ABSTRACT

Intelligent district heating is the combination of traditional district heating engineering and modern information and communication technology. A district heating system is a highly complex environment consisting of a large number of distributed entities, and this complexity and geographically dispersed layout suggest that they are suitable for distributed optimization and management. However, this would in practice imply a transition from the classical production-centric perspective normally found within district heating management to a more consumer-centric perspective.

This thesis describes a multiagent-based system which combines production, consumption and distribution aspects into a single coherent operational management framework. The flexibility and robustness of the solution in industrial settings is thoroughly examined and its performance is shown to lead to significant operational, financial and environmental benefits compared to current management schemes.
On Intelligent District Heating

Christian Johansson
On Intelligent District Heating

Christian Johansson

Doctoral Dissertation in Computer Science

Department of Computer Science and Engineering
Blekinge Institute of Technology
SWEDEN
"I've come up with a set of rules that describe our reactions to technologies:

1. Anything that is in the world when you are born is normal and ordinary and is just a natural part of the way the world works.

2. Anything that’s invented between when you’re fifteen and thirty-five is new and exciting and revolutionary and you can probably get a career in it.

3. Anything invented after you’re thirty-five is against the natural order of things."

– Douglas Adams (1952-2001)
Abstract

Intelligent district heating is the combination of traditional district heating engineering and modern information and communication technology. A district heating system is a highly complex environment consisting of a large number of distributed entities, and this complexity and geographically dispersed layout suggest that they are suitable for distributed optimization and management. However, this would in practice imply a transition from the classical production-centric perspective normally found within district heating management to a more consumer-centric perspective. This thesis describes a multiagent-based system which combines production, consumption and distribution aspects into a single coherent operational management framework. The flexibility and robustness of the solution in industrial settings is thoroughly examined and its performance is shown to lead to significant operational, financial and environmental benefits compared to current management schemes.
Acknowledgments

This thesis is dedicated to my friend and colleague Dr Fredrik Wernstedt. Without him none of this would have been possible. He is dearly missed.

I would like to convey my deepest gratitude and respect to Professor Paul Davidsson who not only served as my supervisor but also encouraged and challenged me throughout the years leading up to this thesis.

Furthermore, I would like to thank everyone at Noda Intelligent Systems for their support over the years. I would especially like to acknowledge Mikael Ganehag Brorsson and Markus Bergkvist for going (and keeping on going) that extra mile.

I would especially like to thank Katya for putting up with me during the writing of this thesis. Thank you for being part of my life.

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

The research leading up to this thesis was financially supported by Blekinge Institute of Technology, the Swedish District Heating Association and the European Spallation Source.

Karlshamn, April 2014
Christian Johansson
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 already in 1999. The ABSINTHE research project was jointly funded by Blekinge Institute of Technology, 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 described in this doctoral thesis can be seen as a continuation of the work previously achieved during the ABSINTHE project, although with a higher focus on actual real-time implementations of the studied solutions. During the work for this thesis it has become apparent that real world domain of district heating systems and energy systems in general is much more complex than assumed in the early stages of the ABSINTHE project. This thesis is a step towards describing how to handle that complexity while implementing operational demand side management for real life applications.

This thesis comprises twelve papers that are listed below and will be referenced in the following text by their associated Roman numeral. The author of this thesis has been the main contributor to papers I, IV, V, VI, VII, VIII, IX, X, XI and XII 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 paper. All of the papers, except XI and XII, have previously been accepted for publication. Paper XI and XII is under review. All papers have been reformatted in order to conform to the thesis template.


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 technical 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 (Constinescu, 2007). 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 it is financially advantageous and environmentally sound. By Intelligent District Heating we refer to the merging of modern information and communication technology with traditional district heating systems, in order to improve the operational functionality of the system. Throughout this thesis the assumption that such a merger is technically, financially and environmentally beneficial has been explored.

A district heating system is at the basic level a collection of interacting or separate control loop feedback systems. In order to make such a system ”intelligent” one needs to take into account all parts of this loop. In the context of this thesis, three major parts of this loop can be identified: (i) measure, (ii) analyse and (iii) act. These parts exist on the local consumer level as well as on system wide production and distribution levels, and they are continuously reiterated within the process. Each of these parts can be also mapped to three basic notions of what entitles an intelligent system (Wechsler, 1944).

- The ability to perceive ones environment (measure)
- The ability to reach informed conclusions based on the perceived input (analyse)
- The ability to act based on those conclusions (act)

It is the conclusion of this thesis that all these three aspects of the system has to be present in order to achieve a level of automation approaching something
that can be characterised as intelligent. However, it is common to see energy systems being labelled as smart or intelligent based solely on the mere existence of remotely accessible metering equipment even though such a system barely even incorporates the first of the three parts of the loop.

In order to implement a system capable of handling all three parts of the intelligence loop described above a distributed multiagent-based framework has been developed. The idea that a multiagent approach is appropriate for district heating systems stems from the fact that most such systems consist of geographically distributed autonomous entities that interact in complex ways. The distribution medium in itself also applies certain time dependent 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 (Parunak, 1998). Furthermore, district heating systems consists of a multitude of consumers and producers who might not want to share all their operational and financial information on a global system wide scale just in order to achieve some optimal operational status. Together these observations lead to the hypothesis that distributed systems in general and a multiagent-based solution in particular is suitable for this specific problem domain.

The general architecture is based on two types of agents which are modelled based on the characteristics of a consumer substation and a production plant. Normally a consumer wants to use as little energy as possible while still maintaining an acceptable indoor temperature in the buildings connected to the substation, while a utility or energy company usually wants to optimize the production in relation to financial and operational aspects. By modelling the agents this way it is possible to assign these sometimes conflicting system goals to two different agent types which in the context of a multiagent system will act in order to achieve and maintain a balance between these goals. Thus, each physical substation in the district heating system is assigned a consumer agent with the main goal of maintaining an acceptable quality of service. Similarly, each production plant is assigned a producer agent which will act in order to optimize the energy usage from financial, technical and/or environmental aspects. In addition to this the system also includes a market agent which acts as a mediator between the producer and consumer agents.

Throughout this thesis variations of this basic multiagent architecture have been implemented and evaluated in order to find suitable techniques for distributed control of district heating systems. Even during the early days of the
ABSINTHE project, it became apparent that there was a need for simulation and modelling tools. Using such tools was the only way to test and evaluate the multiagent system before any appropriate hardware platform could be developed. Unfortunately, there were no available simulation tools capable of handling the complexity of dynamic simulations in a system which combined production, distribution and consumption behavioural models. As a consequence, this thesis also covers the development of simulation and modelling tools in order to support the primary work on the multiagent system.

The thesis consists of two major parts; the introductory section and a number of publications. In the introductory section 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 the introduction consist of journal articles and conference papers that have been published or currently are under review.

1.1 Background

The primary area of research for this thesis is Computer Science in general and agent technology and artificial intelligence applications in particular. However, the application area is district heating systems and in order to cover the problem domain at hand several research areas have been interwoven into an interdisciplinary whole. By combining Computer Science with aspects of Operations Research, Economics, Energy Systems, Automation and Physics the thesis develops the framework for intelligent district heating. 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 fora 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 Multi-Agent Systems

The software agent paradigm is an underlying theme throughout this thesis as it is used to design the framework on which the whole intelligent district heating system is based. A software agent can be seen as a computer program that is capable of autonomous and independent action based on the agents internal and external perceptions. As such they present a flexible way of structuring applications around autonomous and communicative components in open and dynamic environments. Agents are often used in systems handling distributed data and
communication, especially when there are constraints regarding integrity and privacy (Parunak, 1998). An agent can also interact with other agents in so called multiagent systems. This interaction can be either competitive or collaborative in nature, or a combination of the two. In many ways agents can be seen as analogies to physical entities and the agent paradigm tries to capture human notions such as trust, dependence, norms, reputation and other social concepts in order to take into account and model the structures forming relationships between individuals and organizations. The agent framework provides a basis for implementing interaction between computers, machines and human operators (Weiss, 2000a).

A common way to implement multi-agent systems is to use market process analogies based on traditional supply and demand mechanisms (Braeutigam, 2010). In such a situation the agents are bound by a protocol through which to interact but they are free to choose their own strategies in order to succeed on the market. As in economic theory the supply and demand mechanism in multi-agent systems provide a way to find self-balancing system behaviour. The theory of supply and demand is readily adaptable to the district heating domain as the consumer and production entities form obvious analogies providing supply and demand in the network. Economic theory provides a solid framework for introducing efficient methods for allocation and distribution of resources among a group of agents (Ygge & Akkermans, 1996).

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 (Russel & Norvig, 1995). Industrial applications are in many ways the direct opposite of textbook examples as the real world is highly unpredictable and complex. This is also true in district heating systems which also adds another level of complexity in the form of a high dependence on the physical infrastructure for sensory equipment and communication. In a district heating system the agents must be capable of functioning in a real-time environment even considering faulty or incomplete data. This is true for most type of large scale energy systems such as electrical power grids where agent-like mechanisms can be used to identify malfunctioning in switches and relays, handle alarm messages and implement peak load management (Jennings et al., 1996).

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.
1.1.2 District Heating

A district heating system consists of one or several production units, a distribution network and a multitude of consumers. The production units heat water which is then pumped through the distribution network as hot water or steam. 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. 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 (Fredriksen & Werner, 2013).

![Figure 1.1: A simplified district heating system with one production plant and three consumer substations connected through a distribution network](image)

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 (Fruergaard, Christensen, & Astrup, 2010). 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. One of the main advantages with district heating is indeed this ability use different types of primary energy sources such as biomass, fossil fuel, geothermal heat, natural gas or nuclear powered heating.

When building new production units in district heating systems it is many times advantageous to invest in so called combined heat and power generation. Such a production unit generates electrical power while simultaneously generating heat. The electrical power can be sold on the power grid while the heat is used for the connected district heating system. In such a system water is turned into steam which is used in a turbine connected to a generator in order to generate electricity. The steam is then cooled by transferring its heat to the water in the district heating system. By combining these two processes it is possible to achieve a very high level of energy efficiency which is why such production solutions are becoming increasingly popular (Horlock, 2008).

One challenge in district heating systems is that the heat demand is not always correlated with an optimal production scheme. Many of the primary energy sources used in district heating benefit from an even and predictable heat load. However, the heat demand is in practice influenced by both outdoor temperature dependant behaviour and social behaviour which in combination can cause uneven as well as unpredictable heat demand. Due to this most district heating systems include one or several peak load boilers used primarily to bridge deviations between heat demand and heat generation. Normally peak load boilers are fuelled by fossil fuel such as oil and natural gas, which are easy and efficient to use although they are more expensive than most base load fuels. Another common solution for this problem is to use large storage tanks where hot water can be stored temporarily in order to buffer energy for peak loads a few hours ahead. However such storage tanks are somewhat inflexible in operation and they are expensive to build. Intelligent district heating in the context presented in this thesis can in many instances be a financially and technically sound complement, or even in some cases replacement, for such traditional solutions (Olsson Ingvarsson & Werner, 2008).

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, energy producers will have to develop new business models in order to meet the changing demands of the market.
1.1.3 Smart Grid Technology

The smart grid concept is usually used in relation to electrical power grids, and is defined as a grid that uses modern information and communication equipment in order to gather and act on data related to the operation of the grid. The basic idea is that by using such technology it will be possible to manage the grid in a more efficient manner and by doing so save energy and create conditions for more sustainable energy systems (Braun, 2003). Smart grid technology is usually seen as an important part of a sustainable future since many of the increasingly popular environmentally friendly energy sources are harder to manage than traditional fuels such as fossil fuel or nuclear power. Wind, solar and wave power are examples of such intermittent energy sources causing operational challenges when implemented on a large scale due to their unpredictability and other shortcomings from an energy carrier perspective. The situation is similar within district heating technology considering for example the extensive use of biomass and industrial waste heat. The simple fact is that such energy sources are not as manageable as fossil fuel, irrespective of their financial or environmental benefits. In the context of this thesis a smart grid uses information and communication technology in order to coordinate the demands and requirements of all participating actors from technical, financial and environmental aspects. When implemented in a district heating system this is called a smart heat grid. In some literature such systems are called smart thermal grids in order to include cooling as well as heating technologies. A smart heat grid adds another degree of control to the traditional demand-driven management in a district heating system. Instead of simple being able to react on the heat demand, the energy company can manage and control the heat demand.

One of the primary objectives of a smart heat grid is to implement a framework for demand side management and operational load control, just like in a general smart grid (Torriti, 2012). 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 (Newsham & Bowker, 2010). 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. Operational 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 operational 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. This thesis presents several examples of the implementation of such techniques by coordinating short-term temporary heat load management among the consumers within the district heating system.

### 1.1.4 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 (Banks, Carson, Nelson, & Nicol, 2001). These days most work relating to simulation and modelling 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 scientific studies since full-scale experiments are often very expensive and complex to perform in real life. Simulation and modelling technologies are frequently used within operational management and planning in district heating systems (Arvastson, 2001). In an operational setting simulation models are important in order to test new control strategies and to verify the behaviour of system components. In a strategic setting simulation can be used in order to study how to size new parts of the network or to evaluate financial strategies in relation to fuel prices, taxes and system operational costs.

### 1.1.5 Heat Load Prediction

In relation to intelligent district heating a vital part of this is the ability for operators to forecast the heat demand. Forecasting heat demand is usually done by using weather forecasts as input for heat demand models which then approximate the heat load demand for the coming hours and days. The interesting challenge in forecasting heat load demands in district heating arises from fact that the total heat load is a combination of both outdoor temperature dependant control behaviour in the customer substations and social behaviour influencing for example tap water usage and heating fan usage in office buildings. The more simple models for forecasting heat demand are based on linear regression techniques (Jonsson,
2002). More complex models attempt to model outdoor temperature dependant behaviour and social behaviour separately in which case different types of regression is normally used for the former and time series analysis for the latter (Grosswindhager, Voigt, & Kozek, 2011). However, in the literature there exists several other approaches to heat load forecasting, including algorithms based on neural networks and other machine learning techniques (Nielsen & Madsen, 2006).

In regards to intelligent district heating it is important for the consumer agents to have the ability to estimate the indoor temperature in the individual buildings. A consumer agent will not participate in load control if this will jeopardize the quality of service of heating in the building. Therefore the consumer agent must be able to estimate the consequences for the building if it does indeed engage in load control. Basically the agent needs to forecast the change in indoor temperature given different control scenarios, and based on this take appropriate action. To thoroughly model 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 (M. Persson, 2000).

1.2 Research Approach

1.2.1 Research Questions

The purpose of this thesis is to develop better methods for operational planning and resource management within district heating systems, and investigate how to apply these methods 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 distributed 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 real world environments. This flow is formalized in the following three research questions which are central to this thesis:

- Research Question 1 (RQ1): How could the financial, technical and environmental aspects of the operational and strategical use of today’s district heating systems be improved by utilizing system-wide coordination from a consumer-oriented perspective?

- Research Question 2 (RQ2). How could a software tool for modelling and simulation of district heating systems be designed that captures their dynamic and distributed processes and that takes into account the physical, financial, and consumer-dependent aspects?

- Research Question 3 (RQ3). What type of problems can arise when applying system-wide coordination in operational energy systems, and how is it possible to handle these problems?

RQ1 relates to the core principles of the system, while RQ2 explores support tools for evaluating those principles. RQ3 relates to the practical implementation of the principles.

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 (Hevner & Chatterjee, 2012).

RQ1 deals with the development of an appropriate framework for operational planning and resource management in district heating systems. The underlying question of how to improve operational management and planning was used as a starting point and information and knowledge was gathered in order to develop an understanding in relation to the principles of this process. Based on this a hypotheses was formed, stating that an approach based on multiagent 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 multiagent system in a simulated environment and then later in several large-scale test installations in operational district heating systems. The resulting data confirmed the hypotheses and proved that it indeed was possible to improve operational planning and
resource management by utilizing a distributed multiagent system capable of coordinating consumer behaviour.

RQ2 was approached by performing a thorough investigation of the state-of-the-art of simulation within district heating systems. It was 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. The simulation tools for distribution calculations that did exist used very simple models for production and consumption and the process to convert data from a production simulation tool to the distribution calculator was not very smooth. By introducing some level of autonomous intelligence in the consumer sub-stations another control variable was added into the process 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.

RQ3 is in many ways a consequence of RQ1 as there was not only a need to come up with the framework but also a need to make sure that it actually works in a real-world setting. During the practical experiments relevant issues with the implementation were identified and catalogued, which in conjunction with theoretical studies of previous research made it possible 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 RQ1, i.e. a combination of theoretical work, simulation based experiments and demonstration installations in operational district heating systems.

1.2.3 Thesis contribution

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

RQ1: How could the financial, technical and environmental aspects of the operational and strategical use of today’s district heating systems be improved by utilizing system-wide coordination from a consumer-oriented perspective?

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 provides 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 demand side management. 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 by presenting the concept of a quality filter, while also analysing the concept of over-shooting the load 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. In Paper VII a specialized optimization algorithm for combined heat and power generation in district heating systems is presented. This algorithm is implemented and evaluated in relation to a day-ahead power market from the production point of view. The results show substantial financial benefits during times of high spot price volatility. Paper VIII takes a more consumer centric focus and presents the theoretical basis for the quality filter concept first discussed in Paper III. The theory is extended to a practical implementation which is then evaluated in relation to combined heat and power generation active on an intraday power market. Most power markets combine a day-ahead market with some form of intraday market in order to handle volatility in the grid. From this point of view Paper VII and VIII complement each other since one focuses on the day-ahead market and the other on the intraday market. Paper X focuses on the intermediate market process tying together the consumption and production optimization systems presented in Paper VII and VIII. The paper evaluates this process through a simulation study using a general approach to thermal storage in buildings. The results show clear financial and environmental benefits for the producers as well as the participating consumers. Paper XI finalizes the thesis by providing a description of two large scale real-time industrial implementations of the fully armed and operational multi-agent system. Paper XI generalizes the specialised optimization algorithms presented in Paper VII and combines it with the quality filter implementation presented in Paper VIII and ties these together using the market process described in Paper X.
RQ2: How could a software tool for modelling and simulation of district heating systems be designed that captures their dynamic and distributed processes and that takes into account the physical, financial, and consumer-dependent aspects?

Paper I is directly related to this question as this paper deals with the DHEMOS simulation software package that has been developed during the work of this thesis. The paper describes software that is based on a modelling and simulation framework combining models for production, distribution and consumption. These models are coupled with an agent layer which makes it possible 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. Paper XII provides a further verification study of the simulation framework by comparing it to a commercially available simulation tool for district heating systems.

During the development of the systems described in this thesis it soon became apparent that a dedicated simulation tool was needed in order to test and evaluate prototype models of the multiagent system. The general problem was that existing simulation tools focused on different aspects of a district heating system like production or distribution, and it was hard to combine the results from these type of different tools. However, the basic idea with the multiagent system was to consolidate models for optimizing production, distribution and consumption. Hence a simulation tool that was able to model all these three parts simultaneously was needed. During the work of this thesis a dynamic simulation platform was developed. This platform combines models for distribution, production and consumption and due to the modular design it is possible to add new functionality in individual components without disturbing the overall model. This made it possible to simulate the behaviour of different types of multiagent systems in a district heating system. Due to this distributed approach in the simulation platform it was possible 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. Also by changing the level of aggregation and by using a limited range of pre-defined template building models it was possible to adjust the complexity to the desired level without sacrificing the overall goal of analysing the system-wide behaviour.
RQ3: What type of problems can arise when applying system-wide coordination in operational energy systems, and how is it possible to handle these problems?

