ABSTRACT
A district heating system consists of one or more production units supplying energy in the form of heated water through a distribution pipe network to a multitude of consumers. District heating systems come in a range of different forms and sizes; from small independent systems within industrial estates or university campuses to large city-wide systems supplying millions of consumers with heating and hot water. The geographically dispersed layout of district heating systems suggest that they are suitable for distributed optimization and management. However, this would imply a transition from the classical production-centric perspective normally found within district heating management to a more consumer-centric perspective. In this work we use multi-agent based systems in order to implement distributed policies for operational planning within district heating systems. We also develop models for simulating the dynamics of district heating systems in order to evaluate those policies and their use in computer-based demand side management approaches for improving operational planning and resource management. These policies are then implemented in real world industrial settings and their performance, as well as implementation issues, are analysed and evaluated. It is shown that distributed policies can lead to significant benefits compared to current schemes with respect to energy usage and heat load management at an operational level.
Towards Intelligent District Heating

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"I wandered lonely as a cloud, That floats on high o'er vales and hills,
When all at once I saw a crowd, A host, of golden daffodils"

– William Wordsworth (1770-1850)
Abstract

A district heating system consists of one or more production units supplying energy in the form of heated water through a distribution pipe network to a multitude of consumers. District heating systems come in a range of different forms and sizes; from small independent systems within industrial estates or university campuses to large city-wide systems supplying millions of consumers with heating and hot water. The geographically dispersed layout of district heating systems suggest that they are suitable for distributed optimization and management. However, this would imply a transition from the classical production-centric perspective normally found within district heating management to a more consumer-centric perspective. In this work we use multi-agent based systems in order to implement distributed policies for operational planning within district heating systems. We also develop models for simulating the dynamics of district heating systems in order to evaluate those policies and their use in computer-based demand side management approaches for improving operational planning and resource management. These policies are then implemented in real world industrial settings and their performance, as well as implementation issues, are analysed and evaluated. It is shown that distributed policies can lead to significant benefits compared to current schemes with respect to energy usage and heat load management at an operational level.
Acknowledgments

This licentiate dissertation could not have been written without the help of Professor Paul Davidsson and Dr Fredrik Wernstedt who not only served as my supervisors but also encouraged and challenged me throughout this work. Together with my colleagues at the Distributed and Intelligent Systems Laboratory (DISL) they provided vital encouragement and support.

I would like to thank Dr Janusz Wollerstrand who introduced me to the nuts and bolts of district heating systems.

Furthermore, I would like to acknowledge Mikael Ganehag Brorsson and Markus Bergkvist, for making it possible to implement these systems in practical settings.

To my family and friends for providing me with encouragement and motivation.

Karlshamn, September 2010
Christian Johansson
Preface

In 2001 the ABSINTHE (Agent-Based Monitoring and Control of District Heating Systems) project was started by Professor Paul Davidsson and Dr Fredrik Wernstedt at Blekinge Institute of Technology, although their initial research concerning distributed control in district heating systems started in 1999. The ABSINTHE research project was jointly sponsored by VINNOVA and Cetetherm AB, and dealt with the fundamental principles of applying multi-agent based solutions to the problem of operational resource management within district heating systems. The project resulted in the doctoral dissertation "Multi-Agent Systems for Distributed Control of District Heating Systems" by Fredrik Wernstedt in 2005. The work on this licenciate thesis started in late 2007 and has in large parts been a continuation of the work previously achieved during the ABSINTHE project, although with a slight more focus on actual real-time implementations of the studied solutions.

This compilation thesis comprises six papers. These are listed below and will be referenced in the text by the associated Roman numerals. The author of the thesis has been the main contributor to papers I, IV, V and VI and contributing author for papers II and III. The author has contributed to all papers in relation to conducting experiments, analysing data and writing the papers. Each paper is previously accepted for publication and has been revised to conform to the thesis template.


Reykjavik, Iceland.


In addition to the papers included in the actual thesis, the following papers are also related to the thesis. These papers are the results of various research projects financed by the Swedish District Heating Association and they are published as reports in Swedish.


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Chapter 1

Introduction

The district heating industry has a long tradition and now-a-days plays a major role in heat distribution in many countries in Northern and Eastern Europe with expanding markets in Asia and North America. In Sweden more than fifty percent of all heating demand is supplied through the use of district heating, and the conversion to renewable sources of energy within the district heating systems was the single most important reason that Sweden managed to fulfil its obligations in regards to the Kyoto Protocol. In an age were all energy systems within our society are scrutinized, the district heating concept continues to thrive and expand based on the knowledge that the technology at its core is financially advantageous and environmentally sound.

This thesis explores the presumption that the performance of operational planning and management within district heating systems can be improved by distributed control strategies. This idea stems from the fact that most district heating systems are geographically spread over wide areas. The distribution medium in itself also applies certain time dependant constraints on the system, i.e. as opposed to electricity, water does not move at the speed of light. This leads to a situation where the distribution of the heat can take several hours depending on the geographical location of the consumers in relation to the production plants. This combination of physically dispersed hardware nodes and inherent time-dependency makes for a complex situation which further strengthens the notion that a distributed perspective is suitable in which the calculations involved can be divided among several computational nodes. Furthermore, district heating systems consists of a multitude of consumers and producers who might not want to share all their personal information on a global system wide scale just in order to achieve some optimal operational status. Together these observations lead to the idea that distributed systems in general and multi agent based solutions in
particular are suitable for these type of problems. In this thesis we implement and evaluate such solutions in order to achieve distributed control within district heating systems. In parallel with this we develop simulation and modelling tools in order to support the development and evaluation of these systems.

The thesis consists of two major parts; the introductory section and the actual papers. In this first chapter the research area is introduced and presented together with a walk-through of the content and contribution of the different papers in relation to the research questions. The chapters following that consists of previously published papers and articles.

1.1 Main Concepts

This thesis is based on interdisciplinary research which with a starting point in Computer Science combines Operations Research, Economics, Energy Systems, Automation and Building Physics. The application area for the general research effort lies within energy systems in general and district heating systems in particular, while this licentiate thesis in itself is more or less solely focused on the application area of district heating systems. The resulting work alternates between being published through venues related to agent systems or simulation techniques to district heating conferences. Since the papers are published in forums aimed at different audiences the presentational style can differ slightly from paper to paper. All these areas are, however, related in the fact that they form conjoined, albeit diverse, tools used in the evolution of intelligent district heating systems.

1.1.1 District Heating

A district heating system consists of several production units, a distribution network and a multitude of consumers. The production units heat water which is then pumped through the distribution network. The consumers use this hot water in order to heat buildings and tap-water. Normally the heating systems in the buildings are separated from the distribution network, and make use of heat exchangers in order to transfer heating energy from the primary distribution network to the secondary system within the buildings.

Since the energy production is centralized around relatively few production units it is easier to achieve large scale benefits when dealing with operational issues relating to everything from fuel-economy to environmentally sound development of production technologies. A prime example of this is the use of industrial waste heat as an energy source for district heating. This specific source of energy would be very hard to utilize in other heating schemes, and is normally, as the name implies, wasted. For the basic function of a district heating system the
primary energy source is more or less irrelevant as long as it is capable of raising the water temperature to the needed level.

Figure 1.1: A simplified district heating system with one production plant and three consumer substations

District heating as a technology has been around for a long time, and there has been numerous developments made in order to increase the operational efficiency from financial and environmental perspectives. However, the primary focus has usually always been on the production side of the system, while the distribution and consumption part of the system has normally been treated more or less as a black-box in regards to operational management. In the future an increased focus on system-wide coordination and optimization will most likely evolve, where all aspects of the entire system will need to be incorporated as dynamic and time dependant parts of the overall control scheme. As consumers grow evermore aware of energy costs and energy efficient building technologies the energy producers will have to develop new business models in order to meet the changing demands of the market.

1.1.2 Simulation

Simulation is the art of imitating some process or item. This is done by building physical or theoretical models of the process or item in question. These days much simulation is computer-based, and the methodology of simulation provides a powerful range of tools for answering questions in line with what if in relation to complex processes and events. Such tools play an important role in scien-
tific studies since full-scale experiments are often very expensive and complex to perform in real life.

Simulation technologies are frequently used within operational management and planning in district heating systems. In order for an energy producer to be able to meet the demand it is vital that the operators have an idea beforehand about what the demand will be. This is usually done by using weather forecasts as input for simulation models which then approximate the heat load demand for the coming hours and days. Normally such simulation models treat the distribution network along with the consumer nodes as a black-box, i.e. neither the distribution network nor the individual consumer behaviour is modelled explicitly. This approach is obviously inadequate when dealing with distributed management where the behaviour of the entire district heating system is studied and controlled. A distributed approach needs to be able to model not only the operation of the production units, but also the dynamics of the distribution network along with the behaviour of individual buildings.

Building control systems typically operate according to the outdoor temperature, which is why the energy producers use weather forecasts as input when studying future heat load demand. Simulating the details of the thermal dynamics within an entire building is somewhat complex and requires an in-depth analysis of the building in question, in relation to geometry, building materials, heating and ventilation systems, social behavioural patterns and so on. Normally it is not feasible to gather all this material from all buildings in an entire district heating network, and most of the time it is not necessary. By using aggregation techniques and/or a limited range of pre-defined template building models it is possible to keep this complexity at an acceptable level without sacrificing the overall goal of analysing the system-wide behaviour.

1.1.3 Demand Side Management and Load Control

Demand side management and load control lie at the core of the consumption oriented approach to operational management within district heating systems. The basic idea is to be able to control the heat load demand at the consumer level and thus introduce another dimension of control for the energy producer. These techniques can be implemented directly as well as indirectly. An indirect approach might, for example, involve using a certain pricing scheme with differentiable energy cost in relation to the current heat load usage. Such pricing might be used in order to mitigate peak load problems within district heating systems. The fundamental problem with such indirect approaches is that even though the consumer might be able to observe what is going on, they usually have no means to do anything about it until it is too late. Direct load control or demand side management is when the energy producer is able, within certain limits, to
directly control the heat load usage by remote means. Direct approaches might be more appropriate for operational management, but are, on the other hand, much more difficult to implement since they tend to require considerable investments in hardware along with the development of advanced software systems.

Two main objectives with demand side management or direct load control are load shedding and load moving. Many district heating systems have problems with peak loads during certain hours of the day and the ability to effectively shed such peaks is desirable from financial as well as environmental aspects. Many district heating systems utilize combined heat and power generation, and by using peak moving in order to match spot-prices on the power market it is possible to improve the overall efficiency of such systems. These techniques are implemented by coordinating short-term temporary heat load management among the consumers within the district heating system.

1.1.4 Multi-Agent Systems

A software agent is a program that is capable of autonomous and independent action based on the agents internal and external perceptions. An agent can also interact with other agents in multi-agent systems. This interaction can be either competitive or collaborative in nature, or a combination of the two. Agent-based software technologies form a powerful template for implementing intelligent behaviour in a variety of situations, not least in distributed environments such as Internet-based software, robotics or industrial systems.

Since we approach district heating systems from a distributed viewpoint it is convenient to use multi-agent systems as a template for implementing intelligent behaviour in the system. In our implementation we equip each consumer node with an separate agent, as well as incorporating producer agents in the system. All these agents interact in a multi-agent system in order to achieve the goals set forth by the distributed control policies.

1.2 Research Approach

1.2.1 Research Questions

The purpose of this thesis is to develop new policies for operational planning and resource management within district heating systems, and investigate how to apply these policies in an industrial setting. The aim is that these policies should favour both the district heating producer and individual consumers as well as the society as a whole by reducing the use of expensive and environmentally unsound fuel. The working hypotheses for the thesis is that multi-agent based systems are
suitable for this type of resource management. This notion stems from two basic properties of the system:

- A district heating system, due to its physical layout, can be viewed as a distributed network consisting of several geographically spread production units and a multitude of consumer substations along with several other dispersed components such as pumps, valves and storage tanks

- All these units interact and combine in influencing the overall behaviour of the district heating system

Any model capable of achieving the aims of this thesis will have to be able to manage the operation of all these components in real-time, which implies that a distributed system might be more efficient than a centralized solution. The flow of the thesis work is based on three steps; develop simulation and modelling tools, use these tools in order to develop operational polices and finally test these operational policies in a real world environment. This flow is formalized in the following three research questions which are central to this thesis:

- Research Question 1 (RQ1): What is a suitable model for simulating the dynamics of a district heating system in order to evaluate policies for operational planning?

- Research Question 2 (RQ2). What is an appropriate computer-based demand side management approach for improving operational planning and resource management within district heating systems?

- Research Question 3 (RQ3). What are the main issues when implementing such policies in an real world industrial setting, and how does one deal with them?

1.2.2 Research Method

The three research questions are somewhat different in their nature which necessitated the use of a combination of various research methods, including theoretical analysis, simulation studies and practical experiments.

RQ1 was approached by performing a thorough investigation of the state-of-the-art status on the subject of simulation within district heating systems. We found that most previous work in this area was focused on the production units and treated the distribution system and consumers as a black box. This most likely stems from the fact that normally the forward flow temperature and pressure head are the only input variables that a district heating producer can control during operational planning, whereas the consumption is considered to be invariable during the time steps studied. By introducing some level of autonomous
intelligence in the consumer sub-stations we have added another control variable in this equation and the study of the behaviour of these agents necessitated another type of simulation models. These simulation models where then implemented and the resulting output was compared to operational data from actual district heating systems in order to validate their performance.

In RQ2 we begin to approach the core of this thesis, in that it deals with the development of appropriate policies for operational planning and resource management in district heating systems. We used the underlying question of how to improve operational management and planning as a starting point and gathered information and knowledge in order to develop an understanding in relation to the principles of this process. Based on this a hypotheses was formed, stating that a multi-agent based systems would improve the operational management of district heating systems compared to current approaches. Using statistically quantifiable experimental set-ups the hypotheses was tested by implementing the proposed multi-agent system in a simulated environment and then later in a large-scale test installation in an operational district heating system. The resulting data confirmed the hypotheses and proved that it indeed was possible to improve operational planning and resource management by utilizing a distributed multi-agent system capable of coordinating consumer behaviour.

In some way RQ3 follows from RQ2 as we not only need to come up with the policies but also need to make sure that they actually work in a real-world setting. During our practical experiments we identified and catalogued relevant issues with our implementation, which in conjunction with theoretical studies of previous research made it possible for us to zero in on the main issues concerning these type of systems. This is a crucial part of the overall work as the thesis subject does indeed have a heavy emphasis towards applications in real-world environments. In order to evaluate and study the issues relating to RQ3 the same general method was used as during RQ2, expect that the final implementation and testing was performed exclusively in a simulated environment.

1.2.3 Thesis contribution

This section explains the connection between the thesis papers and the research questions, and how the papers together leads us to answering the questions.

RQ1: What is a suitable model for simulating the dynamics of a district heating system in order to evaluate policies for operational planning?

Paper I is directly related to this question as this paper deals with the DHemos software that we have developed. The paper describes software that is based on a modelling and simulation framework that combines models for production, distribution and consumption. These models are coupled with an agent layer which
enables us to perform experiments in which the behaviour of certain components within the district heating networks can be controlled by agents. Paper I describes these models in detail and explains how they are combined. The paper also verifies the performance of the models by comparing the resulting output with operational data from a district heating system.

RQ2: What is an appropriate computer-based demand side management approach for improving operational planning and resource management within district heating systems?

Paper II lays the theoretical foundation for answering this question and also provides results from an early test-case implementation where fourteen buildings were connected through a multi-agent network. The paper gave a clear insight into the actual benefits possible to achieve by using a distributed approach when coordinating control among the consumers within a district heating system. Paper II focused on load shedding as the primary objective of DSM. Load shedding is one of the more interesting applications of DSM in district heating, since peak load problems can be encountered in almost every operational district heating system. The problem of peak loads are heavily dependant on human behaviour and as such cannot easily be avoided using conventional control techniques. Paper III and V expands on the work done in Paper II and adds further discussion regarding controlled load shedding. Paper III most notably contribution is that it expands the discussion on the feedback relating to indoor temperatures, and also analyses the concept of over-shooting the DSM control strategies. Over-shooting was shown to be less desirable since it introduced a more volatile operational state and also caused a more direct impact on the indoor temperature, while not resulting in better performance. Paper V continues to describe a large scale real-time industrial application of the fully armed and operational multi-agent system.

RQ3: What are the main issues when implementing such policies in an real world industrial setting, and how does one deal with them?

In Paper IV we take a more practical view of problems relating to how the multi-agent system reacts to different levels of sensor data availability. The paper describes the problem domain in a slightly more general aspect then in the previous papers, in that it only assumes that the domain characteristics are predictable from a macroscopic perspective while being highly stochastic from a microscopic perspective. A district heating systems does indeed have these characteristics, but so does also other processes, e.g. power grids. The paper formalizes the way the producer agent forms a control strategy by utilizing specific solutions of the Economic Dispatch Problem and the Unit Commitment Problem, while
the consumer agents work pretty much as described in the previous papers. The paper describes three different levels of sensor data availability, global, partial and local. These three scenarios range between the global scenario which is the normal operational mode for the multi-agent system (global availability of sensor data) and the local scenario (the consumer agents only know their own local sensor states), with the partial scenario being a combination of the two. Maybe not so surprisingly the global state gives the best performance, but the paper quantifies just how much better performance can be achieved. This is important when considering investments in infrastructure needed to enable such multi-agent systems. Paper V describes the implementation and operation of a large scale industrial application and contributes a discussion about the practical issues arising during such endeavours. Paper VI deals with temporary heat load reductions and how they affect the thermal dynamics of individual buildings and result in possible reductions of energy consumption. As opposed to the other papers, this paper focuses more or less solely on the behaviour of the individual buildings. Since temporary heat load reductions are a cornerstone of more complex control processes such as Demand Side Management and direct Load Control, this paper constitutes an important contribution to the overall thesis work.

1.2.4 Related reports

In addition to the studies presented in the papers included in the thesis a number of related studies have been carried out. Papers VII, VIII and IX are reports based on several projects that have been performed in parallel with the main thesis work. Although they are not part of the actual thesis, they do indeed amount to an important addition to the overall effort.

Paper VII shows that the primary advantage with load control is to shave peak loads. It is shown that the most important aspect in order to lower the return temperature from the substation is to use properly sized components within the consumer substation, as well as implementing an optimal control scheme in the substation. However, it is also shown that it is possible to use load control during peak load periods in order to achieve lowered return temperatures. During such periods increased return temperatures can normally be expected, which shows that load control is an important aspect in the overall system optimization from this perspective.

In paper VIII an industrial demonstration project is described in which three different district heating systems were equipped with agent-based software for load control. The purpose of the project was to analyse the potential of the technology during practical commercial conditions. Paper V discusses much of the same data from a somewhat more concentrated perspective.

