnets are calculated, the control is returned to the simulator kernel. Based on these new values, the expansion of the temperature wave as well as temperature losses to the environment can be calculated. This is performed by a recursive algorithm traversing the network and advancing the temperature according to the current flow.

At this point the simulation of the current cycle is complete and all that is needed further is to save the values for analysis and for propagation into the next cycle. The flowchart in Figure 5 summarizes a simulation cycle.

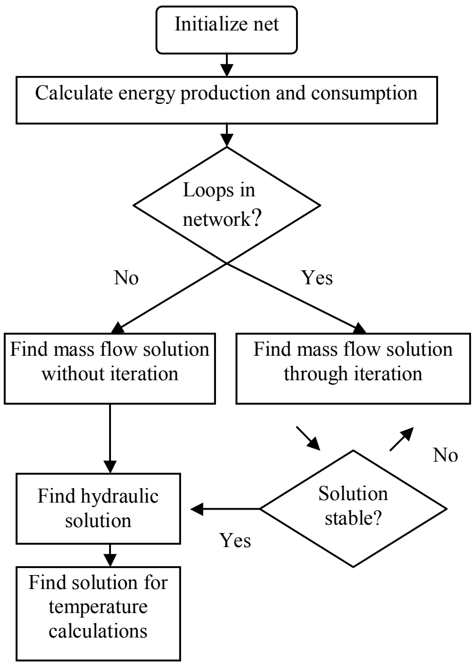


Figure 5: Flowchart of simulation.

In order to simulate the response of management decisions in a district heating network, the ability to prioritise between different heat sources needed to be implemented. Different kinds of heat production models were implemented in the components acting as heat plants. Furthermore, consumption values were needed for simulating the wanted consumption (whether they may get this amount of heat or not is dependent on the actual current state of the simulation). By choosing appropriate production and consumption value sequences we are able to simulate arbitrary states in the network, e.g. heat shortages.

A district heating network is normally composed of a number of additional components, each having their own characteristics and function within the network:

- The *pipe* components usually make up the bulk of the transport system. The mass flow and hydraulic simulation is computed as part of matrix operations on a higher level and not within the pipe component itself. In contrast, the computation of the thermodynamic expansion is in part made within the actual pipe component.
- *Valves* are mainly found in conjunction with different types of substations, e.g. heat plants, heat exchangers or pump stations. However, there are no constraints regarding their placement from a simulation perspective. The valve components main purpose is to introduce a certain time delay into the model, thus simulating the time it takes for the real-life components to react. This is important since each step in the simulation is only one second, and a typical valve needs, e.g., ninety seconds to move from fully open to completely shut.
- When considering *pumps* within the simulation, we basically view this component as a negative resistor (Valdimarsson 1993), Thus, in contrast to all other components which add resistance to the fluid, the pump components decrease it. The amount of negative resistance introduced into the system is dependant on the characteristics of the pump, such as maximum mass flow capacity, time to open and the maximum pressure difference.
- The purpose of a *heat exchanger* is to transfer energy in form of heat from the district heating supply system into the consumer system. This obviously influences both the state of the fluid within the consumer system and within the supply system.
- The *heat producer* is in essence a heat exchanger in reverse; transferring heat from various sources of energy into the district heating transport system.
- It is economically unsound to let the heat production fluctuate too much. For instance, frequent turning off and on should be avoided. Instead of turning off the heat producer when a temporary dip in consumption occurs, the heat can be transferred to a so called *storage tank*. The opposite situation occur when the consumption temporarily peaks. In the simulation model the storage tank acts in a similar way as a heat exchanger, i.e. it either draws energy from the system or inserts it.

The simulation tool provides a great deal of freedom in building hypothetical networks. In doing so one invariably introduce the possibility of the user creating non-realistic networks. This places great demand on the validation process, since there is always a trade off to be made between accuracy and completeness. In this process we have to prioritize the accuracy since we can make greater use of a system that is able to accurately and precisely handle all more or less realistic networks than a system that poorly handles *all* networks. For example, a basic issue was how to correctly represent flow sources and head sources in relation to heat producers and consumers since these change dynamically as the simulation traverses the various subnets within each cycle.

The simulation cycle is one second. However, this does not mean that interaction from the control strategies have to operate at the same interval.

3.4 Simulation Validation and Verification

Valid simulation model components were available and could be combined and calibrated to simulate the performance of a district heating system. The model developed by

Valdimarsson for calculation of the steady state has been found valid in comparison with the commercial software package, PIPE-FLO (Valdimarsson, 1993), and for the district heating system of the city of Almere, Holland (Valdimarsson, 1997).

During every phase of implementation we have taken great care in validating the output. All equations has been implemented and solved in Matlab and continuously been used to validate the output from different simulation configurations.

We use the same initial state for different simulations, i.e., all parameters are set according to their initial configuration when the simulation begins. The warm-up period varies and depends on network topology and simulation setup.

3.5 Usage

The simulator is used to evaluate different agent-based approaches to district heating management. We made extensions to the editor to get capabilities for design of connections between agents in a multi-agent system and components in the district heating system see Figure 6.

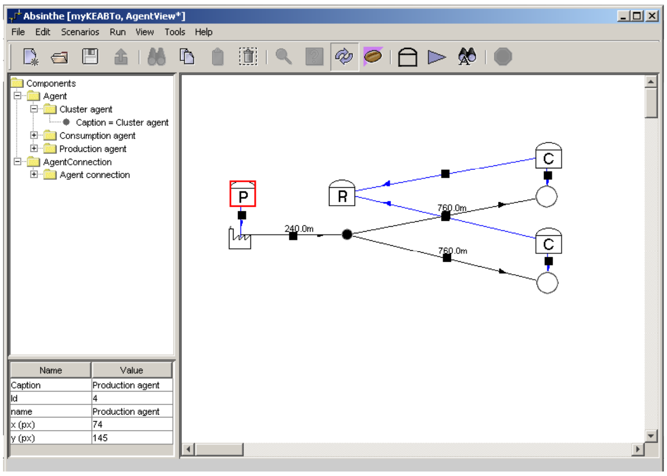


Figure 6. An example of connections from agents to components in the district heating system.

4 CONCLUSIONS AND FUTURE WORK

We have developed a simulation tool which integrates existing models of the various entities in a district heating system in a novel way. We have used the model developed by Valdimarsson, which is valid for steady state but needed much consideration concerning the environment, to be able to be incorporated into a dynamic simulation of district heating systems. For example, a basic issue was how to correctly represent flow sources and head sources in relation to heat producers and consumers since these change dynamically as the simulation traverses the various subnets within each cycle. Different ways to optimize these processes are under consideration, since they constitute a crucial part of simulating the dynamic environment.

Acknowledgement. We would like to thank the 12 software engineering students in the AgentSimHeating team who implemented a major part of the software during their B.Sc. exam project at Blekinge Institute of Technology. This work has been financially supported by VINNOVA (The Swedish Agency for Innovation Systems).

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