Paper IV takes 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 than in the other 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 system 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 other 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 and XI describe the implementation and operation of large scale industrial applications and contributes to the 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. Paper VIII provides a description on how to implement the quality filter in practice. The quality filter concept is a vital part of an intelligent district heating system since it provides a way to ensure quality of service among consumers while performing operational optimization on a system wide scale. The indoor temperature in most buildings vary several degrees from the coldest to the warmest parts of the building and the temperature is constantly fluctuation due to social behaviour, solar irradiation, excess heat from electrical appliances and so on. In other words, the indoor temperature profile of a building is very noisy. The minute changes in indoor temperature actually caused by participating in load control are almost always hidden within that noise. The main objective of the agent is not to calculate the exact temperature in the building, since this is
bordering on impossible anyway. Rather the agent tries to estimate the relative deviation from the indoor temperature that might happen during load control. This is done through the use of an energy balance model that assumes that if no load control is active then the existing control system in the building will be able to uphold an acceptable quality of service. During the work for this thesis a pseudo black-box energy balance model was developed. A black-box model is a simulation type that has no direct relation to the physical process it is describing. The reason to use a black-box model is that it eliminates the need for parameter input regarding the physical characteristics of the building which greatly eases the practical use of the system. By using such a model it is possible to automate an adaptive process in which the agent changes the input parameters until they conform with actual measurements. The combination of an adaptive forecasting model and actual measurements in the building provide the consumer agent with the tools to uphold desirable quality of service while participating in load control in the multiagent system. Paper IX presents a novel approach for information visualization and fault detection by using machine learning techniques. Such performance metric tools are important during the practical implementation of intelligent district heating systems.

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 XIII, XIV, XV and XVI 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 XIII 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 XIV 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 and results from a somewhat more concentrated perspective.

Paper XV 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 XV 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 the 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.

Paper XVI presents the results of further development being done on the simulation system described in Paper I, XII and XV. The simulation system is used to analyse the behaviour of a multiagent system in a district heating system. Operational data from the district heating system was used in order to calibrate the simulation system. The paper provides walk-through of how to use this type of simulation tools in practice.

1.3 Conclusions

The primary conclusion of the thesis is that it indeed is possible to improve the financial and technical operational behaviour of a district heating system by using modern information and communication technology implemented through a multi-agent framework. The theory underlying such a system has been presented and its validity and benefit has been shown through a series of demonstration installations in operational district heating systems. The demand side management system shown has the ability to perform operational load control of 20-30\% on a system scale during several hours and even more during shorter periods of time. Using this ability the system can achieve peak load shaving, balance heat load profiles and optimize combined heat and power generation.

The thesis presents the quality filter concept which enables the multi-agent system to ensure a sufficient level of quality of service among the district heating customers. The consumer agents utilize an energy balance model in order to estimate the impact of each individual load control action. A pseudo-black box energy model is presented in the thesis. The main contribution of that model is that it is easy to use in a practical setting on large scale implementations.

By using a mediating market agent the system achieves self-balancing behaviour. In combination with the quality filter this ensures that no single consumer agent can jeopardize the quality of service on the individual level. The market based mechanism ensures that the most suitable consumer agent will always receive each individual load control instance. The thesis also presents optimization models used as input by the producer agent in order estimate the value of an individual load control instance. Through this process a producer
agent can set the constraints for the market agent which in turn distributes the load control instance among the consumer agents.

The thesis and its related papers present a dynamic simulation platform for district heating systems. By using existing models for district heating simulation based on graph theory it was possible to build an agent-based framework for practical modelling and simulation. The framework combines models for production, consumption and distribution and as such provide a platform for testing and evaluation of the smart heat grid systems presented in this thesis.

1.4 Future Work

The demand side management system presented in this thesis relies to some extent on heat load forecasting. During the work of this thesis several different approaches to this problem has been evaluated. However, further work is need in order to develop a heat load forecasting model that is versatile and robust enough to use in an operational settings in different district heating systems.

During the distribution process a heat load instance is distributed among several consumer agents. Further study is needed in relation to the dynamic sizing of that heat load instance. This would enable the system to increase the fairness in the distribution process. This will become increasingly important as the pricing schemes in district heating systems develop into taking load control into account. This in turn will increase the need for further development relating to the tuning of the consumer agent behaviour. By improving their strategies they will be able to optimize their load control behaviour while ensuring a continued quality of service.

The amount of data measured and collected in energy systems is increasing constantly. Future work is needed in order to develop ways to manage and analyse such large data sets. Fault detection and operational analysis is an important part of intelligent district heating for the future. However, new and innovative ways to manage the data and visualize the resulting information is required.

Another interesting subject for future research is to study the merger of information and control relating to building heating systems and the district heating system in itself. It might be possible to further optimize the overall system behaviour by integrating the behaviour of the secondary heating flow within the building into the overall operational functionality of the system.
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 contain three 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)](image)

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:

$$R = \frac{1}{U_{ext} * A_{ext} + e * n_{50} * V_{air} * \varphi_{air} * C_{air}}$$  \hspace{1cm} (2.1)

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 $e * n_{50}$ and the heat capacity of the air is $\varphi_{air} * C_{air}$.

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

$$C = U A \varphi T_{out} + U A \varphi T_{in} + U A \varphi T_{roof} + U A \varphi T_{floor}$$  \hspace{1cm} (2.2)

where $U$ is the heat conduction in $W/m^2K$, $A$ is the area in $m^2$, $\varphi$ is the density in $kg/m^3$ 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:

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

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

\[
\tau_0 = C \times R
\] (2.5)
and the temperature change is calculated by (Österlind, 1982):

\[
\frac{T_r(t) - T_u}{T_{r,0} - T_u} = e^{-\frac{t}{\tau_0}} \tag{2.6}
\]

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):

\[
\tau = \frac{\tau_0}{1 - k} \tag{2.7}
\]

where

\[
k = \frac{P_v}{\sum U A + P_L} \tag{2.8}
\]

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.
Figure 2.4: Probabilities for different demands during a 24 hour period

The variance over time of the outdoor temperature is simulated by the following model (Ygge & Akkermans, 1999):

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

\[ T_{vio} = T_{outd} + T_r + T_d \] (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:

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

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

(2.14)

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 (Valdimarsson, 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 (Valdimarsson, 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 (T. Persson, 2005). This obviously means that any temperature model which pertains to mimic reality will have to incorporate such considerations. In (Larsson, 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:

$$F = \frac{v_T}{v}$$

(2.15)

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

$$F = \frac{1}{1 + \frac{\varphi_p \cdot c_{p,p}}{\varphi_w \cdot c_{p,w}} \cdot \frac{4 \delta}{d_{i,p}} \cdot \left(\frac{\delta}{d_{i,p}} + 1\right)}$$

(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 district heating 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.

![MAS architecture](image)

Figure 3.1: MAS architecture

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 $-5^\circ C$ the temperature in the space heating system should be, e.g., $44^\circ C$ 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 $44^\circ C$ would mean that the heat exchanger in the HES would heat the supply water in the space heating system to $39.6^\circ C$ instead of $44^\circ C$. 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.

![Reductions](image)

**Figure 3.6: Reductions**

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 recent 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 (?). 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.

![Image](image_url)

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.

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 Keywords

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.
(UCP) (Dotzauer, 2002). 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 to 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 were 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.

\[
\text{Minimize} \sum_{i \in I} F_i(P_i) \quad (5.1)
\]
\[
F_i(P_i) = \alpha_i + \beta_i P_i + \gamma P_i \quad (5.2)
\]

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:

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

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:

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

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 an 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 whatsoever 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 start 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.

![Flow Graph](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.
Figure 5.4: Partial scenario. Agent performance (continuous), reference data (dotted) and wanted DSM level (dashed)

Figure 5.5: Local scenario. Agent performance (continuous), reference data (dotted) and wanted DSM level (dashed)

5.5.2 Agent buffer usage

The level of comfort is dependent on the buffer used by each individual consumer agent. Every agent has a 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.

Table 5.1: DSM strategy deviation values

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>1</td>
</tr>
<tr>
<td>Partial</td>
<td>6.75</td>
</tr>
<tr>
<td>Local</td>
<td>11.07</td>
</tr>
</tbody>
</table>

Figure 5.6: DSM strategy deviation. Global scenario (black), partial scenario (dark grey) and local scenario (light grey)
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 system’s 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
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 considering 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.
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 available 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 maintaining 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 optimization models. This shows that real-time cooperative behaviour among communicating agent nodes is needed in order to successfully implement DMS in real world applications, and that indirect methods, like differentiable taxation, or uninformed 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 status. 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 (, ?).

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 cooperative, 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 another 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 equipment.

- 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 industrial 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:

I. 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 (\(T_{\text{trad, supply}}\) and \(T_{\text{trad, return}}\)) 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 ($T_{out, LC}$) deviates from the actual outdoor temperature ($T_{out}$).

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:

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

(6.1)

Where \(\text{Heatload}\) is the amount of heat load [W] that the system should be able to handle, \(e\text{Sig} \text{[W/°C]}\) is the average energy signature in the area, \(T_b \text{[°C]}\) is the outdoor temperature above which a building needs no heating, \(T_{out} \text{[°C]}\) 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 of 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:

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

(6.2)

Where \( t \) is the time [h] that the system can uphold load control at a \( LC_{\text{max}} \) of 1.0, \( T_{\text{diff}} \) [°C] is the acceptable temperature drop in indoor temperature during load control, \( T_{\text{in}} \) [°C] is the indoor temperature at the beginning of activated load control, \( T_{\text{out}} \) [°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 \( (1 - e^{-1}) \) 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 \( (1 - e^{-1}) \), 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 grounding)
- 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.
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 occupiers 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.
Chapter 7

Paper VI - Heat load reductions and their effect on energy consumption

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 buildings 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 of 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 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 questions 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 were 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 analyse 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 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.
Chapter 8

Paper VII - Combined heat and power generation using smart heat grid

Combined heat and power (CHP) generation is often used when building new district heating production. CHP makes it possible to simultaneously produce electricity and heat, thus maximizing the energy efficiency of the primary fuel. The heat is used in the connected district heating system while the electricity is sold on the local power market. In a CHP plant it is not possible to separate the physical process of producing heat and electricity, which may cause suboptimal behaviour when high spot prices for power do not coincide with high heat load demand. This paper presents the design and implementation of a system which makes it possible to control the heat load demand in a district heating network in order to optimize the CHP production. By using artificial intelligence technology in order to automate the run-time coordination of the thermal inertia in a large amount of buildings, it is possible to achieve the same operational benefits as using a large storage tank, albeit at a substantially less investment and operational cost. The system continuously considers the climate in each participating building in order to dynamically ensure that only the best suited buildings at any given time are actively participating in load control. Based on the dynamic indoor climate in each individual building the system automatically controls and coordinates the charging and discharging of the buildings thermal buffer without affecting the quality of service. This paper describes the overall function of the system and presents an algorithm for coordinating the thermal buffer of a large amount of buildings in relation to heat load demand and spot price projections. Operational
data from a small district heating system in Sweden is used in order to evaluate the financial and environmental impact of using this technology. The results show substantial benefits of performing such load control during times of high spot price volatility.

8.1 Introduction

In a district heating system (DHS) one or several production units distribute heated water or steam throughout a pipe network. Buildings are connected to this network either directly or by heat exchangers. This delivered heat can then be used for a multitude of purposes within the building, e.g. radiator subsystems, hot tap water or heating of ventilation air. The basic concept with centralized production units is normally environmentally and financially sound, since such facilities can easier incorporate large scale energy efficiency schemes. District heating is most common in northern and eastern parts of Europe including Russia and other former Soviet countries, although the concept is utilized around the world and is gaining an increasing acceptance on markets throughout Asia and North America (Constinescu, 2007).

Any type of production can be used in a DHS, as long as it is able to heat the water to the desired level. This flexibility allows a wide range of different production solutions, such as industrial waste heat, geothermal heat, biomass, fossil fuel boilers and nuclear powered heating. In many DHS a cogeneration plant is also added to the system. This provides the possibility to produce electrical power in parallel with the heat production. Such combined heat and power (CHP) systems typically have a very high level of energy efficiency compared to stand-alone thermal production plants (Horlock, 2008). In a CHP plant water is heated to steam, which is then led into a turbine which in turn transforms the kinetic energy to electricity in a generator. The steam is then cooled by transferring its heat to the return water in the district heating system, which in turn is distributed throughout the DHS.

The electricity produced by the generator is normally sold on the power market. In northern Europe the power market is run by Nord Pool Spot, which was the worlds first market for trading power. Nord Pool Spot provides a market for buying and selling power in Sweden, Finland, Denmark and Norway as well as in Estonia, Germany and Great Britain. In 2010 the total power traded through Nord Pool Spot amounted to 310 TWh, which correlates to a monetary value of about EUR 18 billion (NordPoolSpot, 2012). Since the power market is deregulated it is subject to basic market characteristics such as the balance between supply and demand. Since energy in the form of electricity is by nature quite hard to store, the electricity has to be made available at the same time as there is a need for it. And since both this demand and the available supply vary...
throughout the day, the price for electricity will obviously also vary throughout the day. On Nord Pool Spot power is traded based on hourly market prices. These spot prices are traded one day in advance, and are then published on the same day at 14.00 CET as a set of 24 spot prices, each correlating to an hour the following day. There is also an intraday market at Nord Pool Spot. The intraday market acts as a balancing tool between supply and demand in real time. Prices on the day-ahead market can vary quite a lot during a 24 hour period, and situations where the highest spot price for the day is twice that of the lowest is not uncommon. At the intraday market prices can be even more volatile.

These price changes obviously make it financially sound for the individual energy companies to try and match their production with the highest spot prices. In a DHS/CHP system the physical act of producing electricity cannot be separated in time from heat production. However, if the heat can be stored in preparation for the heat load demand, it is possible to optimize the CHP process in relation to power spot prices. By using large heat water storage tanks it is possible to do this, by charging the storage tanks while the power spot prices are high respectively discharging them when the heat load demand rises in the buildings. However, such storage tanks are expensive to build and maintain, and their operational characteristics are inflexible. This paper presents an alternative way to manage heat production in relation to the spot price market. By using its thermal inertia it is possible to charge and discharge a building with slight amounts of heat energy without affecting the perceived indoor climate (C. Johansson & Wernstedt, 2010b) (Olsson Ingvarsson & Werner, 2008). If this behaviour is coordinated among a sufficiently large group of buildings the amount of energy controlled is comparable to any storage tank, albeit at a much lower installation and maintenance cost. Such a system also has the added benefit of having a more flexible operational behaviour than a storage tank, since the heat load changes in an individual building are only limited in time by the speed of the connecting valve.

Controlling the heat load in buildings is known as demand side management (DSM) and can be implemented either by passive tools, e.g. design of price lists, or by active tools such as direct load control (Sipilä & Kärkkäinen, 2000) (Wernstedt, Davidsson, & Johansson, 2007). The heat load demand in a building is basically related to two different driving forces; a) the heating demand and b) the hot tap water demand. The heating demand closely follows the changes in outdoor temperature while the tap water demand is caused by social behaviour. Although social behaviour does display predictable patterns from a macroscopic point of view, the tap water usage cannot be used in relation to heat load control, since the tap water system needs a continuous heat load level in order to avoid Legionella growth. Also the tap water system is subject to direct feedback regarding quality of service (QoS) if the heat load is changed, e.g. a person taking
a shower will instantaneously identify a drop in the tap water temperature. The heat balance of the building itself however, is a physical process characterised by a more slow-moving nature. If the heat load for the heating system is removed it will normally take several hours before any person in the building will notice any change (Olsson Ingvarsson & Werner, 2008). This process is even more inert when only a subset of the heat load is manipulated.

Normally the heating control system of a building will control the forward temperature in the radiator system based solely on the outdoor temperature. Active load control basically equates to temporarily diverting from this. This is done by controlling the heat load demand, and thus the forward temperature in the radiator system, based on some other control signal. The scheme presented in this paper is initiated by a system wide heat load analysis which is synchronized with spot price projections. Active load control is then performed in order to implement the calculated heat load demand strategy while maintaining sufficient levels of QoS.

The paper starts off by introducing related and previous work concerning the subject. In section three heat load storage and load control in buildings is discussed in more detail. Section four details an optimization model for correlating spot price and heat load demand. Section five describes how the load control system is designed while the process of evaluating its behaviour is described in section six. The results are presented in section seven, while section eight discusses the system and the results. The paper is finalized in section eight and nine with conclusions and future work.

8.2 Related work

The basic prerequisite ability to use the thermal mass of buildings as heat storage facilities has been thoroughly investigated in previous work. It has been shown that substantial amounts of energy can be saved in relation to both heating and cooling demand, even just by considering passive use of a buildings thermal mass during the architectural design phase (Hietmaki, Kuoppala, Kalema, & Taivalantti, 2003) (Concrete for Energy Efficient Buildings The benefits of thermal mass, 2007). By actively using the thermal inertia within building structures it is possible to equate this to the operational behaviour of large storage tanks (Olsson Ingvarsson & Werner, 2008).

Such active load control has been studied in relation to building thermal mass, where the validity of the concept is proved through practical experimentation. Such operational load control systems have been evaluated since the eighties (Österlind, 1982). This early system used the electricity network in order to communicate load control commands to each building. This was a one-way communication set-up which prevented the system from considering aspects relating
to QoS, which meant that the system was controlled without any feedback from the individual buildings. It is not until the last decade that technological progress in relation to communication and processing has become sufficiently adaptable and reasonably priced to warrant any large scale installations (C. Johansson, Wernstedt, & Davidsson, 2010b). In particular the development of inexpensive and robust infrastructures for communication has been a pivotal aspect of this development, and previous work has shown how different levels of available communication affect the efficiency of active load control in operational settings (C. Johansson, Wernstedt, & Davidsson, 2010a). Although the realization that reliable two-way communication was of outmost importance is evident even in the earlier works (Österlind, 1990).

The concept of DSM quality filters was proposed in a previous paper as a way of managing the relation between energy companies increasing demand for environmentally and financially optimized operational planning and customers demand of robust and continuous QoS (Wernstedt & Johansson, 2008). Maintaining a sufficient level of QoS is paramount for any load control scheme. System wide active load control is dependent on the coordination of heat load demand in a large group of buildings, and normally the end-customers occupying these buildings are not sympathetic to overly volatile heat deliveries.

### 8.3 Load control in buildings

Normally the control system in a building will manage the heating by continuously measuring the outdoor temperature and adjusting the temperature of the secondary heat system accordingly. In most cases this control is performed by some sort of PI or PID feedback mechanism (KJ & T, 1995). In order to perform active load control in the building this normal control has to be overridden during each load control instance. This is normally done by offsetting the outdoor temperature signal to some degree, either by predefined internal processes in the existing control system software, or by external manipulation of the signal from the outdoor temperature sensor. Many existing control systems attenuate the signal from the outdoor temperature sensor, in order to avoid volatility in the resulting control signal due to rapid changes in outdoor temperature. Such attenuation should preferably be minimized in systems aimed at performing active load control, since they cause the system to react slower than is necessary.

The QoS needs to be maintained at all times in each individual building participating in the load control scheme. One obvious solution for this is to use indoor temperature sensors which give continuous feedback to the system. Many solutions for such temperature measurements exist, and lately solutions based on wireless technology have also become more widely available. The main problem with wired solutions in this regard in the cost of installing such systems, since
the temperature sensors need to be deployed throughout the building. Wireless solutions are cheaper in this regard but suffer from other problems, mainly related to connectivity and power usage. Especially power usage is crucial, since most wireless solutions use batteries, although continuous progress is being made in this regard (Anastasi, Conti, Francesco, & Passarella, 2008). A basic problem when using indoor temperature measurements as a control signal is that they are very susceptible to social behaviour. Installing a number of such sensors in the same building and then using an average value reduces the influence of such stochastic behaviour. Although even such a value is not optimal as a direct control signal, since an individual load control instance should be able to stop long before a temperature drop is measured among a group of physical sensors.

The time constant of a building is often used to describe the thermal inertia of a building. This value can be view as the heat capacity of the building in relation to its specific heat loss. The time constant describes what happens with the indoor temperature when no heat load is input into the building, and the temperature consequently starts to drop. The time constant is expressed in hours, and might vary from just a few hours to several hundreds of hours. Most normal multi-apartment buildings in Sweden have time constants between 50-200 hours.