Paper IX discusses a pre-study on the functionality of a simulator system
that was developed in order to model and analyse the dynamic behaviour within district heating systems. The basis for this software is described in paper I. The purpose of paper IX was to evaluate the current state and future capacity of the simulator system and to conduct a comparison between the system and existing commercial simulator systems. The results show that our simulator system can indeed “do the math”, even though the system lacks important functionality which makes it somewhat inferior to commercial alternatives. However, it is shown that the simulator system has a range of basic design qualities which justifies its continuous development.
Chapter 2

Paper I - Dynamic Simulation of District Heating Systems

Simulation is commonly used within the domain of district heating, both as a strategical decision support tool and as an operational optimisation tool. Traditionally such simulation work is done by separating the distribution models from the production models, thus avoiding the intricacies found in combining these models. This separation, however, invariably leads to less than satisfying results in a number of instances. To alleviate these problems we have worked to develop a simulation tool which combines the physical and financial dynamics throughout the entire process of production, distribution and consumption within a district heating system.

2.1 Keywords

Industrial control, Interactive simulation, System dynamics, Energy, Interacting distribution and production

2.2 Introduction

Dynamic simulation of a district heating system can easily become overwhelmingly complex, due to the large number of interacting components. A district heating system may contain several production plants and literally thousands
of buildings connected through a network of hundreds of kilometres of pipes. The topology of the network is usually described by a complex geometry including loops and numerous branches, and is geographically spread over a wide area resulting in large transport times. Similarly the production plants and the consumer endpoints are in themselves very complex entities.

All in all there is a large number of parameters that need to be taken into continuous consideration. However, in practice most of these parameters can not be determined precisely, e.g. because they are not described in the construction plans or maybe because they are simply too difficult, or even impossible, to measure. In the ideal case, a detailed computer model is available, which is validated by comparison with measurements of high resolution in time. Using measured values from a district heating system in the Swedish town of Gävle, we perform such a comparison using our design and implementation of a simulation tool. This simulation tool and its fundamental design and capabilities are described in this paper.

2.3 District Heating Systems

The general idea with district heating systems is to distribute hot water to multiple buildings, see Figure 2.1. The heat can be provided from a variety of sources, e.g., co-generation plants, waste heat, and purpose-built heating plants. The system contains tree characteristic parts: the distribution net, the production plants and the district heating substation located at the customers.

Figure 2.1: A small district heating system, with one production plant and two consumers connected through a distribution system for hot supply water (light grey) and cold return water (dark grey)

District heating stands for approximately 12% of the total energy consumption (Energy in Sweden: Facts and figures, 2004) in Sweden and is the dominating technique for heating in apartment blocks and offices in densely populated areas (Fjärrvärme på värmemarknaden, 2003). The distribution net in Sweden contains approximately 14 200 km of pipes (Statistik 2003, 2003) and reaches
about 1.75 million apartments, 153 000 houses and a great number of schools and industries (Fjärrvärme på värnemarknaden, 2003).

2.4 Dhemos

Microscopic models can be used to describe the spatially distributed system behaviour. The goal of developing such models is to be able to calculate the flow, pressure and temperature in all components throughout the system as a function of time. This distribution model is then combined with production and consumption models.

2.4.1 Consumption

The consumption model consists of three main parts. The building model describes the energy consumption used in heating the building, while the tap water model handles the energy demand for producing the domestic hot tap water. The third part is the outdoor model, which simulates the influence from the ambient environment.

The building model is composed of three components, an energy demand component, a heating component and a flow controller component. The energy demand component describes the building energy demand to maintain a given indoor temperature at a specific outdoor temperature. The resistance, $R$, of the building is given by:

$$ R = \frac{1}{U_{ext} \cdot A_{ext} + e \cdot n_{50} \cdot V_{air} \cdot \varphi_{air} \cdot C_{air}} $$

where $U_{ext}$ is the mean U-value of the envelope with area $A_{ext}$, which encases the air volume $V_{air}$. The infiltration rate is $e \cdot n_{50}$ and the heat capacity of the air is $\varphi_{air} \cdot C_{air}$.

The total heat capacity of the building, $C$, is given by:

$$ C = U A \varphi T_{out} + U A \varphi T_{in} + U A \varphi T_{roof} + U A \varphi T_{floor} $$

where $U$ is the heat conduction in W/m²K, $A$ is the area in m², $\varphi$ is the density in kg/m³ and $T$ is the thickness in meters for the outer wall, the inner wall, the roof and the floor respectively. The building model have been validated in a series of simulation studies (Gieseler, Heidt, & Bier, 2003). A building looses heat by heat transfer through the building surfaces, and by exchange of air between the heated space and the buildings surroundings. The heat loss is mainly a function
of the outdoor air temperature. By taking the outdoor temperature as the single influencing factor for the weather, the energy demand can be calculated by:

\[ T_{xi} = \frac{1}{1 + \frac{1}{TR_x TC_x} \left( T_{x(i-1)} + \frac{Q_i + T_{outi}}{TR_x TC_x} \right) + \frac{Q_i + T_{outi}}{TR_x TC_x}} \]  

(2.3)

where \( Q_i \) is the heating power, \( T_{xi} \) is the temperature of an object, \( x \), at the time \( i \) which had temperature \( T_{x(i-1)} \) one time unit ago with resistance \( TR_x \) and capacity \( TC_x \) in an surrounding environment with temperature \( T_{outi} \).

The heating component describes how heat is transferred from the district heating water to the building as a function of water mass flow, building water supply temperature and indoor temperature. As an additional output signal, the water return temperature is calculated (no thermostats are used in the building).

\[ Q = m * cp * (T_s - T_r) \]  

(2.4)

where \( Q \) is the heat supplied in W, \( m \) is the water flow in kg/s, \( cp \) is the capacity in J/kg°C, \( T_s \) is the supply water temperature in °C and \( T_r \) is the return temperature in °C.

The flow controller component describes how the indoor temperature controls the district heating water flow. The radiator system, see Figure 2.2, consists of a separate water system. The heat is transferred from the district heating side to the radiator side through the heat exchanger (4). The heat supply is controlled by the regulation (PI) equipment (6) whose valve (2) adjusts the amount of district heat water passing through the heat exchanger.

The system transferring energy from the district heating water to the secondary system within the buildings are modelled as parallel coupled substations. Substations comes in various configurations and there exists types that are of a more complex construction (Fredriksen & Werner, 1993). However, the parallel model gives a good enough description of the relations between flow rate and temperature (Arvastson, 2001). The control of the substation influences both the state of the fluid within the consumer system and the supply system. To handle shortages of energy in the transfer to the consumer system the time constant, \( \tau \), of the building is calculated. The time constant is used to calculate the change of indoor temperature when there is insufficient energy available or reduction of indoor temperature is wanted. The building storage capacity and isolation determines how quickly the temperature adjusts to a change of the outdoor temperature. The time constant is given by:

\[ \tau_0 = C * R \]  

(2.5)
Figure 2.2: A parallel substation

and the temperature change is calculated by (Österlind, 1982):

\[
\frac{T_r(t) - T_u}{T_{r,0} - T_u} = e^{-\frac{t}{\tau_0}}
\]

(2.6)

where \(T_r(t)\) is the room temperature at time \(t\), \(T_{r,0}\) is the initial temperature, and \(T_u\) is the outdoor temperature. Faster gradients can only be caused by active ventilation.

If the heating is not turned off completely, but just reduced, the time constant will change according to (Selinder & Zinko, 2003):

\[
\tau = \frac{\tau_0}{1 - k}
\]

(2.7)

where

\[
k = \frac{P_v}{\sum U A + P_L}
\]

(2.8)

where \(P_v\) is the supplied energy, \(U\) is the heat conduction value in W/m\(^2\)K, \(A\) is the area in m\(^2\) and \(P_L\) is the energy need for ventilation.

In Figure 2.3 we show the time it takes for a building with a time constant of 60h to drop three degrees during different conditions regarding supplied energy at an outdoor temperature of -20°C.
The tap water system can be designed in different ways depending on the demand. The system normally contains a circulation pump that circulate the water at a low speed, this is done to minimize the bacterial content and to get a rapid supply of hot water. Opposite to the radiator system, the tap water system has a dynamic valve set-up, i.e. the flow primarily depends on social factors.

The domestic hot tap water demand of the customers is simulated through a tap water model (Arvastsson & Wollerstrand, 1997) where flow size and tapping durability is determined by the simulation of a random number, $Y$, from a certain distribution with cumulative distribution function $F_Y$, which can be performed using uniformly distributed numbers, and where the time between tapping is a non-homogeneous Poisson process:

$$X = 1 - \exp \left( - \int_0^T \mu(u) du \right)$$  \hspace{1cm} (2.9)

where $\mu(u)$ is the time-varying opening intensity and $T$ the time to derive. The opening intensities are derived from:

$$\mu = \frac{p}{(1 - p) \eta}$$  \hspace{1cm} (2.10)

where $\eta$ is given by measurement data (Holmberg, 1981) and $\mu$ is calculated from the distribution function for open valve time. The probabilities for usage of hot tap water during the day is divided between Bath, Wash and Kitchen according to Figure 2.4.
The variance over time of the outdoor temperature is simulated by the following model (Ygge & Akkermans, 1999):

\[ T_0 = T_m + T_v * e^{-(i * s - 4) mod 24 - 12)^2 / 20} \]  \hspace{1cm} (2.11)

where \( T_m \) is the lowest temperature to expect, \( T_v \) is the maximum temperature to expect, and \( s \) is the time interval expressed in hours. The virtual temperature, \( T_{vio} \), is described by:

\[ T_{vio} = T_{outd} + T_r + T_d \]  \hspace{1cm} (2.12)

where \( T_d \) is a random disturbance, representing small fluctuations caused by, e.g., the wind. \( T_d \) is Gaussian distributed with an average of 0 and a standard deviation of 1. \( T_r \) is a sun radiation component described by:

\[ T_r = 8 * e^{-(i * s + 4) mod 24 - 12)^2 / 20} \]  \hspace{1cm} (2.13)

### 2.5 Production

The purpose of production modelling is usually to optimize the operation in regards to production costs such as fuel, wages, taxes and fees, possible network expansions and so forth. Simulation modelling is a powerful tool used by most district heating operators in order to plan daily production as well as long term financial planning. In addition, we also develop continuous production limitations
for the distribution and consumption simulations. Together, the production and consumption models form the input for the distribution model.

There are several different types of production units and they all have different constraints and operational limitations which influence their respective abilities to produce energy. It is important to propagate these limitations into the distribution and consumption calculations, since these will be prone to error otherwise. Likewise, the production models will greatly benefit from continuous response from the distribution and consumption models (Rossing & Johnsson, 2005). This is one obvious case were the combined production/distribution/consumption model clearly shows its advantages over using separated models.

Dhemos incorporates the use of pumps into the production model, and together with the output temperature from the heating unit, their behaviour form the practical input data into the distribution model.

Finally the total production cost during time \([t - \Delta t, t]\) is based on a series of rather fundamental relations on the form of:

\[
C(t) = \Delta t \sum_{i=1}^{n} C_{U_i}(t)
\]

where the \(C_{U_i}\) unit cost is given by the solution to a linear programming problem (Arvastson, 2001; Dotzauer & Lundh, 2004).

2.6 Distribution

The distribution network consists of a number of components, all of which can be considered to be branches in the theoretical representation. On an abstract level the system can be divided into two partly overlapping parts, the boundary areas and the branches and nodes connecting these boundary areas. The boundary areas define the input variables for the distribution simulation model. These boundaries often, but not necessarily, include, e.g., production plants, heat exchangers, and pumps. The largest variable influence on the distribution model, apart from the boundary conditions, is the hydraulic resistance within the pipe network (ISBN 9979540559, 1993).

Graph theory offers a convenient way of representing and calculating the dynamics of the water flow and pressure states throughout the system. Combining the boundary inputs and the branch resistance equations leads to a system which can be solved directly assuming there are no loops and no more than one heat producer in the network. More complex networks with loops and several heat producers needs to be solved numerically through iteration (Wernstedt, Davidson, & Johansson, 2003). This produces a steady state solution which is a logical starting point for the dynamic simulations.
The formulation of each individual resistance equation depends on the type of component in question. The basic resistance characteristics obviously differ greatly between pipes, valves, fittings and pumps. Even when dealing with only one specific component representation care has to be taken when modelling the resistance, since the hydraulic behaviour of water can vary greatly depending on whether the flow is laminar or turbulent. A resistance value for a specific branch is usually positive, however, a pump within the network, i.e. a pump not acting as a boundary area, can be viewed as a negative resistor. For a more complete review on the subject see (ISBN 9979540559, 1993).

The temperature transport dynamics is dependant on the flow situation, since the water is the carrying medium of the energy. However, due to physical influence of pipe geometry, the transport time for the water flow and the transport time for the temperature front will differ a great deal. In fact, only when the pipe diameter approaches infinity can this difference be ignored (ISBN 91-628-6504-8, 2005). This obviously means that any temperature model which pertains to mimic reality will have to incorporate such considerations. In (ISBN 91-7197-814-3, 1996) a factor $F$ is defined which relates the flow velocity, $v$, to the velocity of the temperature front, $v_T$. $F$ is defined as:

$$ F = \frac{v_T}{v} \quad (2.15) $$

The relationship between the pipe, $p$, and the water, $w$, is shown in:

$$ F = \frac{1}{1 + \frac{\varphi_p * \varphi_{w,p} * \Delta \delta}{\varphi_{w,p} * \varphi_{w,w} * \delta d_{i,p} + 1}} \quad (2.16) $$

where $\varphi$ is density, $c$ is specific heat capacity, $\Delta$ is pipe wall thickness and $d$ is the inner pipe diameter. For example, if a DN 50 pipe is used the temperature front will have propagated 83 metres as the water flow has moved 100 metres.

It is the temperature distribution that limits the computational performance during practical implementation of the simulation models. This is due to the fact that pipes have to be divided into a number of sections in order to retain the energy status throughout the pipe. Dhemos uses variable section sizes which vary dynamically throughout the simulation in relation to the propagation speed of the temperature front and thus also in relation with the water flow. This means a somewhat higher computational cost as opposed to using a fixed section size, but it also means a higher degree of accuracy in the simulation results.
2.7 Simulation of Gävle DH System

The aim of validation is to create realistic simulation models with respect to energy demand and temperature.

The computational program was applied to the district heating system in the town of Gävle in Sweden. This district heating system produces approximately 716 GWh per year. The total network length is 229 km. Approximately 59% of the sold energy is aimed at larger multi-family buildings, about 7% is sold to one-family detached houses, 5% to industrial buildings and 29% to other buildings such as shopping malls etc. In total we simulates approximately 17 000 customers in Gävle.

Figure 2.5 shows the comparison between simulation results and measured data from the Gävle district heating system.

![Figure 2.5: Comparing simulation results with mean values from measured data](image)

The result is based on hourly mean values taken from 30 winter weekdays in 2001, a period with high data reliability. As in any other district heating network there is a wide variety in customer characteristics in Gävle, e.g. the above simulation spans buildings with time constants that range from 50 hours to 150 hours.

To simulate a full 24 hours such as described in Figure 2.5 takes slightly less than 5 hours to complete when using an AMD Athlon 64 3700+, 2.2 GHz, 1 MB cache with 2 GB of RAM.
2.8 Conclusions and Future Work

The practical importance of the simulator is not only for design of distributing networks, but in the operation of district heating systems. The possibility to simulate the dynamic relations for various operating conditions is very useful for dispatchers in power and heating plants. This is a valuable contribution not only from a technical stand, but also from a financial viewpoint.

Dhemos has been compared with calculations made using MATLAB in order to verify the various implementation solutions. After the analysis of the result from the Gävle simulation we have found that Dhemos is reliable.

The distribution model uses a microscopic model which gives the ability to simulate the behaviour of single endpoints within the network, which is necessary when studying the comfort fluctuations experienced by individual customers.

One problem with existing theoretical models is that they neglect the fact that a large population of the customer installations are working well below their original capabilities. Dhemos implements short-circuits within the customer substations in order to be able to simulate such deterioration in heat exchanger performance.

Future work includes developing the presentational software in order to maximize the usability of the system, e.g. operational pressure diagrams and so forth. We also plan to develop an interface between Dhemos and a general optimization engine in order to further optimize the capabilities of the system. The more theoretical future work includes developing models for using genetic algorithms within Dhemos in order to find optimized solutions when expanding existing district heating networks. Also we need to expand the tap water models to include such buildings as single-family houses, industrial buildings, shopping malls and so forth.
Chapter 3

Paper II - Demand Side Management in District Heating Systems

This paper describes a multi agent system that has made the voyage from research project to commercialised product. The purpose for the multi agent system is to dynamically control a system so that the load of the system is below certain threshold values without reduction of quality of service and by that, to avoid the usage of top load production sources and to reduce energy consumption. The fundamental idea behind the system is that a large number of small local decisions taken all in all have great impact on the overall system performance. A field-test as well as a return of investment analysis are presented.

3.1 Keywords

Management, Performance, Economics, Reliability, Agent-based deployed applications

3.2 Introduction

This paper describes a multi agent system that dynamically controls District Heating Systems (DHS) so that the load of the system is kept below certain threshold values without reducing of quality of service provided to the customers. The purpose is to avoid the usage of top load production sources (which often uses
fossil fuel) and to reduce energy consumption. The fundamental idea behind the system is that a large number of small local decisions together have great impact on the overall system performance.

This venture started as a research project in 1999 as a collaboration effort between Cetetherm (now Alfa Laval), and Blekinge Institute of Technology. The project has since evolved throughout the last few years into this current commercial project, an effort within which the spin-off company NODA Intelligent Systems AB was founded in early 2005. A field-test has just been completed and is reported in section 3.5. The main focus was to validate the system from a technical standpoint. However, since our intent is to commercialise the system, the economical benefits were equally important to investigate.

3.2.1 Background

The basic idea behind district heating is to use local heat production plants to produce hot water. This water is then distributed by using one or more pumps at approximately 1-3 m/s through pipes to the customers where Heat Exchange Systems (HES) are used to exchange heat from the primary flow of the distribution pipes to the secondary flows of the building. The secondary flows are used for heating both tap water and the building itself. In large cities district heating networks tend to be very complex, including tens of thousands of substations and hundreds of kilometres of distribution pipes with distribution times up to 24 hours.

The energy load of any DHS is subject to large variations due to the fluctuating demands of customers. The energy load is mainly divided between the rather slow process of space heating and the fast process of domestic hot tap water consumption. A DHS must be capable of meeting all such fluctuating energy demands.