The time constant is a good starting point for evaluating the ability of a building to perform active load control, although it is too simple to use for heat loss analysis in real time control. Active load control involves short term charging and discharging of the thermal buffer within the building. In order to model such thermal behaviour an energy balance model is often used. Within this project we use a system of two differential equations in order to express the change in indoor temperature and building structure temperature in relation to the outdoor temperature. Such models are based on the basic heat load balance within a building on the fundamental form shown in equation 8.1.

$$\Delta T_{\text{indoor}} = H_{\text{input}} - H_{\text{output}} \quad (8.1)$$

where $H_{\text{input}}$ is the total heat load supplied into the building, $H_{\text{output}}$ is the combined heat losses and $\Delta T_{\text{indoor}}$ is the indoor temperature difference this will lead to. Such heat load balance models are the prevalent method of describing the thermal dynamics of building structures. These models can be made sufficiently complex and might include several more variables than just one indoor temperature and one building structure temperature (Andersen, Madsen, & Hansen, 2000).

Figure 8.1 shows the heat loss in three different buildings. The values are calculated by the energy balance model used in this study. As each time step is about nine hours the time interval spans about twenty days. Figure 8.2 shows
Figure 8.1: Heat loss in buildings with three different time constants. 80 hours (continuous), 150 hours (dashed) and 250 hours (dotted). The time scale is in nine hour increments.

data generated by the energy balance model compared to actual measurement data from a real building. The building in question is a very large school building with a considerable time constant of about 380 hours. During one weekend the building heating system suffered a total breakdown, which enabled us to measure the temperature drop during the time it took to repair the heating system (Wernstedt & Johansson, 2009). The repair time is slightly less than 36 hours, which is the time span shown in Figure 8.2. Since this is only a small part of the time constant of the building the graph does not display the full logarithmic behaviour present in the previous figure.

In order to ensure sufficient levels of QoS the proposed systems uses the combination of an energy balance model and physical indoor temperature sensors. Having access to actual measured temperature data is invaluable in order to gain acceptance for active load control among building owners and residents.

8.4 Heat load synchronization

In order to synchronize future heat load and spot price peaks, it is necessary to have projections of both these values. The spot prices on the Nord Pool Spot power market is published one day ahead so this data is freely available. A heat load projection can be modelled based on weather forecasts. Since the projection is short term, in this case one day ahead, and the only variable used is outdoor temperature the weather forecasts are sufficiently accurate. The heat load projections are then arranged in accordance with the spot price, in this case an array of 24 values correlating to system wide heat load demand for each hour.
the coming day. The idea is then to rearrange the heat load array so that it matches the spot price array as closely as system constraints allow. If the heat load demand is discretized and represented in a matrix, this process can be formalized in the following optimization model.

\[
\begin{align*}
\text{max} & \sum_{i=0}^{m} \sum_{j=0}^{n} f(x_{i,j}) \cdot c_j \\
\text{subject to} & \\
 f(x) = & \begin{cases} 
1, & \text{if } x_{i,j} \neq 0. \\
0, & \text{otherwise.} 
\end{cases} \quad (8.3) \\
\text{if } f(x_{i+1,j}) = 0 \text{ then } f(x_{i,j}) = 0 \quad (8.4) \\
 b_{upper} & \geq \sum_{i=0}^{m} f(x_{i,j}) \quad (8.5)
\end{align*}
\]
\[ b_{\text{lower}} \leq \sum_{i=0}^{m} f(x_{i,j}) \] (8.6)

\[ \sum_{i=0}^{m} f(x_{i,j}) \leq \sum_{i=0}^{m} f(x_{i,j-1}) + b_{\text{dynamic}} \] (8.7)

\[ \sum_{i=0}^{m} f(x_{i,j}) \geq \sum_{i=0}^{m} f(x_{i,j-1}) - b_{\text{dynamic}} \] (8.8)

The cost function in equation 8.2 maximises the total earnings of the sold electricity. The amount of electricity is constant, since the total heat demand is constant. The heat load data for each hour is discretized heat load blocks and added into an \( m \) by \( n \) matrix, where \( m \) is the theoretical maximum amount of heat load in the system. The value of \( n \) is 24, i.e. one column for each hour during the period. Equation 8.3 quantifies the existence of heat load blocks in each section of the matrix. Equation 8.4 stipulates that a heat load block must either have another block under itself or be at the bottom itself. This basically means that the heat load must be connected and start at zero. Equations 8.5 and 8.6 set the maximum and minimum boundaries for the production during the entire time span. Equation 8.7 and 8.8 set the dynamic boundaries between each time step, i.e. they control how much the production can shift between each hour. It should be noted that all the boundaries relate to the system wide total, i.e. a combination of all available production units and operational load control ability. The chosen block size affects the computational performance required to solve the optimization problem, since the amount of blocks equals the amount of rows in the heat block matrix. During this study a block size was chosen according to equation 8.9.

\[ \text{sizeblock} = \frac{\text{heatload}_{\text{max}}}{10} \] (8.9)

Obviously any number can be chosen instead of 10, but the higher the number the higher the computational load. Also there is no point in having a much smaller block size, since a real time operational load control system will not be able to implement such a solution exactly anyway. Figure 8.3 shows a simple example solution to the described optimization problem. Matrix A is the reference heat load, i.e. the starting point for the optimization, while Matrix B, C and D are three solutions with different dynamic boundaries.
In the example from Figure 8.3 four time steps are used, which correlate to spot prices of 5, 7, 10 and 4 in that order. The maximum boundary is three, and the minimum boundary is zero in all solutions. The dynamic boundary is one for solution B, two for solution C and three for solution D. The earnings for each matrix is 38 for the reference case, 43 for solution B, 48 for solution B and 51 for solution D.

8.5 Market based heat load allocation using agent technology

When the system has found the solution to the heat load synchronization it must also enforce this in the DHS the following day. This is implemented by active load control, in which the system uses the thermal inertia of buildings in order to manage the heat load demand in order to approach the heat load synchronization scheme. We use a market based allocation system in which an auction-like process distributes load control among the participating buildings. Such an auction process is based on the idea that a mechanism of supply and demand is self-regulating. Our system uses agent technology in order to manage and operate this auction process. An agent is a stand-alone software system which is capable of flexible and autonomous action, and observes and acts upon its environment and directs its activity towards achieving some goal (Weiss, 2000a). Agent technology provides a framework for structuring computer applications around au-
tonomous and communicative components. In our case these components consist
of the individual buildings as well as the production units. Agents are often used
in complex and unpredictable environments, where available data is distributed.
Since an operational DHS display such characteristics agent technology provide
a convenient framework for implementing active load control. Figure 8.4 shows
the basic communication architecture for such an agent based auction process.

![Figure 8.4: Communication architecture of agent based auction](image)

By using the difference between the actual indoor temperature and the accept-
able indoor temperature boundaries the system can represent a form of currency.
If a building has a large difference between the actual indoor temperature and the
temperature boundaries it will have large thermal buffer which can be controlled,
i.e. the building will have large amount of available currency. However, if the
building indoor temperature is close to the limit where the temperature change
might be noticeable, the building will have a small amount of available currency.
This currency is then used by the building agents in order to buy load control
by the production agents through an auction process. The more load control
an individual building agent buys, the more it will charge/discharge its thermal buffer, thus in the process becoming poorer and therefore not being able to compete in the auction rounds. Thus the building agent will stop performing load control and the indoor temperature will slowly return to the original position, which in turn increases the agents ability to start bidding at the auction again. Based on this behaviour the overall system will be self-regulating in regards to QoS while finding an optimized heat load allocation, since the system will have an automatic correlation between a buildings ability to perform load control and its inclination to do so. This type of agent system has been described in detail previous work (Wernstedt et al., 2007) (Wernstedt & Johansson, 2008).

8.6 Experimental set-up

The reference data for this project has been collected in the DHS at Gothenburg Landvetter Airport in Sweden. The system has about thirty buildings served by the production units. These buildings range from large hangars and arrival halls to smaller buildings containing guard facilities and restaurants. The data was collected during the full month of January in 2011.

The spot prices are accessed from the Nord Pool Spot webpage, and encompass data from the same time period, i.e. the month of January 2011. The prices are expressed in SEK but have been converted to EUR and USD for the evaluation of this study. The exchange rate used is 1 EUR = 9.17 SEK and 1 USD = 7.04 SEK. In order to evaluate the performance of the system we used the DHEMOS simulation tool. DHEMOS is a simulation model framework for district heating systems, combining the models for production, distribution and consumption into one tool (Dhemos, 2012). DHEMOS was originally part of the ongoing research at Blekinge Institute of Technology, but is now run as an open source project. The underlying simulation models used in DHEMOS are described in previous work (C. Johansson & Wernstedt, 2005).

The heat load reference matrix and spot price array are built based on the collected data. The optimization problem is then solved, which results in a new heat load matrix. This heat load scheme is then simulated in DHEMOS in order to evaluate the affects this would have on QoS among the consumers and other components within the DHS. Only the 20 largest buildings where used for active load control during this study.

The optimization calculation is done using Octave 3.2.4. The DHEMOS simulations have been run on a Linux/Ubuntu 11.10 computer with Intel Core i5 CPU with 4 GB of RAM.
8.7 Results

The data affecting the simulation, i.e. spot price data and outdoor temperature, obviously changes every day. The data presented in this section is based on a representative period of twenty-four hours. Figure 8.5 shows the heat load demand in the DHS before and after the synchronization process.

![Heat load demand](image)

Figure 8.5: Heat load demand in the DHS, showing reference (continuous) and optimized (dotted)

It is clearly visible where the high and low spot prices triggering the synchronization are occurring. The system tries to move as much heat load demand as the boundary values will allow, from hours with low spot prices to hours with high spot prices. Figure 8.6 shows the indoor temperature changes in an individual building as the load control mechanism enforces the heat load scheme in the DHS.

The starting point for the indoor temperature is 21°C, which the existing control system in the building will be able to uphold if there is no load control being performed. As the load control is enforced the temperature starts to drop slightly, while slightly increasing during the later parts of the day. Even if the heat load is roughly halved during several hours when the first load control is done, the indoor temperature is only slightly affected. The same is true during the later heat load peaks when the spot price is high during the evening. Figure 8.7 shows the rate of change in the indoor temperature as the heat load demand
Figure 8.6: The indoor temperature in a building during load control deviates from the level required by the existing control system.

Figure 8.7: The change in indoor temperature throughout the day

The derivative of the indoor temperature clearly correlates with the changes
in heat load input throughout the day. This is a measure of the charging and discharging of the thermal buffer within the building. It shows how the building is used to synchronize the spot prices, and is essentially a horizontal mirror image of the heat load demand. Figure 8.8 shows the QoS level of the building agent throughout the day.

![Agent status (QoS)](image)

Figure 8.8: Agent status as expressed in QoS

The QoS in Figure 8.8 is expressed in percent. A full 100\% indicates that the indoor temperature is 21°C, which is what the existing control system is trying to uphold. Any deviation from this value will result in a decrease of QoS. In this study the indoor temperature was allowed to deviate up to 1°C from the wanted indoor temperature, i.e. in an interval between 20°C and 22°C. The QoS level will approach zero as the temperature approaches these limits. The QoS is the currency which the building agent uses to engage in the auction process. In Figure 8.8 it is clearly visible that the agents funds decreases as it engages and wins load control through the auction. Conversely, as the agent refrains from auctions the funds increase as the indoor temperature slowly returns to the original state. Table 8.1 shows the financial results in relation to the presented data.

There exists different ways to implement active load control in DHS. The system we use in real-time implementations cost approximately 1000 EUR (1302,56 USD) per building agent, which gives a repayment time of 196,41 days based on the figures presented in Table 8.1 in relation to the twenty buildings used for load
control. Counting a heat season of about six months, this equates to a repayment of the investment by little more than one year.

### 8.8 Discussion

The main object with many production plants, especially those using biomass or other low quality energy carriers for fuel, is to maintain an even production level throughout the day. Such production units will get smaller dynamic bounds, but they are still able to respond to general heat load fluctuations in the system. The synchronization strategy presented in this paper functions by creating artificial heat load peaks during hours with high spot prices in order to maximize the sale of generated power. This might not be advantageous to the end customer if the district heating price is partly priced according to different levels of heat load- or flow usage. Although it should be noted that the load control system is a general tool for managing the heat load demand and it might be used for evening out peak loads just as well as creating or moving them. In this regard it functions similar to a heat water storage tank, and it is hard to generalize since each DHS is different from the next.

The daily spot price spread, i.e. the difference between the highest and lowest hourly spot prices during the day, is the most important factor when evaluating the earnings. A larger spread will obviously lead to higher earnings. This can be compared to the function of daily trading on stock markets, where the difference between bought and sold price during short periods of time influence the potential earning. This is especially apparent when trading on the intraday power market, when there is no prior knowledge of the price. Just like stock market day trading financial instruments can be used to evaluate price projections, either by technical or fundamental price analysis. However, the application of such techniques in relation to active load control is beyond the scope of this paper.

Normally, when optimizing in relation to current spot prices on the power market, large storage tanks are used. Another alternative is to use the distribution network in itself as a storage device. Using the thermal inertia of buildings as proposed in this paper, is just an extension of this established control philosophy. One crucial difference is the ability to adjust to sudden changes when using heat

<table>
<thead>
<tr>
<th>Description</th>
<th>EUR</th>
<th>USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earnings (ref)</td>
<td>2850.66</td>
<td>3713.15</td>
</tr>
<tr>
<td>Earnings (solution)</td>
<td>2952.49</td>
<td>3845.78</td>
</tr>
<tr>
<td>Difference</td>
<td>101.83</td>
<td>132.64</td>
</tr>
</tbody>
</table>
load demand in buildings. Load control in a building can react as quickly as the valves on the heat exchanger can move, while a storage tank requires much longer pre-heating and charging strategies. In practice this is like comparing seconds to hours. This is especially important in relation to intraday power markets, in which the energy company has no prior knowledge of the electricity price. The financial gain in such markets is also potentially larger since they tend to be more volatile and thus resulting in larger spreads.

There is also another, quite important, difference between using the thermal buffer of buildings instead of storage tanks, and this is the installation and maintenance costs involved. The price for a storage tank is heavily dependent on the current price of steel. The total installation cost is more or less linear with the steel price for storage tanks up to about 50 MW, after which it increases even more since the added physical constraints of such large tanks require increased dimensions. A storage tank with a heat load of about 50 MW costs about 3 million EUR (3.9 million USD) while a corresponding system using active load control will cost approximately 1 million EUR (1.3 million USD). The maintenance cost is also substantially lower.

Another solution for spot price optimization is to increase the pressure head throughout the DHS, which enables the possibility of lower return temperatures in the primary flow network. Since this result in a higher temperature gradient in the production turbine, it is possible to get a higher output from the power generation. However, having excessively high pressure heads is expensive, and might also introduce other problems in relation to component behaviour. Performing load control, on the other hand, helps lower the primary return temperature without requiring higher pressure heads (Wernstedt, Johansson, & Wollerstrand, 2008). By coordinating this behaviour among a larger group of buildings it is possible to achieve a lowered temperature on average also.

During this study we have used simulation to evaluate the behaviour of the load control system. However, the products used to implement such systems exist on the market today, and have been extensively evaluated in previous work. This makes it possible for us to draw conclusions about the system limits in regards to the operational managing of heat load demand, which enables us to set realistic boundaries for the synchronization problem.

A basic problem with solutions such as the one proposed in this paper, is that if all parties active on the market used them it would obviously affect the outcome of the trading. In practice this is not a problem, since CHP represents a very small part of all power being traded on the open markets. In Sweden more than eighty percent of all power is produced by hydro power or nuclear power, while wind power, CHP and other marginal production types make up for the rest.
8.9 Conclusions

In this paper we have presented a model for finding an optimized synchronization between heat load demand and spot prices when using CHP. This is then implemented through active load control by using the thermal inertia within individual buildings. The model takes into account the specific boundary conditions present for individual production unit configurations in relation to operational limits of load control in individual buildings. This is done by using a market based auction process as a mediating interface between the buildings and the production units. Agent technology is used in order to implement this auction process. Each building is assigned an individual agent, which will try to maximize the load control while maintaining a sufficient level of QoS.

The results show clear financial incentives for implementing this type of technology, having a repayment time of less than two heating seasons. At the same time it is concluded that it is possible to achieve this without jeopardizing the QoS among the participating buildings.

The financial benefits of this technology are dependent on the spread of the spot prices, in relation to the boundary conditions in the system. But since this spread is normally quite large, even systems with tight dynamic boundaries will experience improved earnings.

8.10 Future work

Based on the flexibility of the agent based load control solution it is likely that the type of solution presented in this paper is appropriate for managing synchronization in relation to intraday power markets. Since the spot prices are not known in advance it places even more focus on high flexibility and the ability to quickly adjust the power production. A distinguishing factor of such intraday markets is their tendency to be very volatile with highly fluctuating prices, much more so than the normal day-ahead power markets. However, such an environment does place additional demands on the ability to evaluate projections of heat load demand as well as spot prices. Hence, further investigation and incorporation of such techniques in the present model should be a primary goal in the near future.

Another interesting venue is to further develop the optimization model in order to use dynamical sizing of the heat blocks. This would enable a closer correlation with individual consumers or groups of consumers, and would make possible a direct mathematical derivation between the entity instigating load control (i.e. the energy company) and the entity performing the load control (i.e. the building). It would also enable a route for quantifying the contribution of individual buildings when performing load control, in turn enabling a way to compensate building owners for letting the energy company use their resources.
8.11 Acknowledgement

We would like to thank Swedavia for letting us use operational data from the district heating system at Gothenburg Landvetter Airport.

Also we would like to thank the DHEMOS team for support when developing and adapting the simulation models used by DHEMOS.

Lastly we would like to thank NODA Intelligent Systems AB for support regarding server and data access during this project.
Chapter 9

Paper VIII - Smart heat grid on an intraday power market

District heating systems (DHS) is in many countries an important part of the heating infrastructure, especially in and around urban areas. Combined heat and power (CHP) production makes it possible to produce heat while simultaneously producing power. This combination helps maximize the energy efficiency in production, often reaching an 80-90% utilization level of the primary fuel, compared to around 30-50% in a traditional power plant. The heat produced in the CHP plant is used to heat the adjacent DHS, while the power is transferred and sold on the power market. The work presented in this paper relates to the Nord Pool Spot power market, which is the leading power market in Europe and one of the largest in the world. On Nord Pool Spot power is bought and sold based on hourly spot prices, facilitated by the primary day-ahead market and the supplementary balancing intraday market.

Since it is not possible to separate the physical process of producing heat and power in a CHP production facility, the energy company will want to synchronize high heat load production with high spot prices for power whenever possible. This can be done by using large storage tanks where heat is buffered during hours with high spot prices, while then distributed to the DHS as the heat load demand increases. However, such storage tanks are expensive to build and maintain, and they have limited operational dynamics. An alternative is to use the actual buildings connected to the DHS, in order to utilize their thermal inertia by the use of active load control.
This paper presents a multi-agent system (MAS) designed to bridge the information gap between energy companies and building owners in order to enable the use of system-wide active load control in order to synchronize heat load and spot prices. The presented scheme provides a self-regulating market analogy in which agents act to allocate load control resources. Each participating building is assigned a consumer agent, while each production unit is represented by a production agent. These agents interact on the market analogy which is in turn supervised by a market agent. The work in this paper is focused on the intraday market although the underpinning synchronization scheme is suitable for the day-ahead market as well as the intraday market. The results show considerable gains for participating entities when applying the presented strategy to the often volatile intraday spot price market.

9.1 Introduction

This work concerns the ability to use active load control in district heating systems (DHS) in order to maximize revenue from the power market when using combined heat and power generation. A district heating system consists of one or more production plants connected to a distribution pipe network which in turn is connected to heat exchanger substations at consumer buildings. Normally water is used as the energy transfer medium within the pipes, although some older systems use steam. Production units can use more or less any available boiler types, as long as they are able to heat the water or steam to sufficient levels. This makes it possible to use a wide range of primary fuels such as coal, oil, biogas or nuclear power and even makes it possible to utilize low or medium grade energy carriers such as peat, different types of biomass or waste heat from nearby industries. District heating is the predominant heating type in urban areas in northern and eastern parts of Europe including Russia and former Soviet countries, although the technology is present all around the world and gaining increased acceptance throughout North America and Asia (Constinescu, 2007).

A combined heat and power (CHP) plant produces electrical power as well as heat for the DHS. In a CHP plant water is boiled to steam which is in turn overheated to about 500-600 °C. The steam is then used to run a turbine, which in turn is connected to a generator which converts the mechanical energy to electrical energy. When the steam has passed through the turbine its pressure and temperature is decreased in a condenser unit which absorbs the heat from the steam and transfers it to the water medium in the district heating system. The condensed water (previously steam) is then led back to the original boiler in which the process is repeated. In a normal power plant the heat is normally emitted as waste heat in the turbine/generator process. By instead utilizing this heat a CHP plant is capable of achieving higher levels of energy efficiency.
in relation to the primary fuel (80-90%) than traditional power plants (30-50%) (Horlock, 2008). CHP plants are common in many DHS and when building new production plants CHP is many times the preferred choice of production, since its efficient use of primary energy makes the system financially and environmentally sound.

The power produced in a CHP plant is normally sold on a regional, national or international power market. The work described in this paper is related to the Nord Pool Spot power market which covers large parts of Northern Europe and which is one of the largest power markets in the world. However, the basic premises are similar for most de-regulated power markets, in that the prices are set based on a balance between supply and demand.

The Nord Pool Spot market is divided into two separate market parts, namely the day-ahead market (Elspot) and the intraday market (Elbas) (NordPoolSpot, 2012). The larger of the two is the day-ahead market through which the majority of all power is being bought and sold. Here power contracts are made for delivery the following day. The contracts cover hourly spot prices throughout the next day, and are published on the afternoon the day before. In addition to this there is also an intraday market which supplements the day-ahead market by securing the balance between supply and demand. Traditionally the intraday market has been used as a balancing market mechanism in order to bridge specific incidents such as unplanned operational stops in nuclear power plants. However, as more wind power production enters the grid, the need for intraday balancing increases. Wind power is undeniably a sustainable and environmentally desirable production type, but it is also somewhat unpredictable. A growing percentage of sustainable power production will thus only increase the importance of the intraday power market. The very nature of the intraday market makes for a higher volatility in price compared to the day-ahead market. It is this characteristic that makes the intraday market enticing for power market actors which have the ability to dynamically adapt and conform to that same volatility.

Load control is the ability to actively control the heat load in a DHS. This ability is what makes it possible for DHS operator to adapt to the changing conditions on an intraday market by dynamically rearranging the heat load demand among the consumer stations. A similar tool, albeit less flexible, is the use of storage tanks which can be charged and discharged according to changes in spot price instead of directly feeding the heat into the DHS. However, considering their limited operational dynamics, the use of storage tank based strategies is more suited for the day-ahead power market (Andrepont, 2012). Load control in DHS can be implemented either actively or passively. Passive load control tries to influence the consumers to act in certain ways, through the use of indirect methods such as differentiating heat load- or flow rates. Such methods are not guaranteed to work, i.e. a consumer might willingly choose to ignore to adapt
to current flow rates, or more likely, will not have the technical ability to do anything much the rate even if they wanted. Such methods are also much too inflexible for applications considered in relation to the dynamics of an intraday market. Active load control, on the other hand, provides a technical framework for performing instant heat load manipulation among the consumers.

Previous work has presented the basic centralized synchronization strategy for heat load and spot price management in relation to a basic day-ahead power market (C. Johansson, Wernstedt, & Davidsson, 2012a). The work described in this paper follows on that previous work by expanding the problem domain to encompass the entire energy system from a multi-agent system (MAS) perspective. Also, the more volatile, and thus potentially more profitable, intraday market is considered. In addition to this the MAS approach provides a framework for compensating the active consumer systems in relation to their actual level of participation. The system is evaluated through simulation experimentation.

9.2 Related work

Different strategies for using heat storage in order to improve operations are presented in (Wigbels, Böhm, & Sipilae, 2005) and (Rolfsman, 2003). The potential of using building mass as short term heat storage is quantified and described in (Olsson Ingvarsson & Werner, 2008). Further work on thermal mass in buildings is presented in (Hietmaki et al., 2003). All these works show consistently that substantial amounts of energy can be charged and discharged within the structure of individual buildings. In other words, due to the thermal inertia of buildings it is possible to manipulate the heat load demand of a building without affecting the indoor climate (Concrete for Energy Efficient Buildings The benefits of thermal mass, 2007).

Active load control for individual buildings has been studied since at least the early eighties, although the technical constraints of the hardware of that time limited the practical use of such systems. However, even those early works recognized the potential of the basic load control technique (Österlind, 1982). The importance of two-way communication in order to enable feedback throughout the system was also early established (Österlind, 1990).

The theoretical aspects of load control in district heating systems were studied in (Sipilä & Kärkkäinen, 2000), while a real-time industrial load control system was implemented and evaluated in (Wernstedt & Johansson, 2009) and (Wernstedt et al., 2008). Load control in electrical grids through the use of time-varying pricing is studied in (Newsham & Bowker, 2010). It is concluded that direct load control, in the sense of technology able to response to the pricing scheme, is imperative in order to attain desirable levels of response.

The heating and cooling behaviour of buildings have been studied in many
projects. Pre-cooling and demand limiting is studied extensively in (Xu, Haves, Piette, & Zagreus, 2006) and (Braun, 2003). The studies conclude that it is possible to improve demand responsiveness while maintaining acceptable comfort conditions. Heating control strategies are studied in (Björsell, n.d.). More adaptive learning algorithms for heating systems are presented in (Rogers, Maleki, Ghosh, & Jennings, 2011) and (Chahwane, Stephan, Wurtz, E., & Zuber, 2011). The common denominator of these systems is that they all directly or indirectly make use of the thermal inertia of buildings in order to streamline the heating or cooling demand in buildings.

As the control strategies become increasingly complex the desire to continuously evaluate the resulting thermal behaviour will become more apparent. This can be done either by simulation, sensor readings or by a combination of the two. A study of how to model the heat dynamics in a building using stochastic differential equations from a simulation perspective is presented in (Andersen et al., 2000). The impact of using real-time sensory equipment is evaluated in (C. Johansson et al., 2010a).

A theoretical MAS platform for load control in district heating systems has been previously described in (Wernstedt et al., 2007). Such a system has since been implemented in a real-time industrial setting which was described in [25]. The implemented system confirmed that the system was able to perform continuous load control schemes corresponding to substantial amounts of the total heat load. Later experiments with the same type of system have shown even greater ability to perform load control (C. Johansson, 2010).

The heat load in a DHS is mainly dependant on the outdoor temperature in combination with social behavior affecting tap water and ventilation. Several studies have been performed in regards to forecasting this behavior. Basic models relating to short-term heat load forecasting are presented in (Jonsson, 2002) and (Dotzauer, 2002). A seasonal autoregressive integrated moving average (SARIMA) process is presented in (Grosswindhager et al., 2011), while basic Box-Jenkins autoregressive integrated moving average (ARIMA) methods are presented in (Box & G.M., 1991). Further studies of such methods are presented in (Chramcov, Dostal, & Balate, 2009). A grey-box approach explicitly using climate measures to forecast heat consumption in a large geographical area is presented in (Nielsen & Madsen, 2006).

9.3 Multi-agent system overview

The general framework for the MAS consists of three different agent types interacting in order to achieve the overarching goal of maximizing profits in relation to CHP production while simultaneously ensuring sufficient levels of Quality of Service (QoS) among the participating buildings. The consumer agent is the
agent responsible for supervising and controlling the heat load at the individual consumer sub-stations. The producer agent calculates the need for active load control based on projections of the heat load demand in relation to current and future power spot prices. Finally the market agent is responsible for coordinating and allocating active load control among the consumer agent based on the requirements of the producer agent.

The different agents act according to their individual conditions and constraints, although they do hold certain knowledge in common throughout the MAS. The same weather forecast is normally shared among all the agents, although its perceived effect on the individual agents might differ. Historical data regarding the allocating process from the market agent is also freely available among the agents, as well as historical data regarding power market spot prices. Based on this it is possible for producer agents as well as consumer agents to calculate their own projections for spot prices and heat load demand, and hence devise strategies in order to further their individual goals. For a production agent this basically equates to selecting suitable valuation levels for load control and constructing allocation contracts considering an appropriate margin of error. Likewise, the goal for a consumer agent is to get paid as much as possible for performing current load control, while simultaneously maintaining a suitable preparation level for future load control and ensuring sufficient QoS.

9.3.1 Consumer agent

The consumer agent (CA) is responsible for maintaining an acceptable level of QoS while at the same time performing load control. These aspects are interconnected since a CA uses its internal QoS status as measurement of load control ability, and can thus only perform load control if the current levels of QoS allow it. In the context of this work QoS is related purely to the indoor temperature. In order to calculate the indoor temperature the CA uses an energy balance model, which in its most fundamental form is shown in equation 9.1.

\[
\Delta T_{in} = H_{in} - H_{out}
\]

where \( H_{in} \) is the total heat load being input into the building and \( H_{out} \) is the total amount of heat escaping the building. Any in-balance between these values will result in a non-zero \( \Delta T_{in} \), i.e. a change in the indoor temperature will occur. Such energy balance equations can be modelled arbitrarily complex. However, in order to adapt to limitations in the current hardware a model based on two temperature zones was developed. The model thus calculates one value for the indoor air temperature and one value for the average temperature of the climate shell of the building. Another issue with such energy balance models is
that they tend to require a large amount of well calibrated parameters, especially in relation to the $H_{out}$ part of the equation, which is exactly what is to be avoided in order to keep the model simple enough to use in practical settings in many buildings. The presented model is built around a traditional heat balance model, although it has been adapted to avoid this very problem. This has been achieved by translating the heat load balance from a physical model into a black box simulation model, in which certain parameters do not necessarily have any relation to actual physical counterparts. By locking parts of the equation and only letting certain parameters be variable it is possible to retain the characteristics of the original equation (calculating correctly), while simultaneously adding the previously lacking characteristics (ease of use). The resulting model is shown in equation 9.2.

$$
\begin{align*}
\Delta T_i &= (1.46 \times T2 \times (T_b - T_i) + 38.9 \times (T_o - T_i) + H_{in})/(T1 \times 1000000) \\
\Delta T_b &= (1.46 \times T2 \times (T_o - T_b) + 1.46 \times T2 \times (T_i - T_b) + (1 - V_s) \times H_{in})/45000000
\end{align*}
$$

where $T_i$, $T_b$ and $T_o$ are the indoor, building structure and outdoor temperatures. $H_{in}$ is the total heat load input into the building and $V_s$ is a state controlled adaptive variable used to adjust the behaviour of the model according to observations in regards to the recovery of temporary temperature fluctuations. The model is first and foremost designed to be used in relation to fast thermal processes; normally the temperature range is only a few degrees up and down and the simulation time frame at most a few hours. The steady state energy balance models which equation 9.2 originates from are generally poorly equipped to handle such transient behaviour. Due to constraints in regards to computationally complexity the model is not able to explicitly take into account the dynamically differentiating influence of the different modes of heat transfer, i.e. conduction, convection and radiation. Another aspect is the free heat load input from social behaviour, electric appliances or from outdoor climate variations, which is normally modelled by adding stochastic variables. This is also not feasible due to the added complexity involved in such a solution. In order to still get a good approximation of the observed behaviour the $V_s$ value was instead added into the model. The $V_s$ variable can be seen as a catalyst which changes the speed of reaction within the thermal process. The variable can only take two values, i.e. 0 and 1. The state evaluation is performed according to equation 9.3.

$$
f(T_w, T_i, T_e) = \begin{cases} 
1 & \text{if } T_w - T_i \leq T_e \\
0 & \text{if } T_w - T_i > T_e
\end{cases}
$$

139
where $T_w$ is the wanted indoor temperature, $T_i$ is the output indoor temperature and $T_e$ is the temperature offset produced by the heat load reductions in question.

In equation 9.2 only two simulation parameters need to be set, i.e. the $T_1$ and $T_2$ values. These can be derived from the energy signature and the time constant of the building in question by using equation 9.2. In contrast, the original version of the energy balance model requires several more simulation parameters, such as the area of the building, mass of the building, average heat capacity of the building structure, air flow throughout the building, mass of air inside the building and so on. The range of parameters has now been reduced to only two parameters. Finding actual values for and involve performing successive runs of steady state situations using equation 9.2 in order to tune the values in relation to the desired time constant and energy signature values. However, in order to make the use of Equation 9.2 more convenient a selection of building templates with pre-set $T_1$ and $T_2$ values are presented in table 9.1.

The error column in table 9.1 shows the errors in the $T_1$ and $T_2$ values. A value less than +/-1 is acceptable for $T_1$ whiles the error for $T_2$ should be zero. In order to actually perform load control the consumer agent has to have the ability to influence the heat load in the consumer substation. In the proposed system this is done through the use of a Linux based computer I/O platform which is connected between the existing control system and the outdoor temperature sensor. By manipulating the signal from the outdoor temperature sensor it is possible to adjust the behaviour of the existing control system while performing load control, e.g. by temporarily telling the control system that it is warmer outside than it really is, the system will decrease its heat load. Figure 9.1 shows a screenshot from the graphical user interface (GUI) from the I/O platform, which displays an instance of load control being performed in a consumer substation.

Table 9.1: Building templates

<table>
<thead>
<tr>
<th>E-sig [W]</th>
<th>T-Const [h]</th>
<th>T1</th>
<th>T2</th>
<th>err (T1/T2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>80</td>
<td>600</td>
<td>2686.4</td>
<td>0.11342/0</td>
</tr>
<tr>
<td>8000</td>
<td>80</td>
<td>2250</td>
<td>10905.5</td>
<td>-0.86813/0</td>
</tr>
<tr>
<td>14000</td>
<td>80</td>
<td>4350</td>
<td>19125</td>
<td>0.35476/0</td>
</tr>
<tr>
<td>2000</td>
<td>150</td>
<td>1080</td>
<td>2686.4</td>
<td>-0.50236/0</td>
</tr>
<tr>
<td>8000</td>
<td>150</td>
<td>4550</td>
<td>10905.5</td>
<td>0.051597/0</td>
</tr>
<tr>
<td>14000</td>
<td>150</td>
<td>8000</td>
<td>19125</td>
<td>0.097113/0</td>
</tr>
<tr>
<td>2000</td>
<td>250</td>
<td>1890</td>
<td>2686.4</td>
<td>0.056136/0</td>
</tr>
<tr>
<td>8000</td>
<td>250</td>
<td>7550</td>
<td>10905.5</td>
<td>-0.01603/0</td>
</tr>
<tr>
<td>14000</td>
<td>250</td>
<td>13200</td>
<td>19125</td>
<td>-0.03615/0</td>
</tr>
</tbody>
</table>
The top line in figure 9.1 shows the supply temperature in the radiator system of the building, while the second line from the top shows the return temperature in the radiator system. The third line from the top shows the indoor temperature. The fourth line from the top shows the difference between the supply and return temperature, which in combination with the current massflow of the fluid is a measurement of the energy being input into the building. The last two lines show the actual outdoor temperature and the manipulated outdoor temperature. Figure 9.2 shows the actual heat load reduction in kW from the same example as in figure 9.1.

In figure 9.1 and 9.2 it is clearly visible that the heat load is affected when load control is being performed. By only manipulating the outdoor temperature signal it is possible to install these types of systems relatively cheaply, since there is no need to change or re-configure the existing control system. This same I/O platform also comes equipped with a module for wireless communication. This is used in a mesh network for wireless indoor temperature sensors, which provides real-time feedback to the CA. This data can then be correlated with the indoor temperature resulting from the energy balance model. The energy balance model is needed since actual indoor temperature sensors provide very random input caused by social behaviour. However, they do provide important
9.3.2 Producer agent

The goal of the producer agent (PA) is to synchronize heat load demand in relation to high spot prices, thereby increasing the earnings when selling electricity on the intraday power market. In order to do this the PA needs to first calculate projections concerning future heat load demand and spot price development. These projections range at most one or two days into the future. The heat load demand is mainly dependent on the outdoor temperature although daily variations due to social behaviour also heavily influence the total heat load demand. The spot price development is more volatile although power shortages, and thus high spot prices, tend to congregate in a way which lends itself to statistical analysis.

The forecasting is done using a seasonal autoregressive integrated moving average (SARIMA) process which uses a dataset of historical operational sensor data in order to forecast future values. This strategy can be used for forecasting future heat load as well as spot price behavior. The basic idea about these types of forecast models is that there is some correlation between historical and future behavior, which on a macroscopic level mostly holds true for the systems in question. The intraday market spot prices normally increase during times of high demand, which in turn is due to predictable behavioral processes in society and industry. However, the most volatile occasions on the intraday market is caused by non-predictable events, e.g. emergency shutdowns in major production units. Although such events are hard to predict, a CHP-based DHS with active load control capabilities would still be able to quickly adapt to the situation once it becomes known.

Projecting the heat load demand in DHS is a major research field. Normally the heat load demand is formulated as shown in equation 9.4.

\[ Q_{\text{production}}(t) = Q_{\text{loss}} + \sum_i Q_{ci}(t + \pi_i(m)) \]  

(9.4)

Equation 9.4 says that the total heat load demand, \( Q_{\text{production}} \), is a combination of the heat losses in the distribution network, \( Q_{\text{loss}} \), and the combined heat load demand among all the customer sub-stations, \( Q_{ci} \). See related work for a full example of short-term heat load forecasting [29].

Using such projections of the heat load demand and the spot price development it is up to the PA to synchronize these. The goal of this process is to align the heat load demand with the high spot prices as far as possible. This is done by dividing the heat load demand into discrete parts and representing this in
matrix form. Based on this it is then possible to find an optimal solution to the synchronization problem by solving equation 9.5.

$$\max \sum_{i=0}^{m} \sum_{j=0}^{n} f(x_{i,j}) \cdot c_j$$  \hspace{1cm} (9.5)$$

where $x$ is a heat load matrix block and $c$ is a spot price array block. The cost function in equation 9.5 maximises the total earnings from sold power. This function is subject to a range of constraints detailing the boundaries regarding the operational dynamics of the production units and the QoS among the participating consumer agents. The formal description of this optimization process along with simple examples is provided in previous work [5].

Using the result of this synchronization the PA will not only obtain the desired heat load profile, it will also learn the monetary value of implementing the specific solution. Hence it is possible for the PA to put a price tag on each load control request. This value is used as the maximum price a PA is willing to pay to the consumer agents for having this specific load control implemented. A total load control request is shown in the screenshot in figure 9.3.

Figure 9.3: Load control request by a producer agent

Figure 9.3 shows load control requested by the producer agent. The top line shows the actual outdoor temperature in the area, while the line second from the top shows the outdoor temperature forecast. The straight line shows the heat load block while deviating from zero, while the line at the bottom shows the total available heat load buffer among all participating consumer agents. The weather forecast in relation to clouds and sunshine is displayed at the top of the screenshot.

Based on the synchronization solution the PA then builds load control contracts. A load control contract specifies the size of the load control to be performed [$W$], the old spot [$h$], the new spot [$h'$] and the maximum value for the spot expressed in a monetary value. In regards to this all time values are in
hours, i.e. a contract will always span one hour and the old and new spots refer to specific hours during the day.

The synchronization solution might specify that heat load demand should be moved both back and forth in during the day. This is accommodated in the contract structure by the old/new spot values. The old spot can be both before and after the new spot in time, although they must obviously always be in the future. This corresponds to charging and discharging the thermal buffer of the participating building structures. Figure 9.4 shows how heat load blocks are moved in order to synchronize with spot prices.

![Figure 9.4: Discharging and charging of heat load blocks](image)

Figure 9.4 shows discharging when moving a heat load block from A to B, in that the consumer substations first discharge while later charging the building structure. In this case a high spot price is expected in the B column. The second box shows charging when the heat load is increased during column D, and later decreased during column C. In practice the A block is moved to B, while C is moved to D.

### 9.3.3 Market agent

The market agent (MA) acts as a mediating layer between the participating agents. When the MA receives a load control contract by a PA it will start first divide the heat load block into smaller slots. This is done since normally no single consumer agent will control a big enough thermal buffer to implement the entire load control block itself. Thus it has to be coordinated among a group of consumer agents, each one being allotted a single slot of the whole block (see figure 9.5).
The MA will then allocate the slots among the consumer agents by using an auction process. A reverse Dutch auction is used in order to speed up the process. In a normal Dutch auction the seller will announce a starting price, and then continuously announce a lower price until a bidder will accept the price. Reversing this price is done by starting at a price close to zero and then continuously increasing the price until either a bidder accepts the price, or the price exceeds the maximum value set by the PA. The consumer agent who wins a slot will then get their heating bill lowered by the same amount as the winning price. After each auction the MA will publish the auction results.