Optimisation of DHS has traditionally focused on production plants and distribution systems. However, in the last ten years, consumer heating systems (HES) have received increased attention. The product development of HES has changed from focusing on the component (sub optimisation) to focusing on the interaction of the components (system optimisation) (Andersen & Poulsen, 1999). HES, as the heat load source of a DHS, determine the operation of the total DHS. Yet it is unusual that the operation of HES can be monitored or controlled by the DHS operator. The operation strategies of the DHS are therefore limited to providing sufficiently high temperature and pressure to all customers, without any possibility of actually optimising the system as a whole.

Load control HES can either be achieved directly by remote control of individual HES or indirectly by usage of various tariffs. Indirect load control is widely used and has primarily been implemented by the usage of flow tariffs,
i.e., customers are charged according to the flow in comparison to a reference value for the flow. Direct load control is very uncommon but there exists a few attempts, e.g., a centralised load control system that was studied by Österlind (Österlind, 1982). Österlind used a one-way communication link on the electricity network to manipulate the outdoor temperature meters of individual HES. By this communication link he was able to manipulate and control the space heating of the connected buildings. The study confirmed earlier theories of centralised load control and showed that it is relatively easy to achieve robustness against shortage situations in DHS. However, the system did not consider, e.g., fairness and the quality of service (QoS) delivered to the individual consumer. Österlind also concluded that two-way communication was a minimum requirement for an operational system (Österlind, 1990). Two-way communication systems for DH substations are currently at a relatively early stage of development. However, as hardware is becoming available focus should now be on how to use the data/information and how to achieve savings (Drysdale & Stang, 2002).

Energy is not an end in itself; instead it is a means to provide a number of services. Businesses and households view energy as an input, an expense of doing business or maintaining a home. They are less concerned with how many kilowatt hours they purchase than with the services that the energy provides, e.g., space heating. This relationship provides the basis of demand-side management (DSM). DSM can be defined as

"The planning and implementation of strategies designed to encourage consumers to improve energy efficiency, reduce energy costs, change the time of usage or promote the use of a different energy source"

(LIPAedge, 2005)

DSM strategies try to reduce the peak load and change the shape of the load profile through the techniques of peak clipping, load shifting and energy conservation. DSM activities should bring the demand and supply closer to a perceived optimum. Correctly implemented, DSM strategies can reduce energy consumption with the associated financial and environmental benefits. The idea behind energy efficiency is quite simple; if people consume less energy, there will be less emission of greenhouse gases as the result of less burning of fossil fuels in heat production plants. Energy efficiency technologies and practices can therefore play a significant role in reducing the threat of global climate change.

There is very little information and expertise available on DSM for DHS. Today, there is a growing interest, but while DSM has become a standard technique for the electricity market (Levin & Wesslen, 1993; Johansson & Ejeklint, 1991; Aune, 2001; Nordvik & Lund, 2003; P. Johansson, 2003), it is still in the early stages when considering DHS (Heating & Cooling, 2002). The goal of DSM is to be able to control the heat load at an overall system level rather than to
even out the consumption of individual HES. Sipilä and Kärkkäinen (Sipilä & Kärkkäinen, 2000) study the dynamics and potential for DSM in individual buildings connected to a DHS and showed that the maximum heat load of a building can temporarily (during 2-3 hours) be reduced as much as 25% on average. Not once during the test conditions did the room temperature shift more than 2 degrees. In simulation experiments, Noren and Pyrko (Noren & Pyrko, 1998) show that the most successful load control strategy for electricity heated commercial buildings is load reductions of about 40-50% during longer time periods (4h). Stronger load reductions during shorter periods can cause recovery loads higher than the previous maximum demand. The results show that it is possible to move the maximum load several hours in time without discomfort for the customers. The possible reductions in each individual HES indicate that if this kind of measures would simultaneously be performed in a large number of buildings, the maximum load of a DHS can be lowered substantially.

The potential of DSM in DHS is mainly claimed to consist of; lower production costs, reduced usage of fossil fuel, running production units in the most efficient states, increasing the net profit of back-pressure Combined Heating and Power (CHP) electricity sales, handling capacity issues in existing DHS, dimensioning production capacity for a lower effect/reserve alternatively with maintained dimensioning increasing the number of consumers in a particular size DHS.

We present results from a project that has made the voyage from research project to commercial product. Our focus is the trade-off between system optimality and QoS for each connected customer, where our goal is to provide as high QoS as possible while using the production resources in an environmentally and financially optimal way.

### 3.3 MAS Architecture

The availability of small high-capacity computational units has lead to an increasing decentralisation within automation systems as well as a distribution of functionality into geographically dispersed devices. The possibility to connect these distributed units in a Local Area Network (LAN) promises highly dynamic systems. However, the problem of providing a suitable framework for coordinating the connected devices remains.

All buildings in a DHS are more or less unique when considering specific details of inhabitant preferences, household equipment, thermal characteristics, etc. To maintain a centralised model of each connected building in a large DHS with several thousands of consumers would be extremely challenging with respect to computation and communication. In fact, it is argued that when the complexity of a DHS reaches approximately 100 components and restrictions, the present computer and software technology is insufficient for finding an optimal opera-
tional strategy (Böhm et al., 2002). Since an optimal operational strategy is not practically achievable, a method based on some heuristic is needed to find a good-enough strategy. It is possible to perform completely distributed computation to generate an operational strategy. However, the computation would be limited by system knowledge, i.e., the distributed units would not have enough knowledge about the production to conclude the best operational strategy. If the performance degradation of a completely decentralised solution is too large and a completely centralised solution is too complex, a compromise will have to be found.

Due to the rising demand of automation of building services (heating, ventilation, and air-conditioning etc.) Siemens have developed the Saphir, an expandable I/O platform with an expansion slot for a communication card, suitable for equipment control. Access to sensor and actuator data is provided by a Rainbow communication card in the expansion slot.

The Saphir contains a database that continuously is updated with sensor data from the I/O channels by a small real-time operating system, which is directly accessible from the Rainbow card. On the Rainbow card a small computational platform (a hand-held PC) makes it possible to deploy software and by that providing the possibility to host an agent. Hence, an agent deployed on such a platform could potentially read all connected sensor input as well as send commands over the I/O channel to actuators on the hardware, e.g., valves on a heat exchanger. The Saphir platform and the Rainbow communication card have been integrated into a new type of HES, developed by Alfa Laval AB during the term of this research project.

We suggest using a semi-distributed approach. In this case each agent, embedded on a HES, is trying to optimise its own usage of the resources and coordinates with a base station in case there is a conflict. Our system has the following three types of agents:

- **Consumer agents**: (one for each consumer) which continuously (i) monitors and controls the local state and (ii) on request, participates on a cluster level market for partial system optimisation. The consumer agent is cooperative and has global responsibility to participate on the market for system optimisation by providing its true cost for participation in system wide optimisation.

- **Cluster agents**: (one for each cluster of consumers) which (i) maintains a market for partial system optimisation at a cluster level for consumer agents, and (ii) informs the producers agents of a selection of choices to achieve optimisation in the cluster, and (iii) propagates chosen optimisation actions from the producer agents to the consumer agents.
Producer agents: (one for each producer) which continuously (i) monitor their local state and (ii) when necessary issues requests for optimisation of clusters to improve the local production state, and (iii) receives lists of possible optimising actions and informs clusters of chosen actions.

The general architecture of the MAS is shown in Figure 3.1.

![Figure 3.1: MAS architecture](image)

The architecture consists of the three layers:

- **Strategic layer**: This layer consists of producer agents that have strategic goals, making decisions based on wide-area monitoring and control perspectives.

- **Heuristic layer**: The cluster agents in this layer include heuristic knowledge to identify consumers willing to participate in optimisation. These agents also update the world model for the agents in the strategic layer.

- **Operational layer**: The consumer agents in this layer handle their individual hardware systems from a local point of view to achieve fast, consistent and informed control.

The abstract architecture, see Figure 3.2, for each individual agent is very similar to the Procedural Reasoning System (PRS) architecture.

The deliberator module is responsible for controlling all other components in order to pursue the goals of the agent. The deliberator also controls the interactions with other agents, i.e., it coordinates the sending and receiving of messages. The sensor component is the gateway to the perceptions of the external environment (including receiving messages). The effector component imposes changes to the external environment (including sending messages). The agent can
through the effector component affect the external environment either indirectly by exchanging messages or directly through physical effectors (if it has physical effectors).

3.4 Agent Behaviour

Our approach is based on the fact that DHS by nature are distributed both spatially and with respect to control. We utilize the naturally distributed control to fulfil a system level goal of making sure that the system load does not go above a threshold value and to ascertain that the water flow is as even as possible, i.e., to reduce sudden shifts in flow, while affecting the individual consumers as little as possible. Also, when we do affect the consumer we make sure to do it on their terms and in a fair way.

The aim of this method is an attempt to move demand away from the peak load periods by reducing the energy destined for space heating. This reduction of demand will help to smooth out the energy supply profile and help obtain higher levels of efficiencies from the plants by trying to achieve a steady output instead of a load following the fluctuating domestic hot tap water regime. Reduction of the heat load of space is based on exploiting the thermal mass of the building and the secondary networks i.e. we do not restrict production of domestic hot tap water. These measures can reduce greenhouse gas emissions associated with using fossil fuels to meet those peak demands.
3.4.1 Consumer Agent

Cutting the load of customers will affect the service delivered, i.e., a constant reduction of space heating will eventually reduce the indoor temperature. The building heat storage capacity and isolation determines how quickly the temperature of the building adjusts to changes of the outdoor temperature. The time constant is defined as the time it takes for the indoor temperature to drop 63% of the difference between the outdoor temperature and the initial indoor temperature. Typical values for time constants are between 30-80 h for older buildings, but the range continues up to time constants of 5 days for highly isolated buildings, i.e., there exists buildings where we might shut down the space heating for quite some time without affecting the perceived QoS.

If the heating is not turned off completely, but just reduced, the operative time constant will change. For example, a supply of 50% of the required energy will increase the time constant by 2, i.e., it will take twice the time to loose the indoor heat, i.e., if we do not completely shut down the heating and only reduce space heating during shorter time periods most buildings fall within the category of potential reductions without affecting QoS.

In Figure 3.3, we show how long time it takes for a building with a time constant of 60h to cool down 3°C during different conditions regarding supplied energy. These values are calculated given an outdoor temperature of -20°C.

![Figure 3.3: Example of the time it takes for a building to drop 3°C in temperature at different levels of energy supply](image)

The described thermal models for the indoor temperature are used in the
utility function for calculating the cost for a consumer agent to participate in optimizing actions. Using this set of models assures that we get fair reductions in the network since buildings that have been reduced previously get higher costs (larger distance to reference temperature) for implementing new reductions and hence, some other building with closer distance to the reference temperature will have lower cost. Since this model considers the dynamic thermal state of individual buildings the building time constant will assure that buildings with different characteristics will be treated in a fair way and that reductions are spread evenly throughout the network of connected customers.

In order to maintain a given indoor temperature, the heat supplied to a building must equal the heat lost by the building. As the outdoor air temperature drops, the amount of heat lost from the building increases. The amount of heat that the space heating system can supply changes depending on the temperature of the supply water. As the temperature of the supply water increases, the amount of heat available from the space heating system increases. Each building has a heat curve to determine the set temperature for the space heating system, e.g., if the current outdoor temperature is -5°C the temperature in the space heating system should be, e.g., 44°C for a specific building. A reduction at a HES is performed by changing the temperature set value, e.g., a reduction of 10% on the set temperature of 44°C would mean that the heat exchanger in the HES would heat the supply water in the space heating system to 39.6°C instead of 44°C. An issue with direct load reduction is that when the load reduction is released, the recovery load can get higher than the load would be without reductions and hence, the maximum load would not be reduced but rather increased. To reduce the recovery load, several different control strategies are possible (Noren & Pyrko, 1998). However, all of these strategies will prolong the time it will take to restore the indoor temperature, so the recovery time must be considered during calculation of cost for reduction at the customer side. The strategy we use to reduce the effect of recovery load is to restrict the rate of change on the set temperature for the secondary side in addition to letting the individual customer agents release their reductions randomly.

3.4.2 Producer Agent

In a DHS, several different energy sources may be used for heating, e.g., waste energy, by-product from industrial processes, geothermal reservoirs, otherwise combustion of fuels such as oil, natural gas etc. is used. When the demand from the customers is high, several heat producing units must normally be used, see Figure 3.4.

To avoid starting peak load production units, the producer in our system issues requests for optimising actions when the heat load is between a lower and
a higher threshold value. As the load is getting closer and closer to the higher threshold the intensity of requests increases. However, sufficient time needs to pass between requests, so that substations get enough time to carry out changes of valve positions. To decide that there is a need for requests the trend, \( e \), of the load needs to be rising, otherwise unnecessary reductions might be requested. To respond promptly to changes of the heat load and to identify the trend of the load, an Exponentially Weighted Moving Average (EWMA) is used. The EWMA, \( e \), is applying a percentage of the current load to the previous moving average load, i.e., the EWMA place more weight on recent values.

### 3.4.3 Cluster Agent

On request from the producer agent the cluster agent calculates the cost for implementing a reduction of a certain percentage in the cluster. The calculation is performed by issuing requests to the consumer agents within its cluster to calculate their costs to take on the restriction. It then selects the best bids from the consumer agents and return a concatenated bid to the producer. If the cluster is selected by the producer the cluster agent informs the correct consumer agents that they are to reduce their consumption. The general idea with the cluster is to divide and conquer, i.e, instead of a large market at the producer...
we use a number of smaller markets. In this way we maintain local information, e.g., which agents populates a certain area, and makes the problem of choosing substations easier for the producer. The cluster agent is also responsible to make sure that restrictions are implemented, e.g., if the environment for a consumer agent (that is supposed to take on a restriction) changes beyond the model of the consumer agent. The cluster agent needs to find another agent within its cluster to take on the restriction. If it fails to find another consumer agent, it informs the producer that the restriction failed. Finally, another task for the cluster agent is to estimate the current consumption within the cluster and inform the producer of this at regular intervals.

3.5 Deployed System

The area where the agent system is installed is composed of 14 buildings with a total of 350 apartments. The district heating network for the area is very favourable since it can be seen as a separate part of the network in the town, see Figure 3.5. We were thus able to monitor the total delivered energy to the area for verification purposes. To monitor the energy delivered to the area we installed a clamp-on flow meter on the pipe at the entrance to the area, close to the PC building.

![Figure 3.5: Connected buildings](image-url)
The PC building, a separate heating station, is not included in the agent society and within this context only act as the flow meter node. Ten of the buildings are buildings with three floors, two are buildings with seven floors and one is a building with six floors. The last building, F, is a service building without apartments which is closed and empty of personnel during night time. Each building is controlled by one agent. The inhabitants of the area represent a broad variation including families with children, elderly, students etc.

We also installed three separate temperature meters to measure the indoor temperature in buildings 5, 9 and 12. In excess we also instructed the landlord to record any complaints on indoor temperature.

3.5.1 Results

The system automatically controls and monitors the amount of delivered energy in the area. All buildings take part on the economic market for reductions through their agents.

In Figure 3.6 we show that the largest amount of reductions are concentrated to the hours of the day when hot tap water is most frequently used, i.e., in the morning and early evening.

![Figure 3.6: Reductions](image)

In Figure 3.7 we show the difference in delivered energy (in terms of temperature difference) between the system with and without agents. Every second that we reduce the gradient between the temperatures will result in less energy consumed.

If we look at how the reductions are divided between the buildings we can identify three characteristics; the reductions are spread over basically all buildings, the reductions are very short in time and there are quite a number of reductions
during a day. This is not something that is statically decided at design time, but instead something that dynamically arises from the usage of an economic market and the utility functions. This is a result of the agent society continually adjusting and adapting to its surroundings in order to find the path of least resistance, i.e., where the cost for reduction is lowest at any point in time.

In Figure 8 we show the implemented reductions for four different buildings, F, 1, 2, and 3. We can see that different buildings are reduced at various times and by different amounts. Also, the robustness of the system is shown by the agent that has not participated at all in the evening. The reason for not participating can either be that the building is in the shadow and thereby a bit cooler than the ones in the sun or that the network connection or agent is down. Even though the result is likely to be better the more buildings that participate we show that the system still works when some of the agents, for whatever reason, fail to engage in the economic auction. Also, in the lower graph in Figure 8 we show the reductions implemented in the service building. Since this building does not have any apartments we configured the agent to bid a bit more generous resulting in more reductions.

During operation we could not detect any reduction of indoor temperature what so ever. Also, there were no complaints from the people living in the area. The people living in the area where not informed that the system was running.

The results from the system show that there exists a considerable thermal buffer within the buildings and that this buffer can be used for DSM strategies. Also, the system shows that the effect is enhanced by coordinated actions between the agents.
3.5.2 Return of Investment

During field-test we showed that the system can reduce the total energy consumption in the area by 4% which corresponds to 78500 Swedish crowns per year for the area (approximately $11100).

We have calculated from the field-test that the full potential of the system will result to savings of more than 10% of the total energy consumption, depending on the characteristics of the buildings. During our field-tests we only used about 1/4 of the available thermal buffer. For the area in question this would mean
savings of approximately 235000 Swedish crowns a year (approximately $33200). Given that the system only has to cover its own investment costs, since the HES normally covers its own costs, the system gives full return of investment within the first year.

### 3.5.3 Discussion

The results from the field-tests show a clear profit for the estate owners, since we reduce the amount of energy consumed. At the same time we argue that the operators of the district heating systems will benefit from the system. At first this might seem contradictory but there are several system wide benefits with DSM which more than compensates the operators for the reduced energy sale. For example, the flow balancing that we showed in the field-tests would in the long run offer the operators a possibility to handle flow and capacity problems in different parts of the network. This is an important issue since much of the core of today networks were built during the 60s and 70s without any possibility to foresee the enormous expansion of many district heating systems during resent years. Another example is operators who have low availability of base load production and are forced to use fossil fuel as a production source for energy during peak loads. There are obvious major economical and environmental benefits in reducing the use of these peak load burners.

### 3.6 Conclusions

A DHS without an overall control system is basically composed of a number of completely selfish and autonomous units, i.e., substations, working only to satisfy their own local goals (sufficient domestic hot tap water and indoor temperature) without any consideration whatsoever about the overall efficiency of the system or the state of other units in the network. We have introduced a level of automatic system control by using a semi-distributed MAS architecture to show the value of cooperation among HES in DHS. In this paper we have shown that the value of a large number of small local decisions taken all in all has a great impact of the overall system performance. The system described in this paper does not consider load moving, only load shedding, i.e. where the total energy delivered is not the same with agents as without them.

However, the results in this paper indicate that it is possible to remove 10% of the heating load without affecting the QoS delivered. The results also indicate that it is possible to extend the number of customers in an existing DHS without the need of increasing the production capacity.

All DHS are more or less unique when considering specific details of inhabitant preferences, household equipment, size etc. This, of course, complicate matters.
when about to draw general conclusions from a single installation. However, we have shown that there are clear benefits of DSM in DHS and that it is a viable approach to address the overall system control with a MAS.

The principle of DSM works when the total system utility is more important than the individual, i.e., there is a need of partial global responsibility from the customers. This responsibility could be created both by economic incentives as well as by environmental incentives. The picture is not clear whether customers will accept reductions without economic compensation or not. In reports regarding the electricity market it has been stated that it is a necessity to compensate customers otherwise they will not participate (Energimyndigheten, 2002) and that there in Sweden today is no incentive for individual customers to save energy during peak load hours since tariffs are constant during the day (Österman, 2005). However, there are also reports indicating that customers are interested in saving the planet for free as well (Pyrko, Sernhed, & J., 2005).

It is worth noting that the project has also given rise to a spin-off research project dealing with the intricacies of simulating the dynamics within a DHS (Wernstedt, 2005). It was necessary to develop this simulator in order to validate the DSM strategy before it was applied in a real DHS with real customers and producers.

3.7 Future Work

We will in future experiments focus on developing load-shifting strategies for the MAS, i.e., not only reducing the load but also moving the load in time. We will also perform studies on primary return temperatures to investigate if it is possible to develop strategies for the MAS to reduce the return temperatures thus facilitating an increased efficiency in the use of CHP production. Future work also include studies on differential tariffs in DHS as well as investigations of possible approaches to a complete market-oriented approach to the management of DHS where producers are competing and where there is third-party access.

Controlling the load has potentially major benefits to CHP production and it would be interesting to connect the load controlling strategies to, e.g., the energy prices at Nord Pool (The Nordic Power Exchange).

3.8 Acknowledgements

This project has been supported by VINNOVA and was a collaboration between NODA Intelligent Systems AB, Blekinge Institute of Technology and Alfa Laval. The commercialising effort has been supported by Karlshamnsbostäder, Karlshamns Energi, Sparbanken i Karlshamn and Blekinge Business Incubator.
Chapter 4

Paper III - Intelligent Distributed Load Control

In this paper we present results from a field test where a distributed load control system uses load shedding to even out the daily fluctuations normally found in the energy demand within a district heating system. We also discuss the framework upon which this system is built. The results promise both economical and environmental benefits without compromising the delivered quality of service, as well as a win-win situation for the district heating provider and the end customer.

4.1 Introduction

The energy load of any district heating system is subject to large variations due to the fluctuating demands of customers. The energy load is mainly divided between the rather slow process of space heating and the fast process of domestic hot tap water production. A district heating system must be capable of meeting all such fluctuating energy demands. Although there are large variations in the heat load between summer and wintertime, there is still a value in evening out these fluctuations. Heat exchanger systems, as the source of the heat load within a district heating system, determine the behaviour of the total district heating system. Yet it is unusual that the operation of heat exchanger systems can be remotely monitored and controlled by the district heating system operator. The operation strategies of the district heating system are therefore basically limited to providing sufficiently high temperature and pressure to all customers, without any possibility of actually optimizing the system as a whole.

The objective of demand side management and load control in energy systems
is typically defined as; to optimize the production and distribution of energy by manipulating the consumption. Traditionally demand side management is achieved indirectly e.g. by the use of various tariffs or by production based systems requesting the cooperation of consumer utilities. Load control, on the other hand, uses remote control in order to directly control the behaviour of the participating consumer systems. However, the distinction between demand side management and load control is becoming increasingly blurred as emerging demand side management based technologies are incorporating direct load control principles.

Basic indirect demand side management is widely used and has primarily been implemented by the usage of flow tariffs, i.e. customers are charged according to the flow in comparison to a reference value for the flow. Sipilä and Kärkkäinen (Sipilä & Kärkkäinen, 2000) study the dynamics and potential for demand side management in individual buildings connected to a district heating system and showed that the maximum heat load of a building can temporarily (during 2-3 hours) be reduced as much as 25% on average. Not once during the test conditions did the room temperature shift more than two degrees.

Direct load control is very uncommon but there exists a few attempts, e.g. a centralised load control system that was studied by Österlind (Österlind, 1982) during the early nineteen eighties. Österlind used a one-way communication link on the electricity network to manipulate the outdoor temperature meters of individual heat exchanger systems. By this communication link he was able to manipulate and control the space heating of the connected buildings. The study confirmed earlier theories on centralized load control and indicated the relative ease with which one could achieve effective and robust protection against shortage situations in district heating systems. However, the system fell short when taking into account a number of real world considerations, e.g. fairness within the process and the quality of service (QoS) delivered to the individual consumer. Österlind also concluded that two-way communication was a minimum requirement for an operational system, and that although the system seemed as a promising approach the available state-of-the-art technology was simply not sufficient. Heat exchanger systems supporting two-way communication and sufficient computational performance are still at a relatively early stage of development. However, as reliable hardware which offers a favourable price ratio is becoming more widely available, it is high time to turn the focus on how to fully utilize the existing possibilities. The system presented in the following sections build and expands upon the ideas and concepts found in the work of Österlind.
4.1.1 Demand Side Management Quality Filter

As sensors and communication devices are becoming more sophisticated, the overlaying control system promises the possibility to exercise a more precise control of consumer behaviour. This new possibility does, however, come with a price. The system wide control system will need to adapt to a more dynamic, unpredictable and open domain. Shortened time windows for decisions and increasing numbers of available sensors leads to vast amounts of data and information. Factors that we argue necessitate a higher degree of autonomy and decentralization. The objective is to achieve the goal of optimizing the production while continuously upholding the QoS delivered to each customer. These two goals may well be in a state of conflict, e.g. consider the problem of deciding when to initiate, and during what interval to run, an expensive and environmentally unsound peak load boiler, without compromising the QoS. The core of the problem lies in combining adequate QoS consideration policies with the sometimes invasive control strategies of demand side management and load control which are nonetheless needed to fulfil operational optimization requirements. In order to address this issue and to form the basis for a future framework within intelligent demand side management and load control we propose the introduction of an intermediary quality insurance filter which adds a layer of intelligence in order to negotiate the balance and bridge the gap between these conflicting goals.

Since such a layer will act as a mediator within a dynamic and changeable domain, we believe it will need to be robust, flexible and responsive. Also, as the complexity grows such a system will need to evolve towards a more distributed architecture, in order to maintain sufficient fault tolerance and computational performance. A distributed system consisting of independent and autonomous entities which coordinate and synchronize their behaviour while being self-aware about their respective QoS constraints is ultimately needed in order to fulfil the requirements. The main methodology for modelling the interactions between such autonomous entities are based on ideas found in economics and game theory. We believe that these ideas combined with the resource constraints and QoS considerations yield a powerful framework for system wide optimization within district heating systems.

4.2 Demand Side Management Quality Filter for District Heating Systems

We consider the QoS delivered to each customer as the most important constraint in this domain. To compromise this constraint would be to undermine the reliability in heat delivery, which is one of the main foundations of district heating system. At an abstract level we define an acceptable level of QoS to be upheld
as long as the end customers do not notice any difference between intervals with active direct demand side management and intervals without any external system control. There are two aspects of this to consider, namely space heating and tap water. We consider it obvious that any sound demand side management strategy will separate the two, and as the consumption of energy for space heating and domestic hot tap water is independent in the heat exchanger systems this is easy to achieve by local control. An obvious consequence of this philosophy is that any load shedding will only be implemented on the space heating system, and never on the tap water system as this would immediately lead to compromised QoS.

We argue that the QoS factor is the key to solving the problem of continuously allocating load shedding. Combining this idea with theories on computational markets and letting the QoS factor acts as currency leads to a demand side management allocation algorithm which is capable of achieving our set of goals while enforcing dynamic scalability, high fault tolerance and sufficient QoS delivered to the end customer. The allocation algorithm is based on an auction process (first price sealed bid), where every participating heat exchanger system acts as an automatic bidder who wants to buy as much instantaneous load shedding as possible, without compromising the local QoS constraints, i.e. without paying more than they can afford. This whole process is automated and is re-iterated continuously based on the dynamic demands of the production and distribution.

We use a dynamic model of the thermal buffer to calculate the continuous usage of energy within each building (Wernstedt, 2005). During the process of tuning the system the theoretical model is synchronized with wireless indoor temperature sensors. This combination of physical sensors and theoretical models constitutes the procedure by which we calculate the QoS factor for each heat exchanger system. Detailed measurements of indoor temperatures claim that efficient direct demand side management systems built after the principles presented in this work is possible without compromising the QoS delivered to the end customer.

4.3 Field Test

We have performed field tests during the winter of 2007/2008 in the area of Fridhem located in Karlshamn, a small town in the southern part of Sweden. The area of Fridhem used to be a separate network but is now a pressure stable and well marked off area within the larger district heating system of Karlshamn. The area has a single intake pipe connecting it to the district heating system which is being used as a monitoring point for total delivered energy into the area, see Figure 4.1.

The heat exchanger systems which are installed in Fridhem are all of the
Figure 4.1: The district heating system area of Fridhem consists of thirteen buildings with 350 apartments in total, one service building (F) and one building with three fuel oil boilers (PC) making it fifteen in total.

type Alfa Laval IQHeat systems, which are equipped with Siemens Saphir ACX 32 processing units. The Siemens Saphir contains a Rainbow Communication expansion card that uses Windows CE as operating system. Windows CE enables the use of a web server, ftp server and other specially developed software. The DSM system used consists, besides the heat exchanger systems specific software, also of a database, a management systems and software for monitoring the flow meters. The flow meters used are ultra sound based Optisonic 6300 made by Krohne. In order to monitor the indoor climate we used 78 wireless temperature sensors distributed over the apartments in the buildings connected through a database.

During the field test we used two different versions of direct demand side management invocation, both of which are based on the concept of distributed countering of the instantaneous usage of domestic tap water, i.e. when tap water was used in the area the system invoked load shedding within the space heating system. Non distributed single heat exchanger systems domestic tap water prioritization is commonly known but such a process has limited actual effect as a single body of a building is often not able to counter its own instantaneous usage of domestic hot tap water to the degree needed to even out the total energy load (Selinder, 2005). On the other hand, using a distributed process of countering
such instantaneous usage of domestic hot tap water, several buildings can use their combined thermal buffer in order to continuously even out the total energy demand within a district heating system. The two versions of demand side management invocation are rather similar, i.e. they both trigger on the usage of domestic hot tap water, the main difference being that one of the versions overcompensated the wanted load level in order to minimize the influence of the usage of domestic hot tap water. The wanted load level is the level that the control system tries to maintain throughout a single day. The level for a specific day is found by measuring the average load level during a four hour period between 02.00 and 06.00 in the night when no demand side management is invoked. This period is used because the social part of the load is assumed to be low between these hours. During the following day, starting at 06.00, the found average load level is used as a trigger for the control system, i.e. when the load level rise above the wanted load level the system invokes demand side management. When the system is in continuous use over several days the demand side management system will be active during 06.00 until 02.00 the following night, with non-demand side management load level finding periods during the intermediate hours. The wanted load level is different for every day, and since the heat load during the night is used mostly for indoor heating the wanted load level will correlate closely to the outdoor temperature. During overcompensation we lowered the wanted load level by a fixed amount in order to make the system react faster to any demand side management activity, i.e. we forced the system to trigger an auction earlier than otherwise would be the case. Distribution of load shedding is achieved through the use of the quality filter auction process described in the previous section. The sequence of work for a single instance of such an auction is as follows:

I. The input data for decision-making reveals the need for load shedding, which causes the auctioneer entity to prepare an auction process.

II. An auction request, detailing information about the desired load shedding, is distributed among the participating heat exchanger systems.

III. All participating heat exchanger systems respond to the request by bidding, using their QoS factor as currency. Any heat exchanger system can at this point opt to refuse to participate in the auction, in which case this is made clear to the auctioneer.

IV. Based on the bids, the overall system will then choose the winning heat exchanger system, which is selected to perform the load shedding. More than one heat exchanger system can be selected in this process, if the situation requires it, or if they bid similar bids. The resulting information is then distributed among all participating heat exchanger systems.
V. The winning heat exchanger system then implements the current load shedding.

This entire process above generally takes less than a second to perform. The process is re-iterated as long as the production strategies at hand require it.

4.4 Results

During the field tests we have evaluated two demand side management strategies, a strategy with and a strategy without overcompensation of the wanted load level. As a reference Figure 4.2 shows the typical heat load during a full day without any active demand side management. The peak loads during morning and evening can be clearly identified.

Figure 4.2: The typical load without any active demand side management. The straight line indicates a wanted load level.

Figure 4.3 shows a demand side management strategy using the actual wanted load level. The expected peak loads during morning and evening are clearly reduced.

In Figure 4.4 we show the system using an overcompensated wanted load level. Since the wanted load level is overcompensated it will be lower than the actual average during the night.

If we compare the two demand side management periods from Figure 4.3 and Figure 4.4a notable difference can be seen, in that the period where we overcompensated the wanted load level displays a somewhat more fluctuating behaviour. This behaviour arises from the fact that the control process behaves
Figure 4.3: The load during a day with active demand side management. The straight line indicates the wanted load level used by the demand side management system during this period.

Figure 4.4: The load during a day with active demand side management using an overcompensated wanted load level. The straight line indicates the wanted load level used by the demand side management system during this period.
as a on/off control system. These kinds of fluctuations are normal in any on/off system, with the amplitude and frequency depending on the application in point. In the case of the overcompensating demand side management these fluctuations are more notable which implies that the actual real world input values should be used instead of trying to overcompensate in advance. When studying the behaviour of the control system over time it approaches a proportional control characteristic. This is due to the fact that it is a distributed system, which will continue to distribute load shedding if needed, even if one particular heat exchanger system has approached its QoS constraint. This property of the system leads to a proportional control behaviour when viewed system wide, i.e. the overall control system will react more intensely as the need for load shedding increases.

The absolute difference between maximum and minimum values throughout the day does not significantly differ between days with demand side management in action and those without. However, there is a noticeable reduction in the average deviation from the mean during the days with demand side management in action compared to those without. This suggests that it is hard to counter every single instance of extreme values, although the overall energy demand during the day is indeed evened out.

![Figure 4.5: The average amount of load shedding among the buildings during a day with active demand side management.](image)

The load shedding shown in Figure 4.5 clearly follows the peak loads found during morning and evening shown in Figure 4.2. This load shedding is an average of all participating buildings within the area, which in turn shows the proportional characteristic as the system reacts stronger as the actual load is moving away
from the wanted level. The quantity of the load shedding is how many percent a building is lowering its space heating supply temperature, in order to achieve the load shedding.

![Diagram of indoor temperature over time]

Figure 4.6: The average indoor temperature in the area during the field test.

The indoor temperatures shown in Figure 4.6 indicate that there are no considerable temperature drops during the load shedding. A slight reduction in the indoor temperature can be seen during the third quarter of the period, although this change is within the quality constraint which during the field test was defined as an accepted maximum drop of two degrees Celsius. During that period of time we used overcompensating demand side management, which resulted in a more active load shedding which in turn gave rise to the lowered indoor temperature. Furthermore, no complaints from the people living in the area have been brought forward. Previous work implementing similar technology also indicates that active DSM is possible without compromising the QoS (Paper VII). The indoor temperature has also been used to tune the quality filter to the actual environment. Once the quality filter is tuned to a specific set of buildings it can function without the aid of actual indoor temperature meters.

4.5 Discussion

The need for active control within a district heating system is very hard to estimate in advance. The best one can hope to achieve is forecasts based on a
certain probability that something will happen, e.g. the probability that people will take a shower is higher during morning and evening hours than in the middle of the night. The overall load shedding need in a system during the day can be estimated fairly good based on weather forecasts and knowledge about social behaviour in the area. Despite the effects of distribution and system wide consolidation of the load shedding we would want forecasts ranging in minutes and seconds when using direct demand side management, which make these kind of longer term, overall estimates less valuable. Since it is very hard for the system to estimate short-range behaviour with any high degree of certainty, it follows that the system instead needs to be very responsive to the changes when they actually do occur.

The demand side management system used in this paper is implemented according to an on/off control scheme which, because of the distributed characteristics, gain a proportional control property during dynamic use. The current system uses a static size on each load shedding which is distributed through a single auction, which is what leads to the on/off property of the system. In the future we will add the feature off dynamically setting the size of the control auctions at run time, which in turn implies the need of a greater understanding of how to model the continuously changing global thermal buffer, e.g. in relation to buildings using heat carried by air. One part of this problem is formalizing the process of forecasting and following up the effect of each and every auction. Another important improvement of the current system would be to combine the existing proportional property with a differentiating aspect which would help the system achieve a more responsive behaviour. In order to add the possibility of changing demand side management strategies during the day, i.e. having a varying wanted load level, one would most likely also like to incorporate some sort of integrating behaviour into the control system.

There are many reasons that a producer would want to implement demand side management techniques. For example, the heat flow reduction techniques that we present in this paper can be utilized in avoiding unwanted use of expensive and environmentally unsound peak load boilers. In the short run the demand for district heat among existing customers is rather inelastic, as the actual instantaneous price of producing heat normally does not propagate to the customer. This makes traditional indirect demand side management a somewhat blunt instrument when trying to optimize the overall system during runtime. In this work we have instead opted for a more direct approach, merged with a mediating quality filter system in order to uphold the QoS at all times.
4.6 Conclusions

In this paper we have introduced a framework for merging direct demand side management with considerations to QoS, and shown the value of cooperation among heat exchanger systems in a district heating system. We have presented a demand side management system which is able to even out fluctuations in the daily energy load. Detailed measurements of indoor temperatures claim that efficient demand side management based on the principles presented in this work is possible without compromising the QoS delivered to the customer.

During the field test we have had a production oriented strategy in focus, i.e. to achieve an even heat load during the day within the entire area. The goal was not explicitly to minimize the heating cost in every specific participating heat exchanger system, even if a lowering effect on the heat usage in each building obviously will occur when one lowers the overall heat load. In previous work we have studied more consumer oriented demand side management strategies (Paper II), and we have shown that similar demand side management techniques can be used in order to optimize the heat usage from a customer perspective where the overall goal is to minimize the actual heating cost, again without compromising the QoS. From a purely technical viewpoint, there is no conflict in using different strategies like these at the same time, as the mediating quality filter will activate to insure that the QoS is not being compromised in either way.

Monitoring systems for district heating system are already very complex and comprehensive systems which we believe are going to become even more sophisticated in the future. This is due to the possibilities in increasing computational and communication performance in combination with more refined sensory equipment producing more elaborate data. Correctly designed and implemented this evolving trend can and, most likely, will contribute considerable to the optimal performance of the district heating system and any demand side management strategies. Using a fully distributed control and monitoring system like this would give individual consumers real-time information about their energy demand and continuous energy pricing, and would create the possibility of complete transparency in the pricing model which could benefit both producer and customer.