### 9.4 Experimental set-up

The system-wide behaviour is evaluated through simulation using DHEMOS, which is an agent-based district heating simulation platform. In addition to this certain key aspects of the system were studied in industrial installations using the previously mentioned I/O platform. The operational constraints of these systems were then used as parameters for the simulation experimentation.

Different CHP system will have a different quota between produced heat and power. In this experiment we used 0.4 as quota, i.e. 0.4 MW power is produced for each MW heat produced. The operational data used in this study comes from the DHS of Landvetter Airport in Gothenburg, Sweden. The upper limit of the production unit is 8 MW, while the lower limit is set to 2 MW. Using a block size of 10% of the average heat load, this correlates to an upper limit of seventeen blocks and a lower limit of four blocks. The dynamic limit is five blocks, which means that the production cannot shift by more than five blocks from one hour.
The consumer agents have a QoS limit of 0.5 °C, which means that the indoor temperature calculated by their internal energy balance model is not allowed to deviate more than 0.5 °C from the wanted indoor temperature. The wanted indoor temperature for all consumer agents is 21 °C in this study, but this can be set individually. In all there are twenty consumer agents in this system.

The optimization model was implemented using Octave 3.2.3, while the simulation experimentation used DHEMOS. Both systems were run on a Linux/Ubuntu 11.10 computer with Intel Core i5 CPU with 4 GB of RAM.

### 9.5 Results

Figure 9.6 shows the projected heat load demand in the district heating system before and after the synchronization process.

![Heat load demand](image)

**Figure 9.6: Heat load demand, before (continuous) and after (dotted) synchronization**

In figure 9.6 it is clear to see were the high spot prices are occurring. This closely correlates to the data in figure 9.7 showing the intraday spot prices.

Figure 9.8 shows the indoor temperature according to the energy balance model in one of the participating consumer agents. It is clearly shown that the energy balance shifts as the consumer agent tries to match the charging and discharging requested by the producer agent.
Figure 9.7: Hourly spot prices on the intraday market

Figure 9.8: Indoor temperature according to energy balance model
Figure 9.9 shows status of the same consumer agent in relation to its QoS level. A QoS level of 100% indicates an indoor temperature at the wanted level. Any deviation from this, up or down, will result in decreased QoS.

The gross financial earnings for the production agent in relation to selling electrical power were 835 in the reference case while being 1610 in the optimized case. The difference is 775. These earnings refer to one day of operation. The 775 is not a net profit for the production agent since it has to use part of this to pay consumer agents for performing load control. The amount required by the consumer agents is obviously dependant on the strategies involved, but during this study between 10-30% of the difference was used to pay consumer agents. The more consumer agents participating in the auction the less they will get for each load control slot, since competition among them tends to lower the price.

9.6 Discussion

The dynamic behaviour shown here is not easily achievable for most other entities present on the power market, such as nuclear, wind or hydro power. Also CHP production is normally not a very large part of the total power production on a power market, e.g. in Sweden only about 5% of the total power production is generated through CHP. So even if all CHP plants would coordinate behaviour similar to that described in this paper, it would not be enough to upset the fundamental balancing market mechanisms.
Even using a synchronization scheme such as the one proposed in this paper, it would probably not be preferable to commit all power production to the intraday market, since there is a chance that the market will be balanced due to the day-ahead market. Therefore a strategy which combines day-ahead and intraday power is advisable. The specifics of such a strategy, however, are outside the scope of this paper. Although, one might presume that such a strategy would have to take into consideration the composition and operational behaviour of the entire power market upon which it acts, e.g. a higher degree of wind power might imply a higher dependency on intraday market balancing.

In this work we have used a reverse Dutch sealed-bid auction in order to allocate the heat load among the participating consumer agents. The reason for using an auction process to settle the load control allocation is that it cannot be certain that consumer agents are cooperative; in fact the opposite is most likely true most of the time. Therefore we must use some mechanism in order to separate the competing consumer entities. On the other hand, in an all-cooperative energy system there would be no need for an auction process at all, since the optimal prices could be computed centrally as in (C. Johansson et al., 2012a). Another good thing about this type of auction is that it strategically equivalent to a first-price sealed-bid auction, in that no relevant information is revealed during the auction process. This is advantageous in relation to the transparency and simplicity of the market agent. Technically there is no reason why any agent shouldn't be able to perform the task of the market agent. In practice however, it might be desirable to have a stand-alone entity to handle the coordination and allocation of load control. In a de-regulated district energy market it is important that such components are transparent in order to create trust in their function. The individual consumer and production agents are then free to implement whatever strategy they deem prudent in order to further their individual goals. Also having a stand-alone market agent provides for competing groups among production agents in third-party-access networks or competing coalitions among consumer agents belonging to different building owners.

There are obvious financial advantages in using such a system for energy companies as well as building owners. However, there is still a question of who should pay for the installation and operation of the hardware and software required to make it work. It might be argued that the energy company or distribution company should do this, since they would then be able to continuously amortize the cost by including this is the on-going valuation process when requesting heat load contracts. The system used in this study costs about 1000 to install per consumer sub-station, which in the DHS in question will lead to a cost of about 20000. Considering the potential earnings this is still amortized within one heating season.
9.7 Conclusions

In this paper we present and evaluate a framework for implementing basic smart heat grid technology in a district heating network. The system is evaluated through simulation experimentation based on operational constraints from an industrial installation. Models for all participating agent types are presented.

The results show obvious financial advantages when using this type of technology in district heating systems. It is also shown that these results are possible to achieve without jeopardizing the QoS among the participating consumer buildings.

Since the financial gain of this system is related to the spread between the highest and lowest spot prices it is convenient to use on an intraday market since these tend to be more volatile.

9.8 Future work

Future work will involve tuning the participating agents in order to improve their strategies in relation to the auction and forecasting processes.

Another next step is obviously also to implement and evaluate similar behaviour on a system-wide scale in a real system. During 2012 such an installation will be done in the DHS from which we received the operational data used in the simulation experimentation for this study.

9.9 Acknowledgement

Our thanks to Swedavia for letting us use operational data from the district heating system at Gothenburg Landvetter airport.
Chapter 10

Paper IX - N-dimensional fault detection and operational analysis with performance metrics

A district heating consumer substation is a complex entity, consisting of a range of interacting components such as valves, pumps, heat exchangers and control systems. The energy efficiency of a consumer sub-station is dependent on several things, e.g. settings of the control system, dimensions and operational behaviour of hardware and accumulation of sediments in the heat exchanger. Visualizing this operational functionality of consumer substations has been studied in several previous projects.

This paper addresses certain shortcomings inherent in those previous works by presenting a novel visualization approach using parallel coordinates and scatter plot matrices. A comparison between these and previous visualization techniques is presented and discussed. Furthermore, the paper presents a scheme for statistical analysis based on n-dimensional relationships found in parallel coordinates and scatter plot matrices, thus providing key performance indicators appropriate for large-scale detection and analysis. It is shown that the presented visualization techniques are at least equal to previous attempts in regards to fault detection and operational analysis, while simultaneously addressing several of their shortcomings. Furthermore, it is shown that the subsequent statistical analysis provides a workable starting point for system-wide fault detection and analysis within any district heating system.
10.1 Introduction

Faulty hardware such as pumps and valves or soil accumulation within the heat exchanger can, and most likely will, result in deteriorating operational behaviour and can over time cause substantial financial damage. Furthermore, substandard operational behaviour in a consumer substation not only affects the individual building but might also influence the district heating system as a whole, e.g. causing increased primary return temperatures. Thus, there is incentive for both property owners and energy companies to detect faults and deviating operational behaviour as well as arranging for possible repair and readjustment.

Fault detection in consumer substations have been studied extensively in previous work, and a range of different approaches in regards to fault detection have been presented and evaluated. An interesting fault detection scheme which has been previously presented is fault detection using contour mapping. Contour mapping visualizes primary return temperatures and mass flow in relation to time and outdoor temperature. By using contour mapping it is possible to visualize large amounts of operational data in a single figure, which greatly streamlines the practical analysis process. However, contour mapping does retain some issues regarding computational load during generation, susceptibility to errors during the extra-/intrapolation process, subjectivity during evaluation phase resulting in lack of automation potential and being confined to the three-dimensionality present in maps. This paper studies these problems and compares contour mapping to other visualization techniques, namely parallel coordinates and scatter plot matrices. Furthermore the paper studies the potential for extended performance metrics analysis using statistical techniques in order to facilitate large-scale analysis. Specifically the problem of analysing the relationships between different variables is studied. Also, outlier detection is discussed and a technique for automated outlier management is presented.

10.2 Related work

Fault detection and operational analysis in consumer substations have been the focus of much research for many years. Previous work has shown the potential inherent in analysing collected data, and has also presented work-flow overviews of the process as in (Råberger & Wallentun, 1996) and (Wallentun, 1999). The basic idea has been to find a way to prioritize between all consumer substations present in a district heating system in order to pin-point substations with technical, and by extension financially, sub-optimal behaviour. These papers study the functionality and quality of service as well as the efficiency of the substation.

Similar work is presented in (Pakanen, Hyvärinen, Kuismin, & Ahonen, 1996) which investigate five different methods for fault diagnosis in consumer substa-
tions. This paper uses similar data analysis as well as simulation and modelling of components within the substation.

Further work is presented in (Yliniemi, 2005) which focus on fault detection by using data available through the heat meter, i.e. temperatures and mass flow on the primary side of the substation. Furthermore, this paper evaluates the possibilities for separating hot water energy consumption in relation to the total district heating usage. It is becoming increasingly common that energy companies use hourly measurement data collected from the heat meter. This obviously increases the size of the dataset which in turn increases the need for automated analysis methods. In (A. Johansson, 2005) two methods for identifying incorrect measurement data are presented. The first method is based on a simulation model which uses historical data in order to estimate feasible datasets. The second method is based on a statistical model which correlates operational data among consumers with similar consumption behaviour.

The problem of analysing the increasing amounts of data was further studied in (Selinder & Wallentun, 2002). Previous work was focused on detecting faults, while this paper presented a way to visualize the data through the use of contour mapping in order to facilitate the fault identification process. This work was later extended in (Lindkvist, Selinder, & Wallentun, 2005) which aimed to increase the efficiency of the process.

In (Lindkvist et al., 2005) it was shown that energy companies already working with process supervision were facing severe problems due to increasing amounts of data. This problem is in no way limited to district heating systems. The problem of visualizing large amounts of data is studied in the scientific fields of scientific visualization and information visualization. Scientific visualization deals with data that have correspondence in physical space, whereas information visualization deals with visualization of abstract data that do not necessarily have a relation to the physical world (Nielson, Hagen, & Muller, 1997). The main idea is to amplify cognition by using visual artefacts. In (Jacobson, 1999) the process of understanding data is described thoroughly through the continuum of understanding. This continuum is defined as starting with data, which are entities which in themselves lack any meaning. An example of data might be a temperature reading from a substation. The second step of the continuum is information, where the data is processed, organized or otherwise presented. An example would be to sort the temperature data in relation to time or other measurement data. The third step is knowledge, where the information provided through the previous step is understood through experience in regards to the process in question. The fourth and final step is wisdom, in which an advanced level of understanding of the underlying processes makes it possible to express qualified judgement.

In order to manage the large amounts of data generated within modern district
heating system it is imperative that the technical analysis systems used transcend from the first step of data presentation to the second and third step of information and knowledge presentation.

10.3 N-dimensional analysis

A consumer substation is a pseudo-chaotic system in that it is largely predictable from a macroscopic viewpoint, while being highly stochastic on a microscopic level. This basically means that even if it is impossible to predict when individual people will, for example, take a shower and thus activating hot water usage, it is possible to predict that the building will on average increase its energy utilization as the outdoor temperature drops. In this paper we are interested in the operational behaviour on a macroscopic scale as an average of the function of the consumer substation in question.

The sensory equipment in a consumer substation provides a wealth of measurement data. On the primary side the heat meter will measure the supply and return temperature as well as the mass flow which is available to the energy company for billing purposes. Many modern control systems provide facilities for measuring and saving data on the secondary side of the substation, e.g. supply and return temperatures in the heating system. In addition to this many building owners have installed systems for measuring and collecting indoor temperature data. All information contained in this dataset represents the operational status of the substation and building.

By examining these variables and how they relate to each other it is possible to evaluate the status of the substation. In \( n \)-dimensional analysis the relationships between these different variables are studied. In contour maps these relationships are visualized in a map where \( n = 3 \), i.e. outdoor temperature, hour and return temperature or mass flow. This is done in order to study the relationship between these three variables, since they have to be put in relation to each other in order to make sense. In contour mapping the purpose is actually to do a \( n = 4 \) analysis. Since contour maps cannot represent more than three dimensions, two contour maps have to be made which are then subjectively compared.

Using such methods it is possible to evaluate the relationships, such as how the return temperature changes in relation to mass flow fluctuations during different times of day and outdoor temperatures. It is the relationship between these variables which are important for the analysis, and not the variables themselves.
10.4 Outliers

An outlier is a measurement which is numerically far apart from the main body of data. Outliers can have many reasons in general, although in relation to a consumer substation they are mostly caused by measurement errors. Outliers have a tendency to distort visualization efforts and disturb analytical analysis, which makes it important to properly manage them. It is not uncommon for outliers to be present in operational measurement data. If this data is used in an automated analysis or control process, these outliers must not only be detected, but also somehow managed and possibly removed. Algorithmically rejecting outliers is sometimes not considered good scientific practice. However, it can be argued that it is appropriate in cases where the error distribution is known within some confidence. For example, in the case of a consumer substation it might be considered safe to assume that certain mass flow levels or temperature variations must be measurement errors.

10.5 Parallel coordinates and scatter plot matrices

Parallel coordinates is a visualization technique in which every attribute corresponds to a vertical axis (Mazza, 2009). These axes are arranged in parallel by equal distance. The relationships between the variables are shown as lines from one axis to another. Parallel coordinates is a powerful tool for evaluating the correlation between large groups of variables. There are two main management tools for parallel coordinates which are present in most visualization software packages. The first tool is the ability to re-order the axes, which makes it possible to arrange variables in suitable order to ease the study of their relationships. The other tool is brushing, were certain intervals of a variable can be chosen. This makes it easy to follow the relationship among the entire set of variables. The figure shows parallel coordinates with and without brushing (Fig. 10.1). The brushing is done on the outdoor temperature variable at an interval around 4-4.5°C.

A scatter plot matrix is an extension of the common 2-dimensional scatter plot (Mazza, 2009). A single scatter plot is obviously restricted to two dimensions, but by arranging scatter plots side by side in a matrix form it is possible to extend the dimensionality. This will result in an $n$ by $n$ matrix, where $n$ equals the number of variables being studied.
10.6 Performance metrics

The mean, median and standard deviation is the starting point for the performance metric analysis. These values form a foundation for much of the metrics described in this paper and are further described in (Råde & Westergren, 2004).

The mean is simply the average of the dataset in question, i.e. given a set of data \( x_1, \ldots, x_n \), the arithmetic mean \( \bar{x} \) is defined as in equation 10.1.

\[
\bar{x} = \frac{x_1 + x_2 + \ldots + x_n}{n} = \frac{1}{n} \sum_{i=1}^{n} x_i
\]  

(10.1)

For a dataset with an odd number of observations the median \( m \) is defined as shown in equation 10.2.

\[
m := \left( \frac{n+1}{2} \right) \text{th value}
\]  

(10.2)

With an even number of values \( m \) is defined as shown in equation 10.3.

\[
m := \left[ \left( \frac{n}{2} \right) \text{th value} + \left( \left( \frac{n}{2} \right) + 1 \right) \text{th value} \right] / 2
\]  

(10.3)

The standard deviation \( \sigma \) is defined as shown in equation 10.4. The part under the square root sign is the variance of the data.

\[
\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}
\]  

(10.4)
Tests for outliers are normally based on an assumption that the dataset has a bell-shaped probability density function, i.e. that the data follows a Gaussian distribution. In regards to consumer substation data this implies that the dataset to test for outliers should not be the entire dataset, but rather a series of filtered subsets of this. The reason for this is that a Gaussian density function assumes a univariate dependency. For example, if return temperature sensory data is collected throughout a heating season this dataset will not have a univariate dependency since the return temperature changes in relation to other variables such as the mass flow which in turn is dependent on other variables such as the outdoor temperature, thereby giving the dataset a multivariate dependency. In order to perform analytical outlier detection the data should therefore be sorted into subsets with univariate dependency, e.g. in the case of the return temperature the data might be ordered in relation to intervals of outdoor temperature and hour of the day. Incidentally this is exactly what is done during contour mapping, indicating the relationship between these techniques. However in the case of analytical performance metrics the resulting data is easier to evaluate since it is presented as an objective numerical value instead of a map-like display open to subjective interpretation.

The mean alone cannot be used to find outliers since it is not robust (Rousseeuw & Leroy, 2003). However, the quota between the mean and median can be used as a simple outlier detection metric. One problem with this quota metric is that is relative to the type of dataset in question, e.g. the quota confidence interval for the primary return temperature is different from the mass flow quota interval. Furthermore, this metric is sensitive to the amount of outliers present. However, based on its computational simplicity it can still be used to rank the content of large datasets. Other, slightly more complex, metrics include Chauvenets criterion, Peirces criterion or Grubbs test for outliers (Taylor, 1997).

Chauvenets criterion uses $\bar{x}$ and $\sigma$. First the difference between the data point and $\bar{x}$ is compared to the size of $\sigma$. This value is then used to estimate the probability of this data point occurring in relation to the data distribution. Based on this probability the statistic value can be calculated. If the statistic value is less than 0.5 the data point is tagged as an outlier according to Chauvenets criterion. The value of 0.5 implies a Gaussian function with $\sigma^2 = 1$. In this paper a lower value is used (0.1) which implies $\sigma^2 > 1$. This is an adjustment to empirical observation which has shown that the dataset in question normally follows a Gaussian distribution with larger standard deviation.

A critical aspect of performance metric analysis is to evaluate the strength of the relationship between two or more variables, in order to identify faults and operational status. Such correlation analysis is normally performed by using multiple regression procedures. In its simplest form this is the 2-dimensional example, which can be visualized through a scatter plot and formally represented
as in equation 10.5.

\[ Y = a + bX \]  \hspace{1cm} (10.5)

However, this can easily be extended into n-dimensional space using a linear equation of the form shown in equation 10.6.

\[ Y = a + b_1X_1 + b_2X_2 + \ldots + b_nX_n \]  \hspace{1cm} (10.6)

The basic idea is to analytically evaluate the relationships between variables such as return temperature, mass flow, outdoor temperature and time of day.

The issue with multivariate dependency is equally important regarding operational analysis, especially since the multiple correlation process is not commutative. This means that the order in which the different variables are compared matters. In order to extend the visualization techniques into a performance metric the data is first sorted and intra/extrapolated in regards to time of day and outdoor temperature. The resulting matrix can then be intersected across outdoor temperature intervals and evaluated through correlation techniques. In this paper we use the Pearson correlation coefficient to evaluate the relationship between variables (Rodgers & Nicewander, 1988). The Pearson correlation coefficient is a value between +1 and -1, showing the relationship between variables. The Pearson correlation coefficient is described as shown in equation 10.7.

\[ r = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}} \]  \hspace{1cm} (10.7)

10.7 Results

Comparing visualization techniques is a highly subjective process, although scientific rigor can be achieved through standardized statistical analysis of empirical research (Bederson & Schneiderman, 2003). In this paper we compare two consumer substations (A and B) using (i) contour mapping, (ii) parallel coordinates together with scatter plot matrices and (iii) analytically calculated performance metrics. A third consumer substation (C) is also studied on the basis that the data-set contains known outliers. The evaluation of (i) and (ii) are obviously somewhat subjective. However, the inclusion of (iii) provides an analytical basis for comparison.