The results presented in this paper promise both economical and environmental benefits as well as a win-win situation for the district heating provider and the customers. All possibilities have to be considered when trying to increase the market share of district heating system and quality ensured demand side management should be regarded as part of any competitive and efficient district heating system.
Chapter 5

Paper IV - A Case Study on Availability of Sensor Data in Agent Cooperation

Multi-agent cooperation can in several cases be used in order to mitigate problems relating to task sharing within physical processes. In this paper we apply agent based solutions to a class of problems defined by their property of being predictable from a macroscopic perspective while being highly stochastic when viewed at a microscopic level. These characteristic properties can be found in several industrial processes and applications, e.g. within the energy market where the production and distribution of electricity follow this pattern. Another defining problem characteristic is that the supply is usually limited as well as consisting of several layers of differentiating production costs. We evaluate and compare the performance of the agent system in three different scenarios, and for each such scenario it is shown to what degree the optimization system is dependent on the level of availability of sensor data.

5.1 Keyworks

Agent co-operation, Team work
5.2 Introduction

Schemes for sustaining cooperative behavior among agents are often dependent on a certain level of communication in order to establish and maintain a reciprocal sense of trust. However, in real-life applications it is not always possible to uphold the desired level of availability and quality of data being communicated among the agents, thus causing suboptimal cooperative behavior. In this paper we focus on a problem domain where multi-agent task sharing cooperative behavior is applied. However, as practical implementations within this domain often are spread geographically over a wide area and lack dedicated network communication infrastructure, there are often practical limitations on the availability and quality of sensor data which in turn limits the effectiveness of the multi-agent system cooperative behavior.

For agents to effectively coordinate their actions, the agents normally need to share information. Information sharing, i.e. communication and its effect on overall performance is a well established area and has been studied by several researchers (Dutta, Goldman, & Jennings, 2007), (Goldman & Zilberstein, 2003) and (Shen, Lesser, & Carver, 2003). Also, the area of multi-sensor networks and sensor data quality and fusion has received a fair amount of interest (Dash, Rogers, S., Roberts, & Jennings, 2005), (Lesser, Ortiz, & Tambe, 2003) and (Jayasima, 1996). However, the quality of information in combination with information sharing has so far, to our knowledge, only received little attention.

5.2.1 Problem Domain

The problem domain is characterised by being predictable from a macroscopic perspective while being stochastic when viewed at a microscopic level. As the macroscopic behaviour is a reflection of a collection of highly stochastic microscopic events which in themselves cannot be predicted, it follows that although a process control system is able to foresee general trends and tendencies within the process, it must be able to handle the stochastic behaviour in order to actually manipulate the process. For example, although it is possible to foresee the overall heating demand within a building being higher tomorrow as the weather prognosis shows a drop in outdoor temperature, it is not possible to predict when individual residents will take a shower, thus creating peak loads in the total energy demand when combining usage of hot tap water and space heating. Basically these processes are driven by one or more producers supplying some kind of utility and one or more consumers acting to satisfy their own demand of the utility.

When optimizing the operational production one tries to determine the financially and operationally most efficient way to combine the production resources, while satisfying the consumer needs. This problem is often formalized by using the Economic Dispatch Problem (EDP) and the Unit Commitment Problem.
By solving the EDP we find out how much load to generate by each of the different available production units at a given time. Since most production units in real life settings cannot be turned on and off at the blink of an eye, it is important to plan ahead of time and determine which units need to be started, when they need to be started and how long they should be committed to being in use, i.e. solving the UCP. These problems are related to each other and are solved using similar optimization techniques. A complicating factor when optimizing production is that the production costs usually display non-linear patterns, due to physical processes like valve effects and the usage of differently priced fuels in production. This leads to objective functions with discontinuous and non-differentiable points, which means that it is generally more appropriate to treat the cost function as a set of piecewise quadratic functions (Koay et al., 2008), (C.E. & G.L., 1984). As demand rises the producing entity is forced to engage increasingly costly production units, and eventually the production costs exceed the possible sale price of the utility. The only way for the producer to mitigate such a situation is to manipulate consumption in order to lower the demand.

By solving the UCP and EDP the producer finds an optimal production strategy for a given time frame, e.g. the next twenty-four hours. This means that the producer wants the consumption to be as close to this strategy as possible; if the consumption falls too low it will result in unnecessarily low income, while a too high consumption will necessitate starting costly peak load production units. In order to achieve and uphold the desired production strategy multi agent systems and other distributed systems can be used to manage the consumption. We evaluate the success of such systems by measuring their ability to stick to the production strategy in question, while at the same time satisfying consumer demand.

Typically the consumer entity has a wanted state which it tries to uphold at all times. This wanted state is dependent on the physical environment in which the system is functioning, e.g. maintaining comfortable indoor climate in a district heating system. Often, however, a consumer agent can accept smaller deviations from this wanted state during shorter periods of time. This is what makes it possible for a control system to manage the society of consumers in order to achieve some local or global goals. By measuring the deviation from the wanted state it is possible to evaluate the impact of change in the overall system caused by individual consumers.

5.2.2 Problem Description

The consumption, and thus the production, follows certain patterns which are predictable to some extent from a system wide perspective. These patterns are
generated by a composition of highly stochastic microscopic behaviour among consumer entities, which, as long as their demand is fulfilled, are oblivious to their surroundings or any other part of the larger system. By reacting on these individual microscopic events and controlling and limiting the effect of them, the overall system can achieve several benefits for both the consumers and the suppliers of the utility. Trying to control the consumption in such a way is generally called Demand Side Management (DSM), and can in many cases be achieved by using agent technology or other distributed control schemes (Paper II), (Aune, 2001) and (Nordvik & Lund, 2003). The reason agent technology is useful in DSM, is that there is no need for any centralized entity supervising the Quality of Service (QoS) among the consumers as each consumer is assigned an agent responsible for this task. Each agent will participate in achieving the overall goal set by the DSM strategy, only as long as sufficient QoS can be upheld. This makes the system highly scalable and easy to maintain.

In theory this a school book example for an agent system to solve. The problem is that the agent based solutions proposed for solving DSM in such environments are dependent on the availability of high-quality sensor data, which in practice can be hard to achieve due to limitations in underlying hardware and communication solutions. That an agent system will perform at its best in a domain where high quality sensor data and communication solutions are readily available is not in question, and it is not the intent of this paper to compare different agent based resource allocation schemes within such a high quality domain. The point of this paper is instead to develop an understanding of how different levels of availability of sensor data influence the behaviour of the agent system in a practical setting. Normally there are practical limitations on the sensor data infrastructure and communication set-up which leads to situations far from any high quality scenario. Investing in modern sensor data and communication solutions can be expensive and there is an apparent need to quantify the performance benefits within different scenarios. In Figure 5.1 this is visualized.

Within this study three different scenarios are used to represent different levels of availability of sensor data, i.e global, partial and local. The global level corresponds to a scenario with full access to high quality sensor data while the partial and local scenarios display various levels of deteriorating access to sensor data. There are several ways to coordinate resource allocation within a multi agent system, e.g. contract nets, different auction processes or distributed optimization models. In this study we have used an auction process in order to compare the different scenarios according to Figure 5.1.
5.3 The Agent System

The agent system we study in this paper is used to implement DSM strategies within district heating systems and its function has been described in previous work (Paper II). In district heating systems one or several production plants heat water which is then pumped through a pipe network throughout a city in order to heat buildings and tap water. Every building has a substation with heat exchangers which transfer the heat energy from the primary pipe network into the buildings secondary piping system. The agent system is based on distributed cooperative entities with an overall goal of combining the production and consumption in an optimal manner.

5.3.1 Agents

Every producer and consumer entity in the system is represented by an agent. A producer agent will try to minimize its own supply cost function while supplying enough utility to satisfy consumer demand. When a producer agent deems it necessary to implement an DSM action it will try to do so by sharing the task among the consumer agents in order to minimize the side effects of DSM on any individual consumer agent. A consumer agent will seek to implement these requests as long as its internal comfort constraints allow for this.

Producer Agent

The producer agent is responsible for supervising the continuous utility consumption and also for instigating and distributing DSM tasks when the measured consumption deviates from the desired DSM level. The task sharing is done by first
decomposing the initial task into smaller tasks. This is done since the optimization action as a whole is usually too large for one single consumer agent to handle. The tasks are then allocated through a series of auctions. The DSM level is found beforehand by solving the optimization problem relating to the production units, and this is then used as input to the production agent. In larger agent systems it is possible to use cluster agents which act as mediators between a producer agent and a group of consumer agents. This eases the computational load in the producer agent when handling large scale auctions.

The producer agent needs to know the wanted consumption level in order to implement DSM. This is found by solving the EDP and the UCP. These solutions are then used as decision basis for the DSM strategy for the following time frame, normally the next twenty-four hour period. In order to solve the EDP the agent uses an objective function which is found in the smooth function described in Equations 5.1 and 5.2.

\[
\text{Minimize } \sum_{i \in I} F_i(P_i) \tag{5.1}
\]

\[
F_i(P_i) = \alpha_i + \beta_i P_i + \gamma P_i \tag{5.2}
\]

This is simply a summation of the utility cost in all supply units (Arvastson, 2001). The value of \(\alpha\) describes a fixed cost for starting and running the production unit, while the values of \(\beta\) and \(\gamma\) describe costs dependant on the level of production. The accompanying equality constraint is the utility balance which should be satisfied accordingly:

\[
\sum_{i \in I} P_i = D + P_{loss} \tag{5.3}
\]

where \(D\) represent the utility demand and \(P_{loss}\) indicates any production and distribution losses. The inequality constraints describes the production units working within their respective limits:

\[
P_{i, min} \leq P_i \leq P_{i, max} \quad \forall i \in I \tag{5.4}
\]

In practical settings these functions are normally not sufficient to describe many situations in utility production. Normally the production entity will have to treat the cost function as a set of piecewise quadratic functions which are defined as (Koay et al., 2008), (C.E. & G.L., 1984):
This behaviour is due to the fact that a utility provider usually has a range of different production units, using differently priced fuels. From a economical point of view there is no smooth transition when switching between the different fuels, which makes the resulting function non-differentiable.

The producer also has to solve the UCP. The UCP is interconnected with the EDP and uses similar optimization methods. The UCP is used to determine which production units to commit to usage and which ones not to use at any given time. In a real world scenario a production unit cannot be turned on and off with a simple switch. It takes a substantial amount of time to start and stop such units, and the cost related to these processes should be kept at a minimum.

By solving the above systems for each relevant point in time it is possible to identify a wanted system wide consumption level within the studied time frame.

**Consumer Agent**

Each consumer unit is controlled by a consumer agent which is responsible for contributing to achieving the overall DSM strategies while maintaining a sufficient level of local comfort. The consumer agents act locally in order to monitor any deviations from the wanted comfort state. The amount of deviation from the optimal comfort state is used as currency when a consumer agent participates in an auction process, i.e the more the consumer agent is straying from its desired comfort state, the less likely it will be to win any auction. The consumer agents are cooperative in the sense that they do not lie about their cost for participating in a DSM task, since this could possibly jeopardize their internal comfort levels. A positive side effect from using the comfort state as currency, is that these calculations are made by the consumer agent in any case and thus the computational effort for valuation and information gathering in regards to the auctioning is kept at a minimum.

**5.3.2 Agent Goal**

For every consumer agent there is at any time a wanted comfort level which is dependent on the level of local consumption. Since the physical nature of the process introduces a delay in the dependency between the comfort level and
the local consumption level a time frame is created within which it is possible to manipulate the local consumption while still keeping the local comfort level within its constraints. An example of this phenomena is that it will take some time before people notice if you shut off the radiators in a building, i.e. there is a delay before the people start to freeze even though the energy consumption is reduced directly. Combining the local consumption from each consumer agent will yield the total actual consumption. The goal for the agent system is then; for each point in time to achieve a total actual consumption as close as possible to the total wanted consumption while keeping all local comfort levels within their individual constraints.

In a steady state system this could be seen as a traditional optimization problem, i.e. to find a optimum between two conflicting objective functions. However, since we are dealing with a dynamic system the aspects of adaptation and re-planning becomes important, which requires a more sophisticated solution.

5.3.3 Auction Process

Whenever a producer agent needs to implement a DSM action it will distribute this by using a private value first priced, sealed bid auction process. For the consumer agent the value is to implement as much DSM tasks as possible, and the currency used is the amount of deviation from the optimal comfort state possible without affecting the local QoS. This type of auction based multi agent system has previously been successfully implemented in district heating networks in order to achieve DSM (Paper III). Strategic decisions are made based on global or local views within the environment, and the specific optimization actions rely on continuous sensor data. Global knowledge is needed in order to identify individual consumer agents able and willing to participate in local task accomplishment. Without sufficient communication abilities the auction process is not able to function, thus making it more difficult to distribute DSM tasks while taking into account the local consumer agent comfort state. By using an action process it is possible to distribute the complexity and computational effort, since all reasoning and planning about the delivered QoS is done by the consumer agents. This leads to a more scalable and extendable system.

5.3.4 Levels of Agent Knowledge

In the described DSM system the agents are able to communicate freely among their peers, in order to continuously propagate system status based on available sensor data and perform coordinated task sharing when needed. In this study we compare the performance of such a fully functional system with two other systems displaying increasingly worse availability of sensor data. These three different scenarios are based on the level of system wide knowledge available to
the participating agents; global, partial and local. We choose to compare these specific three levels of system wide knowledge because they correspond to infrastructural prerequisites which can normally be found in actual physical systems, and because they display a broad and clear view of the problem discussed.

Global Knowledge

This is the normal operational view for the MAS used to operate the DSM strategies. The producer agents are able to continuously supervise the use of production utility and are able to instigate DSM actions as need arises. Each DSM action is divided into control tasks which can be distributed throughout the network of consumer agents by system wide auctions. The consumer agents are able to uphold their individual QoS by deciding when and how to participate in these auctions, i.e. a DSM task is never forced upon a consumer agent against its will.

Partial Knowledge

The producer agents are able to supervise the consumption of production utility, but they are not able to communicate local sensory data with consumer agents. This means that cooperative behaviour through auctioning is not possible. A producer agent is, however, still able to instigate uninformed DSM actions. This is normally done by using predefined activation lists, which force consumer agents to implement DSM tasks in a round-robin fashion. Since no communication of consumer sensor data is available it is not possible for the producer agents to gain any feedback about the impact of these DSM tasks on the QoS delivered to the local consumer. The local consumer agent is still working to uphold its own QoS, and it might decide not to implement the DSM task appointed to it. Either way, as the consumer sensor data communication is impaired, the producer agent will never gain any knowledge about what decision the consumer agent takes.

Local Knowledge

In this scenario the producer agents have little or no knowledge about the continuous consumption of production utility, and they do not have any possibility at all to implement any DSM actions, either by cooperation or force. The consumer agents still have access to their own local sensor data but they cannot successfully communicate this to other agents within the MAS. This basically means that they act oblivious to the state of any other agent. In such a system the consumer agents are often assigned the task of keeping the local utility use to a minimum while upholding the desired QoS. Depending on the situation such behaviour might or might not be for the good of the global system state, but the consumer agent will never know anything about this.
5.4 The Experiment

In this study we investigate the effects of different levels of availability of sensor data within an operational agent based control system. Under normal circumstances the agent system is based on cooperative behaviour which is in turn heavily dependent on functioning and reliable communication of high quality sensor data. Performance of the multi-agent system will deteriorate if the availability or quality of sensor data declines. We have studied how extensive this deterioration will be in a practical setting, i.e. how will the quality of the communication underlying the decision-making affect the overall performance from a system wide perspective. The case study is based on operational data from an agent based control system operational in a district heating network in the town of Karlshamn in the south of Sweden (Paper II), (Paper III). This data is used as input when simulating the various scenarios described in the previous sections.

5.4.1 Reference Data

District heating networks are good examples of the described problem domain as they display most, if not all, of the mentioned characteristics. The reference data in question is collected during a twenty-four hour period with no DSM strategy active, i.e. no external control is applied to the consumers. The data is representative of normal usage during wintertime when the heating demand is substantial. The energy consumption in a district heating system is measured by combining the flow of the water with the primary supply temperature of the water. During the course of a single day the primary supply temperature in this district heating network is rather constant so the flow is a good estimate of the total energy use.

Figure 5.2 shows the flow data from the Karlshamn district heating network during a full twenty-four hour time period. The straight dashed line shows the calculated wanted level of energy consumption which the producer agent uses as a benchmark during this specific day. This level of consumption is based on a solution of the Economic Dispatch Problem and the Unit Commitment Problem. The peaks above the dashed line represents peak loads which would need to be satisfied by using financially and environmentally unsound fossil fuel. In other words, the global goal of the agent system is to keep the consumption as close to the straight dashed line as possible.

5.4.2 Utility Evaluation

The consumer agents all have different comfort constraints based on a function of size, shape and material of the individual building, i.e. the amount of thermal buffer available (Olsson Ingvarsson & Werner, 2008). In the operational system
each consumer agent has access to sensor and actuator data through an I/O hardware platform, which enables the agent to measure the physical behaviour of the heating system within the building as well as the outdoor temperature. Based on this data the agent can calculate the indoor temperature which is then used as the basis for the agents own comfort evaluation. Each agent has a value of wanted indoor climate, and constantly tries to minimize all deviation from this value. However, in order to participate in achieving the global system goal an individual consumer agent can accept smaller deviations from this value under shorter periods of time, as this will not affect the indoor climate to a degree where the inhabitants will notice it. The consumer agent has two basic values to consider, namely the comfort level and the buffer level. These are connected with a delay, so that it is possible to adjust the level of the energy buffer during shorter periods of time without the comfort level having the time to react. It is possible for the consumer agent to use more than the available buffer, but then the comfort level will start to fall. Under normal circumstances a consumer agent will be very unwilling to use more the available buffer, although it might do so during shorter periods of time in order to achieve some global goal. When a consumer agent responds to an auction it will use its currently available buffer level as the price it is willing pay for implementing a single DSM task. This process will ensure that only the consumer agent which is best suited at any given time, i.e will be least in risk of compromising its comfort level, will be appointed the DSM task in question. We evaluate the performance of the consumer agents by measuring how they choose to use their individual buffers.

The producer agent in the system use the energy delivered to the area as
input for its calculations concerning the need for DSM actions. The optimization strategy used in this experiment is that of load shedding, i.e. at any given moment when the total energy use exceeds a certain threshold the producer agent will try to convince the consumer agents to lower their local energy usage in a coordinated fashion. When implementing this strategy the producer wants to limit the utility consumption down to the wanted threshold, as forcing the consumption down even further than the threshold will reduce sale of utility produced by economically viable production supplies. Therefore we measure the success of these system wide optimization actions by measuring any deviations between the wanted fluid flow value and the resulting actual flow level. By analysing these values it is possible to evaluate to what extent the overall agent system accomplishes its objective, i.e. to uphold the wanted DSM strategy level without jeopardizing the comfort among the consumer agents. If the agent system is to be considered successful in its endeavours it will have to fulfil both these requirements.

5.4.3 Availability of Sensor Data

The agents within the Karlshamn district heating area communicate through a LAN network and have direct access to high quality sensor data. In this sense they are extremely spoiled, as this kind of communication solution is rarely part of the hardware set-up in similar real-world environments. As building a physical network and sensory infrastructure can be costly, similar agent systems are usually limited to using communication techniques such as GSM-modems, radio link or standard limited master/slave networks to evaluate operational data. With such solutions there is often limitations in regards to communication bandwidth and temporary sensor breakdowns are not uncommon. In this experiment we evaluate the impact of such system deterioration by simulating different levels of availability of the sensor data. In order to do this we model the three previously described scenarios, i.e. global knowledge, partial knowledge and local knowledge.

In the global scenario the producer agent and the consumer agents are allowed to communicate freely throughout every time step in the simulation. The producer agent can instigate auction processes according to its own desires, and the consumer agents are able to respond to this.

During the partial scenario there is only one-way communication possible from the producer agent to the consumer agents. The producer agent can distribute DSM tasks, and does so according to a previously defined static list. The producer agent can distribute several DSM individual tasks during each time step. A consumer agent might implement such a DSM task or it might not, depending on the current level of its internal buffer. Any which way, the producer agent will
not receive any response about this.

In the local scenario there is no communication what so ever between the agents. The consumer agents can perform local load control, but this is done purely based on local knowledge. The local load is made up of a combination of energy used for space heating and tap water heating. During local load control, the consumer agent will try to limit local space heating when there is local tap water usage. The tap water usage is randomized within the simulation.

5.4.4 Simulation

We use real operational data from the Karlshamn district heating network as input into the simulation model, where actual flow data is used as initial values for the calculations. The implemented agent system is functioning according to the same principles as previously described. In the simulation there are fourteen active agents; one producer agent and thirteen consumer agents. By simulating the described levels of agent knowledge we can evaluate the performance of the agent system during different scenarios.

A simulation run begins by calculating specific solutions to the Economic Dispatch Problem and the Unit Commitment Problem. These solutions yield a wanted system wide consumption level for each time step throughout the day. This wanted consumption level is then used by the producer agent as a decision basis, when deciding when and how to instigate DSM actions throughout each time step. The consumer agents starts the simulation with full available buffer levels. This buffer level is then adjusted through each time step as they perform DSM tasks, which in turn makes it possible to calculate the comfort levels for each time step.

For each time step the producer agent then decides if there is any need for DSM actions based on the current flow level in relation to the wanted flow level. If it deems this necessary it will try to distribute individual DSM tasks. Depending on the specific scenario this will be achieved differently. The system wide consumption is then calculated and used as input into the next time step.

5.5 Results

We evaluate the different scenarios according to how well they manage to achieve the DSM strategy in question while staying within the comfort constraints set by the consumer agents. We present how well the agent system upholds the DSM strategy within the three different scenarios, and then we show how well the system manages to keep itself within the available energy buffer, and thus the consumer comfort constraints during these same scenarios.
5.5.1 Control Strategy

The control strategy is evaluated by measuring the flow of hot water into the area. Energy usage in a district heating network is measured by combining the temperature of the water with the flow. Since the supply water temperature in the primary network is more or less stable throughout a single day the flow in itself gives a good estimation of the energy usage within all the buildings. Figure 5.2 in the previous section shows the reference data without any DSM strategy active, i.e. this is what the overall consumption pattern looks like in a district heating network without any agent system installed. In Figure 5.3, Figure 5.4 and Figure 5.5 we show the flow data achieved during the three different scenarios in relation to the wanted DSM strategy.

![Graph showing flow data](image)

Figure 5.3: Global scenario. Agent performance (continuous), reference data (dotted) and wanted DSM level (dashed)

It is clearly visible that the flow value in the global scenario (Figure 5.3) most closely resembles the desired DSM strategy, with the partial scenario (Figure 5.4) being somewhat worse, and finally the local scenario (Figure 5.5) showing a distinct lack in ability to achieve the desired level of consumption. To make these results clearer we also summarize the deviation of the scenarios for every time frame throughout the simulation. This value has a theoretical optimum at zero, i.e no deviation from the desired DSM level what so ever. The values are then normalized around the value achieved by the global scenario. These results are shown graphically in Figure 5.6 and the actual numbers in Table 5.1.
5.5.2 Agent Buffer Usage

The level of comfort is dependent on the buffer used by each individual consumer agent. Every agent has an maximum allowed buffer usage of 1, with a minimum of 0. The level of comfort will not be negatively effected by a usage between 1
and 0. If the buffer usage is above 1 the consumer agent has used more than the allowed buffer and the comfort can be in jeopardy if such a status is allowed to continue for a longer period of time. In other words a consumer agent has an optimal buffer usage of 1, i.e. the agent participates in achieving the global goal as much as possible but does this without sacrificing its desired comfort level. The values for the individual consumer agents are shown in Figure 5.7, together with a theoretical optimum of 1. The numerical values are then showed in Table 5.2.

Figure 5.8 shows the dynamic system wide buffer usage during the whole time period. The range on the y axis is dependent on the amount of consumer agents, since every such agent has a optimal buffer usage of one. In this case study we have thirteen agents, so an optimal usage of the system wide buffer would obviously be 13. In the global and partial scenarios the buffer usage clearly follows the reference data as the agents continuously try to counter the varying consumption.
Figure 5.7: Individual buffer usage. Theoretical optimum (black), global scenario (dark grey), partial scenario (grey) and local scenario (light grey)

Table 5.2: Agent comfort and buffer usage for each individual consumer agent

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimum</td>
<td>1</td>
</tr>
<tr>
<td>Global</td>
<td>1.01</td>
</tr>
<tr>
<td>Partial</td>
<td>0.54</td>
</tr>
<tr>
<td>Local</td>
<td>0.29</td>
</tr>
</tbody>
</table>

5.6 Discussion

Multi-agent system solutions being applied to the physical processes described in this paper are heavily dependent on the availability of high-quality sensor data to function properly. This study quantifies the way system performance rapidly deteriorates as the availability of high-quality sensor data is reduced. The evaluation is based on the systems ability to adhere to the wanted control level while maintaining an acceptable level of agent comfort. By combining the control strategy and agent comfort values it is then possible to evaluate the performance.

It is important to factor in both the DSM strategy and the consumer agent comfort value when evaluating an implementation for handling DSM within the problem domain. If a system is only evaluated on the basis of its ability to adhere to the DSM strategy it might give rise to problems on the consumer side as no
consideration is given to upholding a sufficient level of QoS.

The notion of what is an acceptable level of the control strategy value is dependant on the process in question. In a district heating network there are several benefits of having the ability to perform load control, the most apparent being the ability to shed peak loads in order to avoid using expensive and environmentally unsound peak load fuels. In our case the global scenario would be considered acceptable since it manages to shed the peaks.

5.7 Conclusions

The local scenario is similar to a type of control system that is often implemented in both electrical grids and district heating networks, as a local uninformed optimization technique. This study indicates that such systems have little global effect in regards to overall production optimization strategies. As Figure 5.5 and Figure 5.8 clearly shows the local scenario is inadequate in order to handle any system wide DSM strategy. The reason that the local scenario never goes beyond a certain level in Figure 5.8 is that the consumer agents are only reacting to their own local peak loads, which are well beyond their own capacity to handle. This is due to the fact that individual peaks are much larger than any individual buffer, so in the local scenario some agents are always maximizing their use of their individual buffer, but without the ability to somehow distribute the load through the producer agents their efforts will always fall short on a system wide scale. This shows a clear advantage of the two distributed DMS solutions in relation to
any local efforts, which can never hope to counter system wide peaks.

Figure 5.8 also shows that producer agent knowledge is needed in order to
dynamically counter the user demand in regards to the DSM strategy. This is
also the buffer usage, which shows that the partial scenario is not able to fully
use the available buffer. This is due to the fact that the agents cannot perform
cooperative work. The difference between the global and partial scenarios in
Figure 5.8 basically shows the superiority of agent cooperation versus centralized
enforcement. The lower use of available buffer of the partial scenario is caused by
the fact that although the consumer agent is handed a DSM task, it can choose
not to implement the task if the agent considers it to jeopardize its internal QoS
level. Since the producer agent never receives any feedback about this, it will not
be able to distribute the task to another consumer better suited for the task, and
hence the system will on average not utilize the maximum of the available buffer.

Figure 5.8 shows that the global scenario is close to using the maximum avail-
able buffer on several occasions, while neither the partial or the local scenarios
are close to utilizing their full DSM potential. The global scenario is rather close
to achieving the DSM strategy, but it does not manage to fully adhere to the
wanted level. To achieve this would require the system to continuously foresee
and counter highly stochastic microscopic behaviour within the process, which is
not feasible in a practical setting.

In this paper we have shown that distributed multi agent systems based on
cooperative auctioning are able to achieve the studied DSM strategy, while main-
taining an acceptable level of QoS. As the availability and quality of the sensor
data diminishes the system performance deteriorates, first into the equivalence
of static distributed models and then into the equivalence of simple local optim-
ization models. This shows that real-time cooperative behaviour among com-
municating agent nodes is needed in order to successfully implement DMS in real
world applications, and that indirect methods, like differentiable taxation, or un-
informed local optimization is not able to produce the coordinated system-wide
behaviour required.

5.8 Future Work

This paper is the result of an case study in regards to sensor data utilization
within industrial multi-agent system applications. In the future we will use this
as groundwork while incorporating the financial factors underlying the discussion,
in order to further study the economical effects found within such systems.

According to Figure 5.1 we have only used an action process in order to
evaluate the the different scenarios. In the future we intend to expand this study
by using other collaboration techniques within the different scenarios.
Another issue is the formalization of a model for the follow-up of DSM actions. Sometimes actions are taken when there is no need for them, and other times actions are needed without them being implemented. By improving our understanding and control of this process it should be possible to better utilize the individual consumer agent buffer. This could be used when combining the multi agent system with a continuous optimization model in order to dynamically follow the process.

5.9 Acknowledgements

The operational data used in this study was supplied by NODA Intelligent Systems. The project has also been supported by Karlshamns Energi and Karlshamnsbostader.
Chapter 6

Paper V - Deployment of Agent Based Load Control in District Heating Systems

This paper describes results and experiences from an industrial proof-of-concept installation of a multi-agent based load control system in three major district heating systems in Sweden. A district heating system is a demand-driven system, i.e. the consumption controls the level of energy input which the district heating producer needs to deliver into the system. The basic idea of load control is that the individual consumers can be utilized as heat load buffers which, when coordinated on a system-wide scale, can be used to adjust the total consumption demand instead of having to change the production scheme. Load control leads to several important benefits such as giving the district heating producer the capability to avoid using expensive and environmentally unsound peak load boilers, while at the same time lowering the overall energy consumption at the consumer side. In order for load control to work the system needs to be able to coordinate the behaviour of a large amount of consumer substations in relation to the dynamic status among a range of production units, while continuously maintaining a sufficient level of quality of service among the consumers. The results show that the multi-agent based system was capable of reducing the peak loads with up to 20% of the total load, and to lower the average energy consumption with about 7.5% without any deterioration of the experienced indoor climate. Different theoretical aspects of load control have long been studied, but it is not until recently that technical advances in hardware and communication infrastructure has made it possible to implement these schemes in real-world settings.
6.1 Keywords
Management, Performance, Agent-based industrial applications

6.2 Introduction
A district heating system consists of one or more production plants, a distribution pipe network and a collection of consumers. The medium used to transport heat is normally water, although steam is also sometimes used. At a production plant boilers are used to heat the water which is then pumped through the distribution network. Each consumer node consists of a heat exchanger system which transfers the heat from the primary distribution network into the secondary radiator network within the building. The heat exchanger system is also used to heat tap water, although the tap water system is separated from the radiator system. District heating networks are consumer driven systems, i.e. it is the consumption which controls the amount of energy that needs to be produced.

The basic idea with load control is that the consumer side can constitute an heat load buffer which can strategically be used in order to perform consumption reductions instead of having to produce more energy (Nordvik & Lund, 2003). Substantial environmental and financial benefits can be found by smoothing out variations in the heat load in such a way. This is due to the fact that a production unit consists of a range of boilers using differently priced fuels.

The results discussed in this article are based on a multi-agent based system which has been deployed in parts of the district heating network in three different cities in Sweden; Stockholm, Västerås and Linköping. All Swedish cities with more than 10 000 inhabitants have district heating networks, and about fifty percent of all heating in Sweden is based on district heating. The Swedish district market is worth about €2.5 billion ($3.5 billion) annually, with the combined total European and Russian market being worth about €100 billion ($140 billion) (Constinescu, 2007).

6.2.1 Load Control
As consumption rises the producer has to engage increasingly expensive fuels. Such peak load boilers are usually fuelled by expensive and environmentally unsound fossil fuels. The cost for producing heat using such peak load boilers is usually not covered by the price paid by the costumer. Using load control it is possible to cut such peaks in the heat load by using the consumer buildings as the equivalence of a large storage tank. If the need for peak load production is lowered then district heating companies will be able to forestall large investments in peak load capabilities. The ability to perform load control also means that new
customers can be added to the district heating system without having to invest in more production capabilities. That there are periods where district heating companies would rather lower consumption need that to sell that power is clearly shown by the fact that they are increasingly using pricing rates based on the level of momentary effect usage and not only on the total amount of energy used. It is not uncommon for customers to install a local effect guard which cuts energy use above a certain threshold of momentary effect usage. This, however, is often not desirable from a system wide point of view, as there is no connection between the locally lowered energy usage and the actual system wide status. Basically it can be said that this is a distributed information problem, in the sense that the consumer systems have no system wide perspective and thus are not able to decide whether it is appropriate or not to perform load control. In order to do this the system needs information about the global status of the district heating network, i.e. the total heat load in connection to the present production state. In essence a system wide perspective is need in order to successfully perform load control (Heating & Cooling, 2002).

To perform load control basically means that the system will cut the energy usage from time to time. In order to do this without jeopardizing the indoor climate some sort of intelligence is needed in the load control system. There must be some kind of feedback between the load control and the indoor climate. A certain level of energy must at all times be supplied to the radiator systems in order to avoid sudden temperature drops and to ensure that the indoor temperature is always kept within the acceptable range, even during longer periods of load control. It is clear that lowered energy usage will result in a lowered indoor temperature, but it is also equally clear that the process of heat loss from a building is very slow and that this makes it possible to utilize the building as a heat load buffer which can be used to move the heat load without affecting the perceived indoor climate.

Earlier experiments with a distributed multi-agent system in a smaller building area in the south of Sweden have shown good system results by having the heat exchanger stations in a number of buildings communicate and cooperate in regards to performing distributed load control without any perceived deterioration of the indoor climate (Wernstedt, 2005).

The question faced in this project was that if this behaviour could be replicated over a larger number of buildings in a geographically spread area while constrained by commercially viable terms. Our previous work has shown a theoretical and small scale experimental feasibility of the load control system (Paper III). This specific project was about investigating the possibility to actually perform load control in an industrial setting using a multi-agent system.
6.3 System Description

There are a range of financial and environmental benefits to be had from a system that facilitates real-time control of consumer energy usage. By having the system coordinate consumer behaviour in a large group of buildings it is possible to achieve substantial system wide benefits. This system is based on the idea that the district heating company is not interested in the behaviour of individual buildings but rather in the total merged heat load. In theory load control gives rise to long line of advantages:

- It is possible to better utilize base load boilers, instead of having to use peak load. Using base load is financially as well as environmentally desirable since peak load is normally more expensive and more likely than not to emit large amounts of carbon-dioxide.

- In connection to shorter peak loads it is possible to perform load control in order to entirely avoid starting a peak load boiler. During start-up of a boiler the emissions are usually higher, since it takes a few hours for the boiler to reach its operational temperature.

- By using load control it is possible to not only shed the peak loads, but also to move them in time. This provides benefits for combined heat and power generation, since it is possible to better match the demand on the power market.

- When adding new customers to the district heating network it is possible to forestall investments in new production capacity.

- In certain circumstances it is possible to use load control in order to bridge narrow segments of the district heating network without having to lay new piping.

- Load control alleviates the need for expensive storage tanks in the district heating network.

- By implementing load control techniques it is possible to prioritize between different customers during periods of shortage or extreme cold.

- Lowering the return temperature in the primary district heating network. This favours environmentally sound production, since these are normally less energy rich than fossil fuels.
6.3.1 Multi-agent System

One of the fundamental aspects of district heating is its reliability and high quality of service in regards to the end customer. An adequate ability to uphold this fact must be considered one of the more important requirements to any energy efficiency measure performed in a district heating network. In regards to load control this is a question of coordinating a connection between two functions in conflict, i.e. to uphold an acceptable indoor climate while achieving the needed system wide consumption profile. It is the ability to simultaneously fulfil these two requirement that differentiates so called intelligent load control from simpler forms of load control. Such simpler forms of load control might for example be local systems which implement load control based on predefined lists, or which uses tap-water prioritization. The basic problem with these type of solutions are not coordinated globally which, along with the fact that they do not incorporate any feedback from the indoor climate in the individual buildings, means that have no ability to achieve global production oriented goals while sustaining a desired indoor climate. In order to solve these issues we have designed the system based on a multi-agent approach, where each consumer and producer node are assigned to an agent. The goal of a consumer agent is to uphold the desired indoor climate while trying to participate in the overall system wide load control as much as its local heat load buffer allows. A producer agent is responsible for recognizing the need for load control, i.e. there is a need to manipulate the energy consumption among the buildings. The producer agent will then try distribute this load control among the participating consumer agents.

Obviously the indoor climate is connected with the local energy consumption, but there is a certain delay in this physical process. During shorter periods of time it is possible to manipulate the local consumption without any noticeable influence on the indoor climate. Normally, changes within a single degree Celsius will not be noticed by the inhabitants of a building. This value can be changed by the system operator and can be set individually for each consumer agent.

An important aspect of quality of service in regards to load control is to only ever try to control the radiator circuit within a building, and never the tap-water circuit. Besides directly affecting the comfort of the inhabitants, lowering the energy usage on the tap water circuit might also give rise to other problems such as growth of Legionella bacteria.