All these three consumer substations are similar in basic technical set-up in order to minimize extraneous influences. Furthermore, they all have similar tap water usage profiles.
All temperature values are shown in °C, while all mass flow values are shown in kg/hour.

10.7.1 Operational analysis

The operational status of substations A and B is such that A is considered to be functioning well, while B is showing clear signs of soil accumulation within its heat exchanger. The relation between primary return temperature and mass flow in substation A is visualized using contour mapping (Fig. 10.2). In the figure it is easy to see that increased mass flow is correlated with decreasing return temperatures, which is to be expected in a normally functioning substation.

Figure 10.2: Contour maps with return temperature (left) and mass flow (right) in substation A

The dataset from substation B is then visualized using the same technique (Fig. 10.3).

Figure 10.3: Contour maps with return temperature (left) and mass flow (right) in substation B

In figure 10.3 it is apparent that the relationship between the return temperature and the mass flow are reversed compared to figure 10.2. The heat exchanger
isn’t able to cool off the water flowing through it as the mass flow increases, which implies some level of soil accumulation.

The dataset from substation A is then visualized through the use of parallel coordinates and scatter plot matrices (Fig. 10.4).

Figure 10.4: Parallel coordinates and scatter plot matrix for substation A

The data has been brushed in relation to an area of mass flow data in order to visualize the relationship within the three other dimensions showing return temperature, outdoor temperature and time of day. The corresponding visualization is also done regarding substation B (Fig. 10.5).

Figure 10.5: Parallel coordinates and scatter plot matrix for substation B

Comparing figure 10.4 and 10.5 it is apparent that the former has a more pronounced inverse relationship between mass flow and return temperatures. The scatter plot matrix help establish the distribution of these relationships. By further brushing it is possible to follow the relationships between the four variables.

The same datasets from substation A and B are then evaluated using performance metrics in order to identify and quantify the relationships visualized through contour mapping and parallel coordinates together with scatter plot matrices. The resulting values are shown in table 10.1.

160
Table 10.1: Operational analysis using performance metrics

<table>
<thead>
<tr>
<th></th>
<th>A-ret</th>
<th>A-flow</th>
<th>B-ret</th>
<th>B-flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>55.09</td>
<td>10120</td>
<td>63</td>
<td>2947.5</td>
</tr>
<tr>
<td>Min</td>
<td>26.9</td>
<td>415</td>
<td>27.5</td>
<td>36.167</td>
</tr>
<tr>
<td>Mean</td>
<td>43.763</td>
<td>3040.4</td>
<td>38.79</td>
<td>928.8</td>
</tr>
<tr>
<td>Median</td>
<td>43.802</td>
<td>2820</td>
<td>38.17</td>
<td>888.5</td>
</tr>
<tr>
<td>Pearson</td>
<td>-0.66</td>
<td>-0.66</td>
<td>0.86</td>
<td>0.86</td>
</tr>
</tbody>
</table>

The performance metrics in table 10.1 provides numerical values to the relationship between the return temperature and the mass flow. Using visualization techniques it is only possible to subjectively identify this relationship, without providing an absolute frame of reference for it. In the data it is clear that substation A is functioning better than B, since there should be a negative relationship between these two variables, i.e. when the mass flow increases the return temperature should decrease.

### 10.7.2 Outlier detection

The dataset from substation C contain erroneous data in the form of severe measurement errors. It is obvious that the contour mapping becomes heavily distorted when such outliers are present (Fig. 10.6).

![Figure 10.6: Outliers in contour maps](image)

Likewise, it is easy to identify the outliers using parallel coordinates and scatter plot matrices (Fig. 10.7).

Even without brushing it is easy to identify the outliers in the parallel coordinates, and the scatter plot matrix display a distinct compression of the main dataset due to the presence of these outliers. However, for clarity the three outliers are brushed in relation to primary return temperature.

Even though these visualization techniques provide an obvious way to identify
Unlike contour mapping and parallel coordinates with scatter plot matrices, performance metrics provide a way to not only numerically quantify the outliers but also to remove them. Using Chauvenets criterion the first outlier detected in the return temperature data results in a value of about 0.000000000003818 which is far less than 0.1, which clearly marks it as a spurious outlier. The value should in fact be even less since the data point actually has a deviation of, however Matlab/Octave has problems calculating deviations less than due to the infinitely small numbers involved. As the actual value of this data point is in fact 13395°C it can safely be concluded that this must be a measurement error. Similarly the first outlier found in the mass flow data is also marked as an outlier due to the fact that it is showing a mass flow of 134180 kg/hour. This mass flow value, as well as the return temperature value, is obviously a spurious outlier considering the physical constraints of a normal consumer substation. After removal of the detected outliers, Chauvenets criterion is iterated until no further outliers are found. The starting and final values of this process in relation to the return temperature data is shown in Table 2.

The same dataset was then analysed in relation to the mass flow data, which is shown in Table 10.3.

In total three outliers were found in the data set using performance metrics. By iteratively identifying and removing these, the statistical relevance of the data was greatly increased.

### 10.8 Discussion

The dataset in the presented analysis only make use of measurements collected through the heat meter. There is obviously a lot of other data that might be
Table 10.2: Outlier detection using performance metrics in relation to return temperature data

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>53.23</td>
<td>47.62</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>246.48</td>
<td>4.82</td>
</tr>
<tr>
<td>Outlier (max)</td>
<td>13395</td>
<td>68.2</td>
</tr>
<tr>
<td>Outlier (mean)</td>
<td>13341.77</td>
<td>20.58</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>54.13</td>
<td>4.27</td>
</tr>
<tr>
<td>Probability</td>
<td>1.22e-15</td>
<td>1e-4</td>
</tr>
<tr>
<td>Data points</td>
<td>3127</td>
<td>3124</td>
</tr>
<tr>
<td>Chauvenet’s value</td>
<td>3.82e-12</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Table 10.3: Outlier detection using performance metrics in relation to mass flow data

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>735.65</td>
<td>693.02</td>
</tr>
<tr>
<td>Standard deviation</td>
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<td>241.88</td>
</tr>
<tr>
<td>Outlier (max)</td>
<td>134180</td>
<td>1749.2</td>
</tr>
<tr>
<td>Outlier (mean)</td>
<td>133444.35</td>
<td>1056.18</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>182.4</td>
<td>2.52</td>
</tr>
<tr>
<td>Probability</td>
<td>1.22e-15</td>
<td>0.045</td>
</tr>
<tr>
<td>Data points</td>
<td>3127</td>
<td>3124</td>
</tr>
<tr>
<td>Chauvenet’s value</td>
<td>3.82e-12</td>
<td>140.58</td>
</tr>
</tbody>
</table>
interesting to include in the analysis, such as indoor temperatures, heating system data or tap water usage. The reason that only data from the heat meter is used is simply because this data is readily available to the energy company.

It should be noted that contour maps and parallel coordinates differ in one important regard. A contour map requires extra-/interpolation in order to work. This is due to the fact that array structures are turned into matrices. This not only requires considerable amount of computing power, but is also prone to error since no existing algorithm can guarantee truth. On the other hand, a visualization solution based on parallel coordinates will only use the unspoiled raw data set.

The main advantage of using parallel coordinates and scatter plot matrices compared to contour maps is that they facilitate the study of multivariate relationships in one visualization artefact. The importance of this only increases as more variables are introduced into the analysis.

An important aspect of parallel coordinates is the use of brushing. Contour mapping requires no such manipulation during use since they are fixed. However, it can be argued that this is actually an advantage for parallel coordinates since it facilities the possibility to angle the visualization in the desired direction and to compare and highlight different aspects of the dataset.

In regards to visualization contour maps have an advantage in that they are related to the time of day over the x-axis, which might make it more directly accessible. Brushing has to be used in order to analyze hourly dependencies using parallel coordinates. This might be done by brushing high mass flow values and studying their relationship with the hour-data. With scatter plot matrices this process is easier since the row of matrices relating to hours basically correlates to a contour map.

It can be noted that contour maps as well as parallel coordinates and scatter plot matrices are sensitive to outliers. Statistically this is due to compression of the dataset, which causes heavy distortion when visualized. Using performance metrics outliers will instead result in different numerical values which serve to not only to identify the presence of outliers but also facilitate their ranking and possible removal.

Given a group of consumer substations it is easier to evaluate their operational status using a list of sorted numbers than maps or graphs. This supports the conclusion that performance metrics are superior to visualization techniques when evaluating larger groups of substations, and certainly if the evaluation process is to be automated.
10.9 Conclusions

In this paper we have compared contour mapping with parallel coordinates and scatter plot matrices in relation to fault detection and operational analysis in consumer substations within a district heating system. It is shown that the same operational relationships can be visualized using parallel coordinates and scatter plot matrices as in contour mapping, while at the same time decreasing the computational complexity and error sensitivity and enhancing the multivariate analysis.

We have also studied the possibilities of using performance metrics as a basis for large-scale operational analysis within district heating systems. Performance metrics is an extension of the previously discussed visualization techniques in that they remove the need for subjective interpretation. It is shown that such statistical analysis is able to detect, identify and analytically evaluate the same relationships studied in relation to the visualization techniques.

10.10 Future work

The focus of this paper was to study data collected through the heat meter. In the future other data will be included in the analysis in order to develop a complete model of the operational status, not only of the consumer substation, but rather the whole building in relation to indoor climate and energy saving measures. This work is expected to intensify as the amount of available data increases through progress in communication and sensory equipment (Gustafsson, 2011).

Furthermore, the performance metrics analysis will be extended and enhanced in order to facilitate large-scale fault detection and operational analysis. As the operational constraints harden for most energy companies it becomes increasingly interesting for them to help building-owners manage their consumer substations as smoothly as possible.

10.11 Acknowledgement

The authors would like to thank Dr. Stefan Axelsson at Blekinge Institute of Technology for valuable discussions regarding visualization techniques.

We thank NODA Intelligent Systems AB for the use of operational data.
Chapter 11

Paper X - Distributed thermal storage using multiagent systems

Thermal storage is an essential concept within many energy systems. Such storage is generally used in order to smooth out the time lag between the acquisition and the use of energy, for example by using heat water tanks within heating systems. In this work we use a multi-agent system in order to maintain and operate distributed thermal storage among a large group of buildings in a district heating system. There are several financial and environmental benefits of using such a system, such as avoiding peak load production, optimizing combined heat and power strategies and achieving general energy efficiency within the network.

Normally a district heating system is purely demand driven, resulting in poor operational characteristics on a system wide scale. However, by using the thermal inertia of buildings it is possible to manage and coordinate the heat load among a large group of buildings in order to implement supply driven operational strategies. This results in increased possibilities to optimize the production mix from financial and environmental aspects.

In this paper we present a multi-agent system which combines the thermal storage capacities within buildings in relation to production optimization strategies. The agent system consist of producer agents responsible for valuing the necessary heat load management, consumer agents managing the quality of service in individual buildings while consenting to participate in heat load management and a market agent acting as a mediating layer between the producer and consumer agents. The market agent uses an auction-like process in order to coordinate the
heat load management among the consumer agents, while the producer agents use load forecasting in order to evaluate the need for heat load management at any given point in time. A consumer agent uses continuous feedback regarding indoor climate in order to uphold quality of service while participating in heat load management.

Real-time data from a district heating system in Sweden is used in order to evaluate the agent system in relation to operational peak load management. The results show clear financial and environmental gains for the producer as well as participating consumers.

11.1 Introduction

This paper describes a multi-agent system used in order to improve the operational management of a district heating system in relation to financial and environmental aspects. District heating and cooling is an integrated part of the energy infrastructure in many countries. This is especially true in Northern and Eastern Europe, although district heating and cooling is growing rapidly in popularity around the world [1]. A district heating system consists of one or more production units which distribute heated water or steam throughout a pipe network. Buildings are then connected to this network, usually through the means of heat exchangers which transfer the heat to the heating- and tap water system in the building. District heating systems are often considered environmentally and financially sound, since the centralized set-up facilitates large scale energy efficiency schemes. More or less any type of production units can be used in a district heating system, and the fuels used range from biomass and industrial waste heat to coal and oil. Many district heating systems also make use of combined heat and power production (CHP) which have a very high level of utilization of the primary fuel used [2]. A CHP plant produces electrical power at the same time as it heats the water for the district heating system. First water is boiled into steam which is used in order to run a turbine, which in turn is connected to a generator which converts the mechanical energy to electrical energy. Afterwards the steam is passed through a condensing unit which transfers the heat to the district heating system. As the steam cools off it can be re-heated before being passed into the turbine again. A traditional power plant has an energy efficiency of about 30-50%, while a CHP plant utilizes about 80-90% of the primary fuel. The electricity produced in the CHP plant is then sold on the power market while the heat is being sold within the connected district heating system.

Normally a district heating system is purely demand driven, in the sense that the production units can only react to the current heat demand within the network. The bulk of the heat demand consist of demand for building heating, although substantial heat load peaks are also generated by social patterns in
relation to tap water usage. The heating demand in a building is correlated to the outdoor temperature, while tap water usage is more correlated to time of day. This combination of outdoor temperature dependencies and social behaviour over the day causes fluctuations in the heat demand. Such fluctuations or heat load peaks are very undesirable for a number of reasons. Most district heating systems have a production set-up using some sort of base load boilers which are complemented with a range of peak load boilers. The base load boilers are often fuelled by cheap and environmentally friendly fuels such as biomass or industrial waste heat, while the peak load boilers normally use fossil fuels such as oil or gas which are not only expensive but also generate undesirable emissions.

In this paper we describe a multi-agent system which uses the thermal inertia of buildings in order to manage the heat load demand in relation to the operational status at the production units. By managing the demand in such a way it is possible to make the district heating system more supply driven, i.e. it is possible to optimize the heat load usage in relation to the production status and not only the other way around. This is similar to using large storage tanks, although here the thermal inertia of the connected buildings is used as a distributed storage instead. By using such a set-up it is possible to shed heat load peaks in order to avoid using peak load boilers, or to move the heat load peaks in time in order to coordinate the heat load peaks with high spot prices for electricity when using CHP. The use of large storage tanks is well understood and is a mature technique within district heating systems, and similar strategies are possible to utilize with the proposed distributed thermal storage [3].

The multi-agent system consists of three different agent entities; the producer agent, the consumer agent and the market agent. This paper focuses on the market agent component which acts as a mediating layer between the consumer and producer agents. The market agent uses as an auction-like process in order to coordinate heat load demand among the consumer agents in relation to the operational status of the producer agents.

The paper starts off by describing related and previous work concerning multi-agent based heat load management within district heating systems. In section three the physical process of managing the heat load usage in relation to thermal inertia of a building structure is discussed. Section four presents the functionality of the coordination process within the multi-agent system. Section five describes the experimental set-up used in evaluating the system, and the results are presented and discussed in sections six and seven. Finally the paper is concluded in section eight and nine with conclusions and future work.
11.2 Related work

The framework for the multi-agent systems is built around three different agent types; the consumer agents, the producer agents and the market agent used to coordinate the interaction between the two former agent groups. This basic set-up was first introduced in a previous paper [4], and has since been expanded to cover the practical issues present in a real-time industrial setting [5]. The last few years the system has matured through a series of industrial installations showing the potential of the concept in operational settings [6]. Lately the theoretical foundation for the system has been refined through work considering the producer and consumer agent entities. An optimization algorithm for coordinating the desired heat load in relation to operational constraints was presented in a recent paper [7]. Together with heat load forecasting algorithms such optimization algorithms are used as decision support tools by the producer agents when calculating their desired future state. Heat load forecasts are produced by relating historical operational data of the district heating system with forecasts of the outdoor temperature, in combination with estimations of social behaviour affecting tap water usage and ventilation. Such systems have been studied extensively in previous papers [8] and [9]. More complex solutions use seasonal autoregressive integrated moving averages [10], or basic Box-Jenkins autoregressive integrated moving averages [11] and [12]. Other approaches for heat load forecasting include a grey-box process explicitly using climate data to forecast heat consumption in a large geographical area [13].

The consumer agent tries to balance the ability to partake in load control while simultaneously upholding required levels of quality of service (QoS). The concept of quality filters was proposed in [14]. This concept is based on the idea that the consumer agent should be responsible for the QoS in the building by means of continues measuring and evaluation, thus being able to take informed decisions regarding participation in any requested load control. Maintaining a sufficient level of QoS is at the core of any heating or cooling strategy, and a consumer agent must only act within the constraints set by hereby. An energy balance model for large-scale QoS evaluation within a multi-agent system was presented in [15]. The focus of [15] and [7] was on the specific application of combined heat and power generation while this paper combines the conceptual foundation for producer and consumer agents with a framework for a general application of distributed thermal storage by extending the market agent process.

The basic process of using heat storage facilities within buildings in order to improve the operational functionality of a district heating system has been previously studied in [16] and [17]. The ability to do this on a large scale throughout an entire district heating network was evaluated and quantified in [18], and further studies on the process of storing heat in building structures are presented in
The process of pre-cooling and demand limiting in relation to this has been studied in several studies such as [20] and [21]. Basic heating control strategies are presented in [22], while more complex adaptive strategies are presented in [23] and [24]. All these strategies make use of the thermal inertia within the building structures in order to improve the heating and/or cooling demand.

An early attempt on demand side management was presented during the 1980s. And although the current hardware and communication capabilities limited the operational functionality of the proposed system, the future potential of the system was apparent [25]. It should be noted that the importance of two-way communication in order to enable feedback was acknowledged even in these early works [26].

### 11.3 Multi-agent system overview

The multi-agent system uses three different main types of agents in order to distribute and coordinate the heat load among the participating buildings; producer agents, consumer agents and market agents. A producer agent will work to optimize its operational production in regards to fuel prices in the general case and power market spot prices in the case of combined heat and power generation. Such operational management is done by distributed heat storage among buildings connected to the district heating network. Whenever the producer agent deems it necessary to perform heat load management it will request load control among the consumer agents. The producer agent will have to pay the participating consumer agents so it is important for the producer agent to set the price constraints correctly. The coordination of this load control between the consumer and production agents is done by the market agent.

The agents are controlled by an implicit norm system in which agents are assumed not to cheat or lie. Specifically, in order to avoid collusive behaviour the agents are not permitted to form coalitions. A consumer agent is assumed to be truthful regarding its internal energy balance status, i.e. it is assumed that a building owner doesn't want the residents to complain about the indoor temperature. Furthermore, in multi-producer agent settings it is assumed that the producer agents will not impose on load management instigated by other producer agents, although they have the information to do this based on the on-line auction status.

An energy company and all its production units are represented by a producer agent. Most district heating systems are run by one single energy company, but there could also be several energy companies competing within a network. In the case of a single energy company the producer agent will only need to consider its own operational constraints, while in a multi-energy company setting it will also need to perform real-time evaluation in regards to the status of its competitors.
Each consumer sub-station participating in the system will be represented by a consumer agent. Normally each building has its own sub-station, but several buildings can also be connected to a single sub-station. A consumer sub-station consists of heating control systems, heat exchangers, valves and pumps, and this is the point of control for the consumer agent. Normally such a sub-station will be connected to an outdoor temperature sensor which acts as the input signal for the control system, i.e. the colder it gets, the more the heat demand will increase. In order to control the heat load demand of the building a Linux-based computer I/O platform is used. This platform is connected between the outdoor temperature sensor and the existing control system. By manipulating the outdoor temperature signal the consumer agent is thus able to influence the control behaviour of the sub-station. Figure 1 shows an example of how this works in practice.

![Figure 11.1: Load control by consumer agent](image)

The data in Figure 1 is collected from an online consumer agent operating on the I/O platform. The data shown covers twenty-four hours. The forward temperature into the heating system is shown by the line A, while the return temperature from the heating system is shown at line B. Together with the mass-flow (not shown in the picture), the amount of energy used can be calculated. Line C shows the average indoor temperature of the building in question. Line D shows the difference between the forward and return temperatures in the heating system, i.e. line A minus line B. Line E shows the actual outdoor temperature, while line F shows the manipulated outdoor temperature. In the example it is shown that E and F are identical until the consumer agent performs a short load control, when E and F diverge in the middle of the figure. When this happens the forward temperature into the heating system (A) is lowered, which leads to a decrease in heat load instantaneously. Conversely the opposite can be done if the consumer agent wants to buffer the thermal inertia of the building by inserting extra heat.

Unlike the producer and consumer agents there is no physical object corresponding to the market agent. However, there is a good reason to separate this
functionality since it will make for a more transparent coordination process. Since actual money is involved in the process it is important that the market process is deemed trustworthy by all participating entities.

11.3.1 Heat block value

In a previous paper we presented an optimization algorithm for synchronizing heat load usage in relation to power market spot prices. It was shown that such optimization resulted in substantial financial benefits when using combined heat and power generation on a day-ahead and intraday spot price market. In this paper we extend this algorithm to cover the general case, i.e. adapting it for distributed heat storage in general. The generalized optimization model is shown in equations 11.1 to 11.7.

$$\max \sum_{i=0}^{m} \sum_{i=0}^{n} f(x_{i,j}) \times (\text{price}_{j} - \text{fuel}_{i,j} - \text{op}_{i,j})$$  \hspace{1cm} (11.1)

s.t.

$$f(x) = \begin{cases} 1 & x_{i,j} \neq 0 \\ 0 & x_{i,j} = 0 \end{cases}$$  \hspace{1cm} (11.2)

$$f(x_{i,j}) = \begin{cases} 0 & f(x_{i+1,j}) = 0 \end{cases}$$  \hspace{1cm} (11.3)

$$b_{\text{upper}} \geq \sum_{i=0}^{m} f(x_{i,j})$$  \hspace{1cm} (11.4)

$$b_{\text{lower}} \leq \sum_{i=0}^{m} f(x_{i,j})$$  \hspace{1cm} (11.5)

$$\sum_{i=0}^{m} f(x_{i,j}) \leq \sum_{i=0}^{m} f(x_{i,j-1}) + b_{\text{dynamic}}$$  \hspace{1cm} (11.6)

$$\sum_{i=0}^{m} f(x_{i,j}) \geq \sum_{i=0}^{m} f(x_{i,j-1}) - b_{\text{dynamic}}$$  \hspace{1cm} (11.7)
Equation 11.1 maximises the total earnings. The value of sold heat can only change from hour to hour, while the cost for producing the heat can change both in time and in relation to the level of heat load demand. The costs are separated in fuel costs and operational costs. Such operational costs include costs for starting and shutting down boiler and costs related to managing the boilers. An $m \times n$ matrix represents the heat load demand during a time period, where $m$ is the theoretical maximum amount of heat load in the system. The value of $n$ is normally 24, i.e. the heat load demand is evaluated one day ahead and is discretized into hours. Equations 11.2-11.7 define the operational boundary conditions for the optimization model.

An optimization model for production is dependent on heat load forecasts ranging from hours to a few days ahead. Such forecasts are calculated based on a combination of previous operational data and weather forecasts. The main parameter from the weather forecast to consider is the outdoor temperature, although general weather conditions such as precipitation and wind affect the situation to some extent. Using the heat load forecasts a producer agent can arrange the wanted heat load demand hour by hour in relation to fuel prices and other related costs. By doing this it is possible to minimize the use of expensive and environmentally unsound peak load fuels. In order to make the model useful in practice the heat load demand represented by a matrix which is discretized into blocks. Each such block is called a heat block, and it is these heat blocks that the producer agent will sell to the consumer agents through the market process.

A heat block represents a certain monetary value for the producer agent, since if the consumer agents successfully implement the load control specified by the heat block this will translate into an improved operational status at the physical production units. However, some of these added earnings will have to be used to pay the consumer agents participating in managing the heat load demand within each heat block. Based on the optimization model the producer agent will be able to evaluate the financial value for heat block, and will thus be able to set a maximum price it is willing to pay for the implementation of the associated load control. The producer agent is also able to set the size for the heat blocks based on the boundary conditions in the optimization model, i.e. the size of the matrix is based on the operational conditions within the production units.

### 11.3.2 Consumer agent asset

The consumer agents get paid by the producer agents in order to perform load control. The payments are accumulated during the payment period, usually a month, and then subtracted from the heating bill. Obviously a consumer agent would want to maximize this revenue, by performing as much load control as possible. At the same time the consumer agent is responsible for maintaining
an acceptable level of quality of service, i.e. a building owner wants to save money on the heating, but only to the point where the residents of the building are not complaining about it. Therefore the consumer agent assets are modelled based on the indoor temperature, and thus the agents ability to accumulate heat load control through the auction process is inversely proportional to any deviation from the wanted indoor temperature. The consumer agents also has an upper and lower limit of maximum allowed deviation from the wanted indoor temperature, outside which the agent is not allowed to perform any load control at all. Furthermore the consumer agent also has time constraints in regards to how long the temperature is allowed to deviate from the wanted temperature, i.e. the agent cannot just set the temperature at the upper or lower limit and let it stay there indefinitely. All these operational constraints are set by the building owner depending on characteristics of the building in question.

In order to fulfil the task of maintaining quality of service the consumer agent must have some way of evaluating the indoor temperature. The I/O platform used in the installed system is equipped with wireless communication for such sensors which make it easy to collect indoor sensory data. In addition to this the consumer agent continuously calculates an internal energy balance model of the building based on sensory data from the consumer sub-station in relation to the energy signature and time constant of the building in question. The energy signature is a characteristic value for each individual building indicating the amount of heat load needed to uphold one degree of difference between the outdoor temperature and the indoor temperature. The time constant is another value specific for each building indicating how long time it takes for the indoor temperature to reach equilibrium with the outdoor temperature if no external heating is supplied. Using these values is convenient since they can normally be estimated within acceptable levels without any costly energy analysis of each building. It is also convenient in relation to the auction process since a change in the indoor temperature in relation to the specific energy signature of a building translates to a specific amount of heat load, while the time constant translates into an estimate of how long a specific heat load change can be upheld without jeopardizing the quality constraints. This makes it possible for the consumer agent to relate the indoor temperature status directly to an amount of available currency, expressed in the possible heat load change, to be used in the auction process.

### 11.3.3 Auction process

When a producer agent estimates the need for load control it will issue one or more heat blocks to the market agent. Each such heat block is the size of the heat load times one hour, i.e. the length of time for a heat block is static while the size
in heat load may vary. The market agent will then divide each heat block into heat slots which it auctions off among the consumer agents. This basic set-up is visualized in figure 11.2.

The reason to divide the heat block into smaller slots is that normally no individual building is large enough to handle a whole block by itself. The market agent performs the sizing of these slots based on knowledge regarding the outcome of previous auctions, i.e. the market agent will have a rough idea about how large chunks the consumer agents can handle at a time. If the market agent does not have any such prior knowledge it will start by trying to auction off the whole block as one slot, then dividing it in half until consumer agents start to respond to the auction calls.

Each slot is sold through a reverse Dutch auction process. A Dutch auction starts at a high price which is then decreased in increments by the auctioneer until a buyer accepts the price. The purpose of using such auctions is mainly that they come to a conclusion fast, thus minimizing communication overhead which is imperative in an industrial setting such as this. A reverse Dutch auction is like a normal Dutch auction except that it starts from zero and works itself up until either a bid is accepted by some consumer agent or the maximum price set by the producer agent is reached. Once a bid is accepted the market agent will issue a contract to the winning consumer agent. The contract specifies the size of the heat slot and also the time when to start implementing the load control. A consumer agent can participate in several successive auctions, as long as it is able to maintain the quality of service.

A producer agent can issue a heat block many hours, or indeed days, before it is to be implemented. However, if the block is issued to early the consumer
agents might be reluctant to commit themselves since they cannot predict their indoor temperature state too far into the future. On the other hand, if the heat block is issued too late, a large portion of the consumer agents might already be under contract, potentially preventing them from participating further.

If the market agent isn’t able to allocate the whole heat block, then the producer agent can choose to either accept the partially filled block or to reject it. In this case the consumer agents involved are bound by contract until the producer agent either accepts or rejects the block. On the other hand, if the market agent does succeed in allocating the entire heat block, the producer agent is obliged to accept it.

The market agent will keep track of the outcome of all auction activity. This data is publicly available to all entities participating in the agent system, which serves two purposes. First of all it ensures transparency in the process, which is important since both consumer and producer agents want to be able to ensure the functionality of the debiting system. Secondly if such data is freely available all agents will share the same knowledge, thus decreasing the risk for unfairness in the market process.

11.4 Experimental set-up

The experiments in this project were performed using data from a district heating system at Gothenburg Landvetter Airport in Sweden. This system has around thirty buildings connected, and the size of these buildings range from large arrival halls and air plane hangars to smaller buildings of various kinds. The data studied spans the month of January 2011. This district heating system is installed with the previously mentioned I/O platform, although the overall agent system was not yet operational at the time of this study. Hence the agent coordination evaluation was done using the DHemos simulation environment, although operational data from the district heating system was used. DHemos is a simulation framework for district heating systems, combining simulation models for production, consumption and distribution [27]. The basic function of DHemos is described in [28]. The optimization calculations for the producer agents are done using Octave 3.2.4. The DHemos simulations have been run on a Linux/Ubuntu 11.10 computer with Intel Core i5 CPU with 4GB of RAM.

The scenario studied involves the management of peak load. The production units use a base load burner using biomass fuel and an oil based peak load burner. The oil burner is necessary to use at heat load demand levels above 4.5 MW. The goal is to minimize the use of the oil burner since it is both costly and environmentally unfriendly. The prices involved are based on averages during the month of January 2011. The fuel costs are valued at 32.29/MWh for biomass and 75.84/MWh for oil, while the income is 54.17/MWh. Biomass emit zero CO2
while oil results in emissions at 271 kg/MWh.

11.5 Results

Figure 11.3 shows a comparison between DHEMOS and the measured operational data at the production site. The DHEMOS data has distributed heat storage (DHS) inactivated in order to compare to the operational data. During the first half of the month the operational data displays somewhat of a volatile behaviour in comparison with the simulated data. These violent fluctuations are caused by measurement errors. However, the general correlating trend between the measured data and the simulation is apparent. If the simulation data is used as a measurement of actual heat load demand it can been seen that short periods of heat load shortage has most likely resulted during the first and last peaks, at around 50 and 630 hours. The fact that no-one has complained during these times might be considered an indication in regards to the potential of thermal storage within buildings.

![Figure 11.3: Comparison between DHEMOS and measured data](image)

Figure 11.4 shows a simulation run with DHS activated in order to avoid peak load usage above the limit of 4.5 MW. The producer agents wants the heat load demand to be as close as possible to this limit, since they want to sell as much as possible of the energy produced by biomass.

It is obvious that the agent system isn’t able to fully avoid all peak load usage. During the latest peak load, at around 600 hours, the consumer agents are not capable of responding to the heat blocks being offered by the market agent. However during the major part of the month the system is able to successfully manage the heat load demand. At around 400 hours it can be seen how the
consumer agents buffer heat by increasing their heat load demand in order to prepare for the coming peak at around 450 hours.

Figure 11.5 shows an example of the indoor temperature variations in a building during the simulation period. The consumer agent used the energy balance model in order to calculate this value.

The lowest temperature value accepted by the consumer agent in this case is nineteen degrees, while the wanted temperature is twenty-one degrees. The consumer agent approaches the lower limit on several occasions, most notably during the latest peak at around 650 hours. When this happens the consumer agent will start to lose auctions, thus rendering it unable to perform further load management. It should be noted the calculated indoor value shown above should be viewed as a control variable for the consumer agent, and not necessarily a representation of the actual indoor temperature. This is due to the fact that the
Table 11.1: Energy in MWh, gross and net income and profit in Euro, CO2 in kg

<table>
<thead>
<tr>
<th></th>
<th>Energy</th>
<th>Gross</th>
<th>Net</th>
<th>Agent cost</th>
<th>Profit</th>
<th>CO2</th>
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<tr>
<td>DHS on</td>
<td>3245.62</td>
<td>175819</td>
<td>69157</td>
<td>30%</td>
<td>65480</td>
<td>11660</td>
</tr>
<tr>
<td>DHS off</td>
<td>3548.24</td>
<td>192212</td>
<td>63905</td>
<td>0%</td>
<td>63905</td>
<td>85540</td>
</tr>
</tbody>
</table>

energy balance model doesn’t take into account heat contributing factors such as solar radiation, excess heat from electronic equipment or social activities.

As the producer agent manages the heat load demand the total amount of energy sold will be reduced, but since the majority of this energy is produced by expensive oil the net profit will increase. Table 11.1 shows a comparison between active and non-active distributed heat storage.

Table 1 shows that the profit will increase by 3675 during the period and that the CO2 emissions will decrease by more than 86%. The agent cost represents the amount of money the producer agent uses to pay the consumer agents. In our simulations this value was between 10-30% although this is dependent on the ratio of competing consumer agents in relation to the amount of heat blocks available on the market, i.e. a direct relation between supply and demand. The cost of the installed system is about 20000 Euro which in relation to a profit of about 3500 Euro per month will lead to the system being amortized within one heating season.

11.6 Discussion

The presented system uses an implicit norm system, which assumes that the agents are benevolent and acting towards globally known goals using universally accepted strategies. However, in a fully operational system these agents would be acting on a financial market including energy companies and building owners who want to maximize their own financial gains. In the current system norms are present in such a way that agents are expected to behave in a certain fashion, e.g. not to cheat or lie about their status. In a practical setting it is possible to maintain this system since the implementation of all agent parameters where set within this project. However, in a real-life system the participating building owners or energy companies would be able to set any parameters they like, and could even re-program the agents as long as they adhere to the communication protocol.

The strategy of the consumer agent is to bid as a combined function of its valuation of the load management and its estimation concerning other agents valuation. This obviously opens up for coalition forming among the consumer agents, although the current implementation doesn’t allow for this. Consumer
agents might want to form coalitions in order to achieve high prices by agreeing to withhold auction bidding and then splitting the proceeds. If a group of consumer agents were successful in rigging the market like this they could achieve more than the 10-30% profit share they got during the presented experiments.

In regards to the producer agents there is no incentive for them to lower the maximum price below its true valuation, since this would only harm the producer agent itself by depriving it of financially profitable load management.

11.7 Conclusions

In this paper we have presented a multi-agent system for distributed heat storage. It was shown that such a set-up can be used to reduce, and in many instances remove, the need for financially and environmentally unsound peak load fuel usage. Since the multi-agent system is operationally adaptable it is able to adjust the heat load demand in relation to actual operational constraints among the production units. This makes it possible to increase the net profit for the energy company even though the total amount of energy being sold is less.

It was shown that the consumer agents will cooperate in load management as long as they are able to simultaneously uphold their desired quality of service.

The net profit in district heating system in question was increased by about 2.5% which translates to a return of investment in less than one heating season considering the installation costs involved. At the same time the CO2 emissions were reduced by more than 86% due to the shift in fuel composition.

11.8 Future work

In the future a framework for explicit management of norms will have to be added. This is imperative since the physical entities represented by the agents need to maintain trust in the system, even when those entities are allowed to set their own agent parameters. This system should be based on a set of explicit norms or ground-rules, which are then managed through a layer of individual trust among agents coupled with a globally visible reputation system. The market agent will act as the main manager for this system, and will use punishment by exclusion in order to maintain order. Exclusion translates into financial loss, which will act as deterrence for the agents to deviate from the norms.

11.9 Acknowledgements

The authors would like Swedavia for letting us use operational data from the district heating system at Gothenburg Landvetter Airport. Also, we would like

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to thank NODA Intelligent System for the use of the agent I/O-platform.
Chapter 12

Paper XI - A smart heat grid framework using intelligent software agents

In this paper we present a coherent system combining the characteristics and performance of different aspects of so called smart grids for district heating systems. The system is based on a multi-agent architecture which provides a flexible and robust framework for distributed coordination and interaction between distinct entities within dynamic and unpredictable domains such as heat or power grids. We examine the system performance in an industrial setting and provide results from three different demand side management strategies implemented in the system. It is shown that an increased ability of the system to automatically coordinate production and consumption leads to significant benefits on a system wide scale as well as on a local scale.

12.1 Introduction

In several previous papers we have described and examined the characteristics and performance of different aspects of so called smart grids for district heating systems. In this paper we integrate these aspects together into a coherent system and detail the theory and practice underpinning this merger and disseminate results relating to the development and implementation of such a system. The theoretical foundation for this system was previously proposed by the authors (Wernstedt et al., 2007). Although the general agent-based framework is still evident in the current system several developments have been implemented since
then, mostly relating to the process of converting theoretical ideas to robust applications capable of handling the practical dynamics and commercial constraints within operational district heating systems.

An agent can be seen as an autonomous software entity that can act independently based on the needs and desires of the agent in relation to the constraints set by the domain which it inhabits. Agents can also act together with other agents in multi-agent systems, either by competition or cooperation. Multi-agent systems is a powerful framework for implementing software-based intelligence for handling distributed and complex environments and such systems have been successfully applied to many industrial systems and robotic applications (Wooldridge, 2002). Since most energy systems in general and district heating systems in particular are by their nature distributed as well as complex we have used multi-agent systems as a framework in order to implement the smart grid paradigm.

District heating is the most common heating type in urban areas throughout Northern and Eastern Europe, although this type of technology is used all over the world. In Europe district heating is becoming increasingly vital as part of a long-term sustainable infrastructure for energy, not least in relation to the increasing use of combined heat and power production (CHP) (Constinescu, 2007). A district heating system consists of one or several productions units connected to the customer units through a distribution network. Normally water is used as the transfer medium although steam is also used in some systems. The heated water is normally accessed by the consumer through a substation containing a heat exchanger which transfers the heat into the building heating and tap water system. A district heating producer can use basically any heat source able to heat the water to the desired temperature, normally around 80-120°C, which makes district heating a versatile system (Fredriksen & Werner, 1993). The energy efficiency of district heating production can be increased by using a combined heat and power production plant which produces electrical power simultaneously with producing the heat. Such a set-up normally involves overheating water into steam which is used to run a turbine which in turn is connected to a generator for producing electricity. The steam is then fed into a condenser unit which decreases the temperature and pressure of the steam by transferring the heat to the district heating water. A traditional power plant has a energy efficiency of about 30-50% in relation to the primary fuel, while a CHP is capable of achieving efficiency levels of 80-90% (Horlock, 2008).

Even though a district heating system is demand driven there is usually no direct information link between consumption, distribution and production. Normally these sub-systems are operated independently of each other even though they are intertwined within a confined physical system. The most basic problem is that the production units normally work optimally with an even load while the social behaviour of the end-customers give rise to a variable consumer head
demand. This results in a disharmony between demand and supply. In the case that this problem is addressed at all, the traditional approach is to use storage tanks or to use the distribution network itself as a thermal buffer in order to handle volatile heat demand (Andrepont, 2012). However, a storage tank is just that; a thermal buffer without any operational dynamic behaviour, and although they can be used to alleviate peak loads to a certain extent, their lack of operational dynamic behaviour makes them less suitable for active optimization. However, by implementing systems like the one proposed in this paper it is possible to achieve a framework for more active operational optimization. There are a large number of financial and environmental benefits to be had by directly coordinating the operational behaviour of consumption in relation to distribution and production. This was realised a long time ago and even in the early nineteen eighties experiments were carried out in order to evaluate these ideas in a practical setting (¨Osterlind, 1982). However, at the time it was also concluded that the current technology in regards to computational and communication performance was somewhat lacking and that a theoretical framework for handling distributed and dynamic environments in order to maintain quality of service was missing. Since then computational devices and communication solutions have experienced an exponential development in performance and cost efficiency. An multi agent based framework for district heating systems was examined in (Wernstedt, 2005) and further developed in (Wernstedt et al., 2007). By utilizing the inherent characteristics of a multi-agent system it was possible to provide a architectural framework for distributed optimization and information sharing while upholding the operational behaviour required by the different actors within the district heating system. Within this framework we have developed the behaviour of the different agent-based entities in order to coordinate production optimization and consumer quality of service (C. Johansson, 2010).