Allocating Resources by Auction

When the producer agent wants the system to perform load control it will start by analysing the size and time needed for the total load control, and based on this, the producer agent tries to distribute this change in energy usage among the consumer agents. This is done continuously as long the producer agent deems
it necessary to perform load control. As the available heat load buffer in the
individual buildings is drained, the system will try to re-allocate the load control
among the consumer agents. This allocation is based on a first-price sealed-bid
auction process (Clearwater, 1996). The reason for using this type of auction is
that all the agents within the system are programmed to be completely cooper-
avative, so there would be no gain in using other, possibly more complex, auction
processes. Each consumer agent will continuously calculate the amount of load
control that the building can afford without jeopardizing the indoor climate. The
parameter for this can be set for each individual agent, i.e. while one building can
handle a temporary deviation of 1°C from the desired indoor temperature an-
other building might only be able to handle a temporary deviation of up to 0.5°C.
The calculation is done by an energy balance equation based on the geometry and
characteristics of each individual building in combination with continuous sensor
data from the heat exchanger station in that building. This value is then used
by the consumer agents as currency when participating in the auction process.
This basically means that the more suitable a building is to perform load control,
I.e. a building with low or no deviation from the desired indoor temperature, the
more currency, i.e. size of heat load buffer, it will have to spend on the auction,
and thereby be more likely to win. Each such bid consists of three parts:

- The shifted outdoor temperature. The consumer agent uses shifted outdoor
temperatures to make the heat exchanger station perform load control, e.g.
by telling it the outdoor temperature is five degrees Celsius when in reality
it is two degrees Celsius. This makes it easy to manipulate the behaviour
of the heat exchanger station without extensive work and expensive equip-
ment.

- How much the heat load usage will change.

- The amount of time this change can be implemented while staying within
acceptable quality of service constraints.

These bids are then used by the system as a basis for computing how much of
the heat load that can be shed and how large the total available heat load buffer
is. This data can then be used in order to display real-time information about the
system-wide status through a graphical user interface. When developing indus-
trial implementations of research based systems it is important not to forget the
importance of providing ways to offer direct interaction with human operators.
After each completed auction the winner or, more often than not, winners will
implement the load control according to their local prerequisites. The auction
process basically consists of the following steps:

1. The producer agent identifies a need to perform load control.
II. An action is started were all participating consumer agents will submit bids

III. The producer agent distributes the load control among the consumer agents according to the bids. If the total need for load control is larger than the winning bid the producer agent will give the winning agent load control corresponding to the full bid, then to the second agent and so on until either the total need for load control is fulfilled or all the consumer agents are given load control corresponding to their full bids. In the latter case the total need of load control cannot be fulfilled using the available buildings.

In order to calculate how the dynamics of the indoor climate in the individual buildings each consumer agent uses a mathematical energy balance model. The agent continuously uses this in order to calculate its bids. The parameters for this model are unique for each building and is based on the geometry of the building and building materials in combination with continuous input and output of energy through the building. There is an obvious connection between the indoor climate and the energy input into the building, but due to the physical process of energy loss there is a substantial delay between energy input change and indoor climate change. This delay creates a time frame which the consumer agent can utilize in order to participate in load control without jeopardizing the perceived indoor climate. There is, in other words, a heat load buffer in each building and the size of this decides how much the building can participate in the system wide load control strategy. The energy balance model is used continuously by the consumer agent in order to calculate the future ability of the building to participate in load control as well as to calculate current status within the building and to perform controlled returns in energy input after a load control instance is finished. Such controlled return in energy input is needed in order to prevent the underlying control system to overshoot the desired indoor temperature by trying too hard to compensate for the energy input drop during the load control. The energy model uses outdoor temperature and radiator system temperatures as input, and is modelled as a system of differential equations which are numerically solved over and over again based on changes in the input.

6.3.2 Additional Hardware and Software

In order for the deployed system to work there was a need to develop additional hardware. The complete system is based on the system-wide multi-agent system software, the computing and communicating capabilities in the individual buildings and server systems for data handling and user interface. In particular the hardware for the individual buildings had to be developed. There were no systems available on the market that could provide the needed functionality while not being overly expensive. In order to handle the multitude of sensors present
in different buildings a new hardware platform had to be developed. This took the form of an I/O card which could handle 10 inputs and 4 outputs, both analogue and digital, which was connected to a small computer that could handle the consumer agent software. This computer then used either normal Internet access or GPRS modems for communication.

A lot of companies and organizations use different types of network solutions in order to secure their networks, and it is not uncommon for communication to be a problem even if there exists the physical infrastructure for Internet access. In order to overcome such problems a Virtual Private Network (VPN) was set up, within which all the agents could communicate freely without disturbing underlying network structure. The VPN used within the project is based on OpenVPN, which is a full scale SSL VPN solution based on open source software.

6.4 Deployed System

The system described in this paper is by its very nature distributed and uses the combined heat load buffer within a range of buildings in order to achieve system wide advantages. In order to study this behaviour in a operational system it is thus important to have access to a large enough collection of buildings. During this project fifty-eight district heating consumer stations were connected through three separate multi-agent systems, Stockholm (27), Västerås (21) and Linköping (10). Each consumer station can serve several buildings, so the number of actual buildings participating in the system was greater than fifty-eight. The buildings in Stockholm and Linköping were mostly multi-apartment buildings of different sizes and types, while the buildings in Västerås were schools and other public buildings. This provided a good diversity among the buildings which made it easier to draw general conclusions based on the results.

6.4.1 Results

Normally a building heating system uses the outdoor temperature as a control signal. The agent system uses this outdoor temperature sensor as an interface towards the existing control systems in the building. By manipulating this sensor a consumer agent can force the control system to act according to the agents desire, without actually having to implement any changes on the existing control system. When the agent decides to implement load control it does this by faking the outdoor temperature signal, thus causing the building control system to lower or raise its heat load accordingly. Figure 6.1 shows an example of how this works in practice.

The difference between the supply and return temperature of the radiator system (Trad, supply and Trad, return) shows the energy usage. This value
Figure 6.1: Controlling the energy usage behaviour through the outdoor temperature sensor

clearly drops when the faked outdoor temperature (Tout, LC) deviates from the actual outdoor temperature (Tout).

That the existing control system in a building will increase or decrease its heat load when it registers that the outdoor temperature changes is hardly controversial. The complexity of the process instead arises when the system tries to coordinate this behaviour among a group of buildings in order to achieve system-wide goals. In order to evaluate the system we have to analyse both the momentary heat load and the energy usage (heat load over time). Figure 6.2 compares the heat load on a day with two load control instances being shared among a group of consumer agents with a day without any load control. The first load control starts at about six o’clock in the morning and the other starts about six o’clock in the evening. Both load control instances take about two hours to complete.

Figure 6.3 shows the momentary heat loads from Figure 6.2 sorted according to size.

Figure 6.4 shows the energy usage in relation to the outdoor temperature in the same group of buildings during the same two days. The energy usage follows the same pattern as the heat load.

Figure 6.5 shows the same energy usage sorted according to size.

The outdoor temperature is slightly lower during the day with load control, so normally this day would have a higher energy usage. However, by using load
Figure 6.2: Heat Load during Load Control

Figure 6.3: Heat Load data points sorted left to right according to size
Figure 6.4: Energy usage during Load Control

Figure 6.5: Energy usage data points sorted left to right according to size
control the total energy usage during the day without load control is 26578 kWh while the energy use during the day with load control is 24727 kWh. Despite the difference in outdoor temperature the saving in energy usage is still about seven percent.

Figure 6.6 shows the total energy usage in a group of coordinated buildings during periods of different weeks, with one data point for each weekday of the week. The data for load control comes from a single week, and the data without load control comes from two reference weeks. The figure shows the energy use in relation to the outdoor temperature.

![Energy usage graph](image)

Figure 6.6: Total energy usage in an entire system of buildings

The values shown in figure 6.6 are actual measurements from the buildings. For the week with load control it is also possible to calculate what the energy usage should have been without load control, based on the historical energy performance of the building in relation to the outdoor temperature. The actual amount of energy used during the week with load control is 197 215 kWh and the calculated value for the same week but without load control is 213 352 kWh. This gives an energy saving of about 7.5%. This value is an average value from a large group of buildings with energy usage behaviour coordinated by a multi-agent system. The value of 7.5% is about the same as was shown in figure 6.5.

### 6.4.2 Indoor Climate

An important aspect of the system is to secure an adequate indoor climate at all time in connection with load control. The most basic measurement of this if the building occupiers have complained during time intervals with load control
active. Another way to measure this is to install indoor temperature sensors and see what happens with the indoor temperature during load control. This was done during the project in selected buildings within the multi-agent system.

In practice the system will reduce the heat load in the building, which will inevitably lead to a reduced indoor temperature if allowed to continue uncontrolled. Each consumer agent is responsible for making sure that this reduction in indoor temperature is small enough for the building occupiers not to notice. There were no complaints during the project that were derived from load control.

The indoor temperature sensors showed no sign of being influenced by load control. The indoor temperature could vary wildly in individual apartments. This happens all the time and is due to social behaviour such as using electrical appliances, opening windows, or having ten kids over for a birthday party. It was not possible to determine when load control was active or not by studying the data from the indoor temperature sensors.

6.4.3 Available Load Control Ability

In order to evaluate the financial aspects of this type of system it is important for the energy company to be able to estimate the number of buildings need within the multi-agent system. The system-wide operational benefits of the system is directly proportional to the number and size of buildings available in relation to the total size of the district heating system. A large building has a greater available heat load buffer than a smaller building. Normally it is possible to estimate an average size of buildings within the district heating network, which can then be used as a basis for a first estimation of the potential of the system. It is the possible to make a rough estimate of the amount of buildings needed for a given district heating system:

\[
\text{Amount} = \frac{\text{Heatload}}{eSig \times (T_b - T_{out}) \times LC_{max}}
\]

(6.1)

Where \(\text{Heatload}\) is the amount of heat load [W] that the system should be able to handle, \(eSig\) [W/°C] is the average energy signature in the area, \(T_b\) [°C] is the outdoor temperature above which a building needs no heating, \(T_{out}\) [°C] is the outdoor temperature at time of using load control and \(LC_{max}\) is the maximal share of the total heat load that the system should be allowed to control. This last value, which is set to 70% for this study, is a general limit that is used in order to ensure that the system doesn’t completely shut off the heating, not even during shorter periods of time. This is a social, rather than physical, consideration, e.g. if someone puts their hand on the radiator it should not be completely cold. This is the maximum value that the system can control of the heat load,
although normally the system will control significantly less than this. In order to calculate how long this amount of buildings can uphold load control at each time the following equation can be used:

\[ t = \frac{T_{diff}}{T_{in} - T_{out}} \ast (1 - e^{-\frac{1}{\text{Timeconstant}}}) \] (6.2)

Where \( t \) is the time [h] that the system can uphold load control at a \( LC_{\text{max}} \) of 1.0, \( T_{diff} \) [°C] is the acceptable temperature drop in indoor temperature during load control, \( T_{in} \) [°C] is the indoor temperature at the beginning of activated load control, \( T_{out} \) [°C] is the outdoor temperature during the load control and \( \text{Timeconstant} \) [h] is the time constant of the average building within the installation area. The value of \( (1 - e^{-\frac{1}{\text{Timeconstant}}}) \) is derived from the definition of the time constant for a building (Barley, Torcellini, & Van Geet, 2004). The time constant tells you how fast the indoor temperature of a building will drop when the heat load is totally shut off, given a nominal outdoor temperature, normally -20°C. The time constant is measured in hours, e.g. in a building with a time constant of 100 it will take about 100 hours before the indoor temperature will have fallen \( (1 - e^{-\frac{1}{100}}) \), or about 63% of the difference between the initial indoor temperature, e.g. 21°C, and the nominal outdoor temperature. Finding the exact time constant of a building can be time consuming, but normally it is possible to use approximate values. During this project the following templates were used:

- **Light building:** 80h (light construction)
- **Semi-light building:** 150h (light/semi-light construction, concrete ground-ing)
- **Heavy building:** 300h (heavy construction)

Calculating the amount of time the system can uphold each turn of load control basically means to estimate how long it takes for the indoor temperature to drop below the acceptable limit. In practice the system will have a certain capability to enforce load control, and this capability will diminish as the individual buildings exhaust their heat load buffers. If a larger group of buildings are available through the agent system it is possible to uphold load control during longer periods of time since the buildings can relieve each other as they drain their heat load buffer. By using the auction process, this behaviour automatically manifests itself when a large enough group of buildings is connected.

The ability to perform load control is dependant on the total level of heat load in the buildings. If there is a high level of load control, then the ability to perform load control is equally high. This means that the ability to perform load
control increases as the outdoor temperature drops, which in turn means that the ability to perform load control is at its highest when the need for it is the greatest.

6.4.4 Cost-Benefit Analysis

The largest financial value of lowered heat load is probably when load control ability will help to avoid the need for more peak load production. The amount of heat load that can be moved or lowered is dependant on the characteristics of both the production units and the building types available in the district heating system. Normally the need to perform load control only occurs during shorter periods of time. Normally 30-40% of the heat load has a length of less than 500 hours. In most district heating system these loads are produced by oil, electricity or coal. An oil boiler costs about €200/kW ($270/kW) to install, which is the financial value of the load control system if this installation capability can be avoided. During this project the load control system has lowered heat loads during peak hours between 15-20% on average. Avoiding 15% oil based peak load in a 100 MW system is then worth about €3M ($4.1M) in saved installation costs.

Transferring peak load to base load also means lowered variable production costs. As an example the ability to move from tree oil (cost €0.04/kWh ($0.055/kWh) including taxes) to bio-fuel (cost about €0.02/kWh ($0.027/kWh) including taxes) gives a saving of €0.02/kWh ($0.027/kWh). Fortum, who owns the district heating network in Stockholm, produces slightly less than 10 000 GWh annually. The value of reducing fossil fuel in production is not only a financial one, but also based on environmental considerations. For security reasons it is unlikely that peak load production can be avoided all together, but the benefits of reducing it as much as possible are numerous. Load control not only gives the ability to lower the heat load, but also to move it in time. In this case the buildings can be viewed as the equivalence of the large storage tanks found in many district heating systems. When using combined heat and power production (CHP) it is normal to optimize the production in relation to the price variation on the spot-price market for power. The spot-price varies during the day but normally there are price peaks in the morning and evening. The physical process of producing heat and power cannot be separated, but by using load control it is possible to move the heat load consumption a few hours in time by controlled pre-heating of the buildings.

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6.5 Discussion

Performing uninformed local load controls by manipulating the outdoor temperature sensor has been shown to be easy enough, although due to aspects of dynamic (time dependant) indoor climate feedback a certain level of intelligent behaviour is required when actually implementing energy saving process using such techniques. More interesting and complex problems arise when trying to coordinate this behaviour from the system wide aspect of the producer, while still considering the indoor climate in all the individual buildings. When sorting the data from figure 6.2 according to size like in figure 6.3 it becomes apparent that the largest reductions in heat load have been done during the higher peaks. It should be noted that the outdoor temperature during the reference day is +2,9 °C and during the day with load control +1,7 °C. No adjustment for this temperature difference have been made so the effect of the load control is in reality even more significant than what is shown in this example.

In order to satisfy the heating need an energy company would normally use a whole range of different production units, with different characteristics and fuels. The production units are started in order by their production costs, which normally means that the boilers using oil will only be started during periods of peak load with short duration. The absolutely highest peak loads normally have durations of a few hours. During this project it was noted that in order to lower the heat load with 10% the system needed to control the load during no more than eight hours at most. This is well within the capability of the system studied.

The theoretical optimization normally used in order to find the financially best operational strategy for the production units is based on solutions of the Economic Dispatch Problem (EDP) and the Unit Commitment Problem (UCP) (Koay et al., 2008). By solving the EDP and the UDP an energy company can find a desired consumption level for each hour during the next few days. This value can then be used as decision data by the multi-agent system in order to implement load control throughout the day in order to uphold the desired consumption level.

6.6 Conclusions

This system consists of distributed units with communication ability that can measure sensor data and control the heating system in individual buildings. These units are then controlled by consumer agents which enables the system to coordinate the heating behaviour on a system wide scale. By using this system a energy company can, within the constraints set by indoor climate limits, actively plan, optimize and control the heat load within a district heating network.

The results show that the system has lowered the total heat load with about
20% in connection with the highest peak loads. This value is, however, still far from the maximum set limit of $LC_{max}$ in equation 6.1, i.e. the limit of 70% of the heat load which is used in this study. In figure 6.3 it is shown that the largest heat load reductions are done during time intervals with the highest heat load (measured in kW). A district heating network utilizes several differently priced fuels in order to satisfy the demand, ranging from cheap waste heat and bio fuels to more expensive alternatives such as oil and electricity. The normal situation in Sweden is that the highest 5-15% of the heat load needs to be satisfied with some peak load boiler (usually oil)(Constinescu, 2007). Compare this with figure 6.3 where the highest heat loads are sorted left to right. It is clear that the agent system manages to shed these peak loads in the left-most part of the figure.

By using correct pricing strategies within the district heating network the energy company wants to achieve transparency so that the costumers understand and act based on the costs of producing the heat. This is a very complex problem and it is not always easy to make the pricing strategy understandable as well as transparent in regards to actual production costs. Also, it is not easy to set a price according to different conditions since if the customers actually react to this price it would change the conditions. This leads to a situation with a variable pricing goal which in practise demands that it is possible to dynamically adjust prices in order for the right production situation to arise. By a correct pricing strategy it should be simple to give the customers the incentive to invest in load control equipment. It is, however, important that this equipment is capable of interacting on a system-wide scale, since local uninformed load control can do more harm the good from a production perspective. If there is no method for system-wide control it is very hard, if not impossible, to use the behaviour of the buildings in order to optimize the production. It is also not enough to use static predefined lists of buildings to cut heat load in during times of peak loads. Using such predefined lists does not take the dynamics of the indoor climate into consideration. It is essential to pay attention to the dynamics of the quality of service as well as the production status.

In relation to this discussion it should be noted that it is not suitable to let human consumers themselves make the dynamic decisions to implement load control, e.g. by having a wall mounted display showing graphs of energy consumption and then expecting people to actually do something when the energy price is high or the heat/power load is above some threshold. Such schemes have been tried several times and the results are normally the same, i.e a consumer will use the system for a month or two, but will then eventually grow tired of the whole thing and stop using it. We believe that the only way to implement such systems in the long term is to exchange the human decision maker with an automated system of some sort.

Besides reducing peak loads the system has also shown a clear ability to lower
the energy usage in the participating buildings, without any noticeable difference in the perceived indoor climate. During the project the system showed a energy reduction of about 7.5% during week-long periods. From the perspective of the energy company and the national economy it is preferable if this reduction in energy consumption in connection to peak load production instead of during base load production. Only by using system-wide load control can such a consumer behaviour be enforced.

The system controls the heat load in individual buildings by manipulating the outdoor temperature sensor that the existing control system uses. Each load control is implemented by faking the outdoor temperature for the existing control system, e.g. if the existing control system during a short period of time is led to believe that the outdoor temperature is 10 °C when in reality it is 5 °C, then this will lead to a reduction in energy usage during that time. A lowered heat load will obviously led to a lowered indoor temperature sooner or later, which is why such load control has to be done within a controlled process. Several indoor temperature sensors were placed within the buildings during the project, in order to identify lowered temperatures due to load control. Despite of this it has not been possible to identify where and if any reduction of the indoor temperature was present. It was shown that the indoor temperature within individual apartments varies so much due to social behaviour that the influence of load control is lost in the noise. In all likelihood the lowered energy usage must have led to a temporary reduction in the temperature, either in the building body or in the air contained within the building, but neither the indoor temperature sensors or any building occupants have been able to perceive this.

In a heating system where the ventilation has a considerable impact on the indoor climate it is complicated to implement load control by manipulating the secondary circuit of the heating system. An alternative in these cases is to only control the heat load in the radiator system and not to include the ventilation hot water in the load control.

During this project we have studied load control within district heating systems, but these system-wide techniques are equally interesting in other energy systems, e.g. power grids or industrial production processes. When, for example, comparing a power grid and a district heating system it is obvious that there are major differences in the physical process of how energy is transported (water versus electricity), but on a system-wide scale we believe that there are still many overlapping themes.

This project has been a step up from previous small scale experiments and simulations. It has been shown that the theory holds in practice, and that coordinated load control within district heating systems as a technique does indeed work.
6.7 Future Work

Early small-scale practical experiments have shown a 4% decrease in energy usage when using a multi-agent based system for load control in a district heating network, and has predicted a theoretical energy saving of about 10% (Paper II). During this study we have shown an energy saving of about 7.5% averaging over groups of buildings. With further tweaking of the behaviour of the system we expect this figure to be able to reach the predicted 10%. This might be done by selecting other techniques for allocating the resources. Using an auction based mechanism for this implies that the consumer wishes to spend as little as possible of its utility, when in reality all agents within the system are cooperating in achieving the desired load control, i.e a consumer wants to spend as much as possible of its available buffer but never more than this. This might be interpreted as a suggestion that other methods could be even more successful at distributing the resources among the agents in such a system, e.g. bargaining schemes or some sort of distributed/centralized optimization technique.

6.8 Acknowledgements

This work has been a collaboration between NODA Intelligent Systems AB and Blekinge Institute of Technology. The results are based on a project financed by NODA Intelligent Systems AB, Fortum Värme AB, Mälarenergi AB, Tekniska Verken i Linköping AB and The Swedish District Heating Association.
In this paper we investigate the consequences of using temporary heat load reductions on consumer substations, from the perspective of the individual consumer as well as the district heating company. The reason for using such reductions are normally to save energy at the consumer side, but the ability to control the heat load also lie at the core of more complex control processes such as Demand Side Management (DMS) and Load Control (LC) within district heating systems. The purpose of this paper is to study the way different types of heat load reductions impact on the energy usage as well as on the indoor climate in the individual buildings. We have performed a series of experiments in which we have equipped multi-apartment buildings with wireless indoor temperature sensors and a novel type of load control equipment, which gives us the ability to perform remotely supervised and coordinated heat load reductions among these buildings. The results show that a substantial lowering of the heat load and energy usage during periods of reductions is possible without jeopardizing the indoor climate, although we show that there are differences in the implications when considering different types of heat load reductions.

7.1 Introduction

The main purpose of this paper is to investigate the consequences of using temporary heat load reductions on consumer substations within a district heating
network. The most common way to perform temporary heat load reductions is to use night time set-back, i.e. to lower the wanted indoor temperature during night time while social activity is expected to be low. Emerging technologies like Demand Side Management (DMS) and Load Control (LC) also use temporary heat load reductions in order to accomplish system wide control strategies, although the characteristic of these heat load reductions differ significantly from night time set-back.

In the context of this study we regard a heat load reduction to be the whole process from the initial change of heat load, through the return to normal heat load, and until no evidence of the heat load reduction can be noticed in the dynamics of the building energy balance. This definition is based on the fact that the heat load reduction will continue to exert an influence on the building thermal buffer for some time even after the heat load reduction in itself is ended. The length of this interval is specific to each building and is related to the thermal inertia of the building in question.

In this paper we study the consequences of using different types of heat load reductions, and try to analyse the way the thermal buffer of the building is affected along with the actual heat load and energy usage from both a local and a global perspective. We study the performance of both long low-intensity heat load reductions (e.g. night time set-back) as well as short high-intensity reductions (e.g. those frequently used in DMS schemes). The use of night time set-back has received some attention in previous works, e.g (Björsell, n.d.), and the possibilities to use the building as a heat buffer has been evaluated (Olsson Ingvarsson & Werner, 2008), but heat load reductions such as those used in DSM and LC have to the knowledge of the authors not been thoroughly investigated.

7.1.1 Night Time Set-back

Night time set-back means to lower the wanted indoor temperature during night time, with the purpose of saving energy through reduced heat losses due to decreased difference between indoor and outdoor temperature. This is the most common way to perform temporary heat load reductions, and many commercial control systems support this feature. This is normally done by a parallel displacement of the heat control curve during night hours. During night time set-back the wanted indoor temperature will be set to one, or a few, degrees lower than during normal operations. There is, however, an ongoing debate on whether night time set-back actually gives an energy saving or not (Lindkvist & Wallentun, 2004), and most practical implementations of night time set-back suffer from morning peak loads when the control system returns to the original operational level. Still, almost all control equipment companies sell equipment that facilitates the use of night time set-back, and the use of this technique is widespread.
7.1.2 Demand Side Management and Load Control

While night time set-backs are a solely local energy saving technique, DMS and LC are usually performed with a system wide perspective in mind. A building owner is normally only interested in lowering the energy consumption, while the district heating company is more interested in being able to optimize the whole production and distribution process. Optimizing the production normally translates to avoiding expensive and, more often than not, environmentally unsound peak load boilers or trying to move heat load demand in time in order to maximize utility during combined heat and power generation. Basically, from the perspective of the district heating company it is a question of finding a balance between lowering expensive heat load demand while still selling as much energy as possible. Implementing this on a system wide scale requires complex coordination control strategies that dynamically adapt to the state of the district heating system (Paper II). On the local building level this is implemented by performing temporary heat load reductions. On a local level these reductions are normally very short, i.e. one or a few hours, but they can be of high intensity, even sometimes completely shutting off the heat load during shorter periods of time. This behaviour requires the control system to be highly adaptive in relation to the dynamics of the buildings thermal inertia in order to avoid jeopardizing the indoor climate. By coordinating such local heat load reductions among a large group of buildings it is possible to achieve system wide DMS and LC.

7.1.3 Previous Work

Most previous work regarding temporary heat load reductions deals with night time set-back. This is a technique that has been around for a long time, and is based on the general idea that if you decrease the difference between the outdoor and indoor temperature in a building you will save energy. One of the first large-scale evaluation of night time set-back was performed in 1983 when buildings in Sweden, USA, Belgium and Denmark was evaluated. This experiment concluded that night time set-back did not save as much energy as was expected, at most a few percent for multi-apartment buildings (Jensen, 1983). In hindsight it is possible to see that these meagre results was a consequence of several interacting factors. First of all the control systems of the time were not capable of properly handling the transition from night time set-back to the original operation mode, which causes a considerable over-compensation of heat load when the systems tries to find the new control level. This extra boost in heat load during the mornings counteract large portions of the energy saving done during the night. The theoretical part of the experiment also had a few draw-backs, e.g. assuming optimally adjusted radiator systems and linear relations between indoor temperature and energy savings. Other articles show that there is indeed a substantial
level of energy saving to be found by controlling the local heat load (Morris, Braun, & Treado, 1994).

Most of the previous work done on the subject is based on simulated results. This is expected since the dynamic thermal processes within a building are extremely complex and it is not surprising that comparisons between measurements and calculations sometimes show large discrepancies. It is noted that most calculations are dependant on variables that cannot be measured and verified, and that the building time constant is really not a constant (Isfält & Bröms, 1992).

7.2 Experimental Method

In order to study the effects of temporary heat load reductions we equipped a building with several wireless temperature sensors in order to measure the fluctuations in indoor temperature. The building in question is an office building with semi-light thermal characteristics (light construct with concrete slab) and a time constant of about 150 hours (Ruud, 2009). The indoor temperature sensors were placed on different locations within the building in order to get a good overview of the thermal behaviour of the indoor climate. In addition to the existing outdoor temperature sensor an extra wireless sensor was also placed on the outside of the building. Unlike the existing outdoor temperature sensor the wireless one was placed in a position where it was fully exposed to any possible sunshine. This gave us an extra indication of the impact of free heating through window areas, even though we did not have any ability to measure the actual solar irradiance.

In order to control the district heating consumer station we connected a load control platform for system wide LC and DSM (Paper VIII). This platform is based on a novel form of hardware and software which enables us to manage the heat load of the substation without any major alterations or any damage on the existing hardware. The software system is based on the open source Linux operating system and is equipped with an application programming interface (API) for I/O. This makes it easy to apply additional sensors, e.g. for measuring the forward and return temperatures of the radiator system. The platform also features connections to a database system which enables real-time logging and analysis of sensor data. The actual heat load reductions are implemented by supplying the existing control system with adjusted outdoor temperatures, which gives us the ability to manage the behaviour of the heat load without exchanging any existing hardware. This adjusted outdoor temperature can be managed with a resolution of at most 60 seconds. The computer platform uses either Ethernet or GPRS modems to communicate with the database. In our case we used the existing Internet access in the building. In addition to this primary experimental
building we also collected and analysed data from previously installed buildings using the same basic computer platform.

Energy and heat load usage was primarily evaluated by studying the dynamic differences between the forward and return temperature of the radiator system in relation to the flow. These readings were then verified by specifications from the district heating provider regarding energy consumption and momentary heat load usage.

Using this set-up we scheduled different types of temporary heat load reductions and studied their effects on the measured data. During this study we studied three primary types of temporary heat load reductions:

- Long  Four to eight hours of continuous heat load reduction with different intensity
- Short  Up to one hour long heat load reductions with different intensity
- Recurring  Several short subsequent heat load reductions with short pauses in between

When we studied the different types of heat load reductions we took care in allowing the buildings thermal process to return to its original state between each reduction so that the reductions would not influence each other. This was done in between each reduction except in those cases when then purpose was to explicitly study the interaction between subsequent heat load reductions.

### 7.3 Results

Figure 7.1 shows the temperature difference between the forward and return temperature in the radiator circuit during a short heat load reduction. The heat load reduction starts at about 60 minutes and continues until the 120 minute mark. Between the 120 minute mark and about the 160 mark the control system performs a controlled heat load recovery in order to avoid unwanted heat load peaks after the reduction.

The same values are shown for a long heat load reduction in Figure 7.2. The heat load reduction starts slightly before the 600 minute mark and continues for several hours until about the 900 minute mark. After that the control system performs a controlled recovery in order to return to the original operational state.

Figure 7.3 shows the same values for a series of recurring heat loads.

Each of the heat load reductions in Figure 7.3 is one hour long intersected by one hour long recovery periods. The first reduction starts at the 60 minute mark and continues until the 120 minute mark.
Figure 7.1: dT in radiator circuit with short heat load reduction

Figure 7.2: dT in radiator circuit with long heat load reduction
Figure 7.3: $dT$ in radiator circuit with recurring heat load reductions

Figure 7.4 shows the energy consumption in relation to the outdoor temperature during week long periods with and without heat load reductions implemented as LC. The squares are from periods without LC and the triangles are from periods with LC. LC in this regard means that temporary heat load reductions are being performed in recurring sets throughout the week as long as the thermal inertia of the building allows it, i.e without jeopardizing the indoor climate. In this example the energy usage is about 8.2% lower during periods of heat load reductions.

Figure 7.5 shows the heat load (kW) during 24 hours when using reductions compared to not using reductions. The control scheme is also added to the figure in order to show when the reduction was performed.

Figure 7.5 clearly shows that the reduction in heat load closely follows the control scheme. The largest heat load reduction is about 30% in this example.

Figure 7.6 shows recurring heat load reductions instead of single long ones. It is clear that the building is able to respond to the control scheme in this example also. The largest heat load reduction during the recurring scheme is about 25%.
Figure 7.4: Energy usage in relation to outdoor temperature. The squares are values during periods without LC, and triangles are from periods with LC.

Figure 7.5: Heat load showing 24 hours without reductions (black), 24 hours with reductions (dark grey) and control scheme for reductions (light grey).
Figure 7.6: Heat load showing 24 hours without reductions (black), 24 hours with reductions (dark grey) and control scheme for reductions (light grey)

Figure 7.7 shows a range of indoor temperature readings during periods with heat load reduction (triangles) and during periods without (squares). The average deviation during heat load reduction is about 0.29 while the average deviation during periods without reductions is about 0.19.

Figure 7.8 shows readings from two different outdoor temperature sensors during a time period of two days.
Figure 7.7: Indoor temperature during periods with heat load reductions (squares) and during periods without heat load reduction (triangles)
Figure 7.8: Outdoor temperature sensors placed in the shade (black line) and in full view of the sun (grey line)
The graph shows the outdoor temperature sensor which is connected to the actual consumer sub-station in the building (black line). Normally these sensors are placed somewhat in the shadow to avoid large fluctuations due to solar radiation. We added another temperature sensor (grey line) in order to estimate the impact of this solar radiation. Hence this sensor was placed in full view of the sun. The first day was sunny during most of the morning until midday, while the second day was more cloudy.

7.4 Discussion

When dealing with temporary heat load reductions it is important to include the whole process of the reduction. This also includes what happens after the actual heat load reduction has been performed. For example, when just restoring the wanted control level after a long reduction, e.g. night time set-back, the forward flow temperature in the radiator system will rise much faster than the return flow temperature. This causes a substantial, although temporary, heat load increase in the radiator system which negates large portions of the energy saving done during the actual reduction. Apart from decreasing the local net energy saving this behaviour is also less than desired from a system wide perspective, since it causes massive heat load peaks if done in many buildings simultaneously, e.g. contributing to morning peak loads. In order to avoid this it is important to factor in the whole process of the reduction, and make sure that the control system properly handles the transition from the reduction level to the original level. The inability among most commercially available control systems to properly handle this over-compensation is most likely contributing a great deal to the lingering controversy whether night time set-back actually gives an energy saving or not.

It is important to realize that the definition of an acceptable indoor temperature is not about having the indoor temperature at a certain precise level at all time, but rather to have it within a certain, socially acceptable, temperature interval at all time. This has been discussed at great length in previous work (Isfält & Bröms, 1992). The general idea is that a greater temperature interval will lower the need of additional heating from the radiator system, by coordinating the thermal inertia of the building with freely available heat, e.g. heat from sunlight or electrical appliances, to balance the heating need. This notion is supported by our results as we have shown that the thermal inertia of even a small or medium sized multi-apartment building is considerable. How people perceive the indoor climate is dependant not only on the actual indoor temperature itself but also on other factors like air quality, individual metabolism and behaviour, radiation temperature and air movement. In relation to this it can be noted that previous work have shown that about five percent of any group of people will always be unsatisfied by the indoor climate (Skoog, 2005), and that
it is not possible to create a perfect climate that will make everyone happy.

### 7.5 Conclusions

There is an ongoing debate whether night time set-backs lead to an energy reduction or not. Results from this study clearly show an energy saving in relation to heat load reductions, although this assumes that the control system is able to smoothly handle the transition from reduction to normal operation. The results showing energy saving is evaluated in relation to the total energy usage which also includes tap-water usage. Normally this is estimated to about 30% of the total energy use in a multi-apartment building.

In prior studies of temporary heat load reductions the focus has been on the fluctuations in the indoor temperature as a way of evaluating the energy saving (Jensen, 1983). This idea is based on the widespread notion that any energy saving is linearly proportional to the temperature difference between the indoor and outdoor temperature. This model might be true in a steady state simulation where the temperature difference is assumed to have had time to permeate the air mass as well as the entire building structure, but it is obviously inadequate in a dynamic situation. We have instead focused on the heat load and energy usage directly, i.e. the difference between forward and return temperature in relation to the flow within the radiator circuit. In most of the buildings evaluated there has been a considerable reduction of energy consumption without any noticeable change in indoor temperature. The reason that there does not need to be a measurable change of the indoor temperature is due to the dynamics of the thermal inertia of the building, e.g. the time constant of a building is not a constant (Isfält & Bröms, 1992). This aspect comes into play when using very short heat load reductions, at most one or a few hours long. During this first part of the reduction it is mainly the actual air mass that is influencing the indoor temperature drop since this body has a low resistance to change, i.e. the short time constant (Norberg, 1990). If the heat load reduction is prolonged, like during a night time set-back, the building mass will start to interact with the air mass and thus stabilizing the continuing temperature drop, i.e. the long time constant (Norberg, 1990).

The influence of external and internal free heat is large enough that when these heat sources interact with other parts of the thermal process it hides shorter heat load reductions in the ambient temperature. This can be seen in Figure 7.7 where it is shown that although the average indoor temperature is not noticeably affected there is still a somewhat larger deviation in the indoor temperature which implies that there is indeed a higher level of temperature flux within the air mass and that this is triggered by the heat load reductions. The control policies used during this work obviously set a high bar for the control system to handle, but as
the average hardware develops it should be possible to implement such techniques on a larger scale.

Figure 7.8 gives a another clear indication of just how substantial such sources of free energy can be. This extra heating due to solar radiation through the windows directly interacts with the mass of air inside the building, thus raising the temperature. In addition to being able to help save energy usage in a building temporary heat load reductions also form the backbone of DSM and LC, in which the goal is to manage the heat load (kW) rather than the energy usage (kWh).

7.6 Future Work

In the future we plan to further develop models in order to dynamically estimate the temperature flux within buildings and develop theoretical and practical interfaces for incorporating this data dynamically into the control systems.

7.7 Acknowledgement

This work has been financed by Blekinge Institute of Technology and NODA Intelligent Systems AB.
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ABSTRACT
A district heating system consists of one or more production units supplying energy in the form of heated water through a distribution pipe network to a multitude of consumers. District heating systems come in a range of different forms and sizes: from small independent systems within industrial estates or university campuses to large city-wide systems supplying millions of consumers with heating and hot water. The geographically dispersed layout of district heating systems suggest that they are suitable for distributed optimization and management. However, this would imply a transition from the classical production-centric perspective normally found within district heating management to a more consumer-centric perspective. In this work we use multi-agent based systems in order to implement distributed policies for operational planning within district heating systems. We also develop models for simulating the dynamics of district heating systems in order to evaluate those policies and their use in computer-based demand side management approaches for improving operational planning and resource management. These policies are then implemented in real world industrial settings and their performance, as well as implementation issues, are analysed and evaluated. It is shown that distributed policies can lead to significant benefits compared to current schemes with respect to energy usage and heat load management at an operational level.