12.2 System overview

An agent can be described as a autonomous entity which observes and acts upon its environment and directs its actions towards achieving certain goals. Modelling system components as agents generate several benefits since it provides a way of structuring applications in complex computational systems with several conflicting entities (Wooldridge, 2002). In this case the overall goals for the system is to optimize the energy usage in relation to financial and operational aspects while maintaining an acceptable quality of service. Due to the previously mentioned disharmony between supply and demand these two goals can sometimes be in conflict. In order to handle this situation the system is modelled as a collection of individual agents based on three distinct agent types.
Producer agent

The task of the producer agent is to optimize the energy generation in relation to financial and environmental aspects. This optimization can be used in several different situations, such as the previously mentioned peak load avoidance scheme. Other uses include optimization of combined heat and power production in relation to electricity spot price or distribution optimization related to for example pressure maintenance or return temperatures within the district heating network. The primary goal of the producer agent is normally to minimize the production costs given a set of constraints related to the heat load demand in the network and the physical and financial properties of the production and distribution infrastructure.

A production agent optimization scheme for combined heat and power production has previously been presented in (C. Johansson et al., 2012a). In this scheme the production agent coordinates the thermal buffer of a large amount of buildings taking into account hourly spot price projections. However, this scheme can be generalized in order to apply to a wide range of basic demand side management strategies. Normally an energy producer in a district heating system have two basic parameters on which to operate; the pressure head in the distribution network and the supply temperature at the production units, basically indicating a totally demand driven system. By using operational load control a third parameter is provided to the energy producer since this allows the producer to manipulate the heat demand within certain constrains rather than just reacting to it. In a traditional optimization setting, i.e. using the two basic parameters, the energy producer will solve the optimization by minimizing in relation towards production costs (Arvastson, 2001). However, given the ability to perform operational load control the energy producer can instead optimize by maximizing in relation towards earnings. As before the input for the optimization is an hourly heat load forecast for a day ahead, although instead of rearranging this heat load array in relation to spot price it will be arranged according to general earnings in relation to system constraints.

In the spot price-based optimization process the producer agent received day ahead data from external providers, like Nord Pool Spot in Northern Europe. This data could then be used to evaluate the financial value of different heat load levels. In the generalized optimization process the producer agent instead has to calculate this financial data based on the operational constraints in the production units available in the specific district heating system. It should be noted that the previously mentioned spot price situation can be modelled as such operational constraints in the generalized case. The starting point for such an analysis is a forecast estimating the heat load hour by hour for the coming day. Such heat loads forecasts are normally based on regression analysis of historical data (Jonsson, 2002; Dotzauer, 2002), but they can also be based on other types
of forecasting techniques such as time series analysis (Grosswindhager et al., 2011; Box & G.M., 1991; Chramcov et al., 2009) and neural networks (Kato, Sakawa, Ishimaru, Ushiro, & Shibano, 2008).

The heat load forecast is considered to be the representation of what will happen if no operational load control is performed, i.e. the situation in the normal production cost minimization case. However, incorporating the systems ability to perform load control in the constraints for the optimization model enables the possibility to find better operational strategies from a financial point of view. A typical example of such a situation relates to the use of expensive peak load boilers where the production costs exceed the customer price of delivered heat. In the traditional situation the utility will have no choice but to enable such peak load boilers in order to cover the heat demand, while by using operational load control it is possible to also consider the choice of removing or shifting the demand. By slightly adjusting the optimization scheme for combined heat and power production the generalized case can be formalized in the following model. Like before the heat load demand is discretized and represented in an $m \times n$ matrix. The $m$ value is the maximum heat load in the system and $n$ is the amount of time units considered in the optimization, normally 24 hours.

$$\max \sum_{i=0}^{m} \sum_{j=0}^{n} f(x_{i,j}) \times (\text{income}_{i,j} - \text{cost}_{i,j}) \quad (12.1)$$

s.t.

$$f(x) = \begin{cases} 1 & x_{i,j} \neq 0 \\ 0 & x_{i,j} = 0 \end{cases} \quad (12.2)$$

$$f(x_{i,j}) = \begin{cases} 0 & f(x_{i+1,j}) = 0 \end{cases} \quad (12.3)$$

$$b_{\text{upper}} \geq \sum_{i=0}^{m} f(x_{i,j}) \quad (12.4)$$

$$b_{\text{lower}} \leq \sum_{i=0}^{m} f(x_{i,j}) \quad (12.5)$$
\[ \sum_{i=0}^{m} f(x_{i,j}) \leq \sum_{i=0}^{m} f(x_{i,j-1}) + b_{dynamic} \]  
(12.6)

\[ \sum_{i=0}^{m} f(x_{i,j}) \geq \sum_{i=0}^{m} f(x_{i,j-1}) - b_{dynamic} \]  
(12.7)

In the original optimization model the heat demand was assumed to be constant, while this does not need to be true in the generalized case. The peak load case described above is an obvious example when the heat demand is not constant. In equation 12.1 the \textit{income} variable represents the money made by selling the energy content of the \(i\)’th and \(j\)’th cell in the heat load matrix, while the \textit{cost} variable describes the production cost of that same energy. The value of \textit{income} is normally the same throughout the matrix while the value of the \textit{cost} variable can vary substantially depending on position within the matrix. Normally the production cost increases with higher \(m\) values. The reason for this is that utilities tend to start the cheap production units first. Equation 12.2 defines the existence of heat load demand in each matrix cell. Equation 12.3 ensures that all non-zero matrix cells are connected to the ground either directly or indirectly through other non-zero cells. Equation 12.4 and 12.5 defines the maximum and minimum production levels for each time step during the optimization. Equation 12.6 and equation 12.7 defines how much the heat load can change from one time step to the next. As before, all values apply to the system wide situation as a combination of all participating production units and load control ability. The result of the optimization is an array of \(n\) values describing the desired heat load level for each time step.

**Consumer agent**

The consumer agent has two distinct and possibly conflicting goals:

- ensure an acceptable quality of service (QoS) for the physical consumer
- participate in as much load control as possible

Obviously the QoS could deteriorate if the consumer agent accepted to much load control, which is why these goals need to be constantly balanced against each other. The behaviour to achieve this balancing is based on the implementation of a consumer quality filter (C. Johansson et al., 2010a). The implementation of a consumer quality filter is vital to the function of operational load control. Simple load control schemes without such quality filters where implemented as early as
the early eighties. And although they worked from a production point of view it soon became apparent that the system needed online feedback from the individual consumers in order to work properly, i.e. without causing reduced quality of service (Österlind, 1982). In our system we use the multi-agent framework in order to implement such a quality filter through the use of consumer agents.

A district heating substation contains a control system which normally works by relating the outdoor temperature to the supply temperature in the heating system through a control loop feedback mechanism. This control system is responsible for the basic heating as well as tap water generation in the building. The consumer agent doesn’t have to do anything unless there is a need for load control in which case it will be alerted by the market agent. When a load control instance is initiated the consumer agent receives a request by the market agent. The consumer agents responds to this request by calculating a bid which defines its ability to perform load control. Such a bid is defined as:

\[ bid = [id, amount, time] \]

(12.8)

The \textit{id} value identifies the consumer agent. The \textit{amount} value defines the amount of load control, while the \textit{time} value defines how long the consumer agent can maintain this load control. The \textit{amount} value can be both negative and positive since the market agent might be requesting an increase as well as decrease in heat load. In order to calculate the buildings ability to perform load control the consumer agent will use an energy balance model of the building (C. Johansson, Wernstedt, & Davidsson, 2012b). With such a model it is possible for the consumer agent to estimate what will happen with the indoor climate given certain levels of load control over different periods of time. The consumer agent then chooses the case in which it can uphold the maximum level of load control during the desired time frame, without jeopardizing the QoS. This value is then used as \textit{amount}. The energy balance model is not used in order to try to evaluate the absolute indoor temperature in the building, since this would be a very complex endeavour. Instead the existing heating system is assumed to be able to maintain the required indoor climate in the normal case, while the energy balance model is only used to estimate the relative deviation during load control. Normally in a market based coordination approach the agents are assumed to display a selfish behaviour which in this case would be to focus solely on the QoS. However in this context the consumer agents are programmed to be unselfish in the sense that they have the second goal of participating in load control for the benefit of the system as a whole.
Market agent

The goal of the market agent is to uphold the heat load levels that the producer agents request. This is achieved by distributing load control in manageable chunks among the participating consumer agents. For each step of the time range the market agent will estimate the difference between the requested heat load level and the heat load forecast while also supervising the operational heat load levels in real time. Whenever there is a difference between the forecast or real time data and the requested heat load level the market agent will initiate load control in order to minimize this difference. Normally load control will be initiated in order to reduce heat load but in some situations it is desirable to instead increase the heat load level. This can, for example, be the case when the system wants to even out the heat load levels in general over a period of time, i.e. decreasing heat load during peaks and increasing heat load during downs. If there is more than one producer agent requesting heat load levels that require load control then the market agent will divide this load control among the consumer agents in relation to the size of the required load control. Exact control of the heat load level is very hard to achieve and will often lead to unstable oscillation in the system. In order to avoid such problems the implemented system uses target zones. A target zone is defined as:

\[ tz = [hl_{ceiling}, hl_{floor}, t_{start}, t_{end}] \] (12.9)

Instead of having an exact target value the system will try to keep the heat load level within the \( hl_{ceiling} \) and \( hl_{floor} \) values. This ensures that there is a buffer for natural fluctuations in the heat load, helping the market agent to avoid having to constantly instigate load control for small deviations. The \( t_{start} \) and \( t_{end} \) values define the start and end times for when the target zone should be active. When there is a need for load control the market agent will calculate the appropriate size of this load control. This is called a heat load block, and is defined by the amount of heat load in combination with the length in time of the block. Normally such a block is too large for a single consumer agent to handle, in which case the block is divided up into slots of smaller heat load size but with the same length in time. The market agent favours large bids by the consumer by starting with a slot size equal to the block size. If no consumer is bidding for this size the market agent will divide the block into two slots each half the size of the original block. The market agent will continue to divide the slots into smaller slots until they are small enough for consumer agents to accept. Each slot is auctioned out among the consumer agents through a closed first price sealed bid auction. This type of auction is used because it ensures a fast auction process with low communication requirements while also inhibiting collusion (Weiss, 2000b). The consumer agents want to buy as much load control
as possible but they are restricted by their quality filter which prevents them from jeopardizing their indoor climate. In this way the system becomes self balancing, since a consumer agent that has won large load control slots will get larger and larger deviations in their energy balance model and will thus be more likely to loose subsequent auctions. The market agent will perform this process whenever it considers there to be a need for it, and this normally happens several times during each time step. However, in the implemented system the market agent is programmed to do this no more often than each fifteen minutes, in order to avoid unnecessary valve fluctuations in consumer substations.

12.3 Implementation

The performance of the Smart Heat Grid system has been evaluated in two different district heating systems using three different demand side management strategies. The strategies used are manual load control, peak load avoidance and global system optimization. When using manual load control the system is on stand-by without doing anything unless the operators at the energy company starts load control by manually defining and activating target zones. In the peak load avoidance set-up the agent system is connected to measure the differential pressure in the district heating network. Normally when the pressure drops a peak load boiler will be automatically activated, but in this setting the agent system will instead initiate load control in order to reduce the heat load demand and thereby removing or at least delaying the need for the peak load boiler. The global system optimization strategy implements the full optimization process described above. All three strategies are based on using target zones and the auction mechanism in relation to the consumer agent quality filter.

The two district heating systems used for this study are located in Sweden and France. In the French network 10 consumer substations were equipped with consumer agents. These substations were some of the largest in the network and together they represented nearly half of all consumption in the total network excluding distribution losses. The heat load in this network varied between 5-15MW during the test period. In the Swedish network 24 of the largest buildings were equipped with consumer agents which equals about 60-80% of the total consumption excluding distribution losses. Here the heat load varied between 1-5MW during the test period. The outdoor temperature was rarely below 0°C in the French network while the Swedish location had temperatures below -15°C. All consumer agents were implemented by using the NODA Intelligent Energy Controller (IEC) platform. This system includes a server back-bone for the production and market agent implementation as well as the database and communication interface. The Swedish system used existing Ethernet connections for communication while the French system used wireless modems. The manual load
control and peak load avoidance strategies where used in the Swedish network, while the global optimization strategy was used in the French network.

Certain parts of the basic load control functionality has been evaluated earlier (Wernstedt & Johansson, 2008). This system used a basic quality filter for the consumer agents, but did not implement the full production and market agent functionality described in this article.

## 12.4 Results and discussion

The data in Table 12.1 shows the progress of an auction process with nine participating consumer agents, denoted A to I. This example is from the French network so there are ten consumer agents in total but the last one is prevented by its quality filter to participate in this particular example. The consumer agents are all connected to different types of building structures, ranging from large multi-building substations to substations supplying single buildings. In this case each time step is fifteen minutes, which means that there will be a new auction four times each hour. For each time step the whole auction process is re-iterated. The values show the load control in kW that each consumer agent wins for each time step, and since this specific example shows a reduction in heat load all values are negative. The total load control starts slow and then increases during the first few time steps since the market agent wants to avoid causing pressure hammers caused by rapid changes at the substation level. The total load control then continues to vary for each time step in order to adjust to changes in the actual heat load levels in the network. Only the winning bids are shown in the table.

In Table 12.1 we see that the market agent favours those consumer agents who are able to accept the largest load control slots, since they continue to win auctions throughout the example. This behaviour is most notable for consumer agent A. Other consumer agents are not able to win any load control until the size of the total heat load block exceeds the ability of agent A, which happens during time step 1 when both agent F and I win their first load control slots. As the total heat block size increases more and more consumer agents are able to win heat load slots from the market agent. Only agent C and G remain without any auction wins even though they are participating in all the auctions.

Figure 12.1 shows an example of the heat load levels during 24 hours in the French network. A target zone is active during certain hours during the day, which is marked by the grey area. The dashed line shows the approximate heat load profile during a day without load control. This approximation is based on an the average heat load profile during several days without load control but with similar outdoor temperature. No day has exactly the same outdoor temperature hour by hour but by doing such an approximation it is possible to estimate how the heat load levels would have been without load control. The arrows indicate
Table 12.1: Auction process results for agents A to I

<table>
<thead>
<tr>
<th>Time step</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1686</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1686</td>
</tr>
<tr>
<td>1</td>
<td>-1589</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-999</td>
<td>0</td>
<td>0</td>
<td>-334</td>
<td>-2922</td>
</tr>
<tr>
<td>2</td>
<td>-1768</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-298</td>
<td>-1130</td>
<td>0</td>
<td>-259</td>
<td>-273</td>
<td>-3728</td>
</tr>
<tr>
<td>3</td>
<td>-1604</td>
<td>-203</td>
<td>0</td>
<td>-215</td>
<td>-364</td>
<td>-1003</td>
<td>0</td>
<td>-349</td>
<td>-269</td>
<td>-4007</td>
</tr>
<tr>
<td>4</td>
<td>-1563</td>
<td>-91</td>
<td>0</td>
<td>-95</td>
<td>-246</td>
<td>-1002</td>
<td>0</td>
<td>-252</td>
<td>-266</td>
<td>-3515</td>
</tr>
<tr>
<td>5</td>
<td>-1548</td>
<td>-90</td>
<td>0</td>
<td>-88</td>
<td>-246</td>
<td>-1000</td>
<td>0</td>
<td>-241</td>
<td>-266</td>
<td>-3480</td>
</tr>
</tbody>
</table>

Figure 12.1: Heat load levels (full line) during an active target zone (grey area). Dashed line shows heat load profile without load control.
Table 12.2: Load control ability over different time ranges

<table>
<thead>
<tr>
<th>Load control [%]</th>
<th>Time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-20</td>
<td>+8</td>
</tr>
<tr>
<td>20-30</td>
<td>4-8</td>
</tr>
<tr>
<td>30-50</td>
<td>1-4</td>
</tr>
</tbody>
</table>

in which direction the market agent is applying load control, i.e first by reducing heat load and then by increasing heat load. The target zone has a $h_{\text{ceiling}}$ value of 12 MW and a $h_{\text{floor}}$ value of 10 MW, which means that the market agent will try to keep the heat load level between these values while the target zone is active. During the first six hours of the target zone the heat load demand is substantially higher than the target zone ceiling, which causes the market agent to initiate continuous reductions. It is clear in the figure that the actual heat load level is indeed at about, and even slightly over, the ceiling value of 12 MW. This variation provides an example of how hard it is to achieve an exact and even level of heat load in a practical setting. After midday the heat load demand is below the floor value of 10 MW, which causes the market agent to try to increase the heat load instead. When the target zone is deactivated it is clear that the heat load levels drop significantly.

Earlier projects have indicated an ability for operational load control of about 20-30% of the total heat load level on a system-wide scale during several hours. The projects in both Sweden and France confirm this. During the test period individual buildings routinely performed load control of up to 50% during shorter periods of a few hours, and the system as a whole had no problem of maintaining load control of 20-30% during several hours in a row. Every load control instance is different from each other since the total heat load consists of both the temperature dependant part and a part which is influenced by social behaviour in the buildings. This makes it hard to provide an absolute value for each conceivable situation. However during the project we have performed load control on a daily basis over a period of several months and based on this we have been able to make a statistical analysis on the results. Table 12.2 shows the level of load control the system is able to perform during certain periods of time with a confidence of above 90%. This means that the following data can be expected to be valid in at least 9 out of 10 situations. The data is valid for load control concerning reduction as well as increase in heat load.

A buildings ability to perform load control is obviously directly related to the constraints of the physical heating system in the building. However, many buildings seem to have a greater resistance to heat load manipulation than is commonly believed. During the course of this project we have studied 34 sub-
stations with a range of different buildings connected, many of which have had indoor sensors installed. Indoor climate is a rather complex subject and most building owners are surprised when shown how noisy such data is in reality. Instead of being noticeably affected by shorter periods of load control the influence of the heat load manipulation is hidden within that noise.

Figure 12.2 shows indoor sensors in one building from a participating consumer agent. Load control is being performed at several times during the time range shown, although there is no measurable correlation between the fluctuations in the indoor data and active load control. Load control is being performed at times of both increase and decrease of indoor temperature, and the indoor temperature fluctuates several degrees Celsius even when no load control is active. The indoor temperature is mostly dependant on social behaviour on the short scale over hours, e.g. heating fans turning on when people come into the office, and the outdoor temperature over longer time scales such as days and weeks, e.g. during times of sudden weather changes the indoor climate will react before the heating system is able to adjust. This latter example is a highly contributing factor for building owners receiving many more complaints from their tenants during autumn than spring, even though the outdoor temperature is seemingly similar.

In the Swedish network manual load control was used during the first part of the project in order to calibrate and adjust the system in relation to the operational constraints on both local and system-wide operational level. During the second part of the project the differential pressure signal was connected to the system. Whenever the pressure dropped below a certain level, normally due to supply malfunction, the market agent would initiate load control in order to reduce heat load demand, which in turn would help the energy company overcome
their supply problems without having to start the peak load boiler. Such temporary malfunctions appeared quite often and during the test period of four months such pressure drops caused the market agent to initiate load control twenty-three times. These load control instances varied in size from 0.15 MWh to 17 MWh in total energy content. The average energy content of a load control instances was about 5 MWh. In total these load control instances comprised 100 MWh. The majority of the load control lasted between 3 to 6 hours. Most of load control was initiated during the two coldest months of the test period. In addition to this manual load control was used on a few single occasions when the energy company knew that there would be supply problems even before the differential pressure dropped.

12.5 Conclusions

We have presented a working system for demand side management through multi-agent based operational load control. In addition to this we have confirmed earlier results relating to certain aspects of operational load control in district heating systems. The system has been active in two different district heating systems and the results show the ability of the system to routinely perform operational load control of 20-30% on a system scale during several hours.

It is shown that a multi-agent architecture for demand side management can be used to implement different types of operational load control strategies. We have presented results relating to three such different strategies; manual load control, peak load avoidance and global system optimization together with heat load forecasting and optimization. The manual load control and peak load avoidance strategies are relevant for most district heating systems where peak load boilers are used. The cost of producing energy through peak load boilers is often higher than the consumer end price, which makes it highly relevant to handle. The peak load avoidance strategy is easy to implement since it uses the same control feedback system normally used for the peak load boiler itself, in this case the differential pressure in the network. The global system optimization strategy is somewhat more complex since it uses heat load forecasting as well as optimization models in order to find future heat load levels, and it normally requires a more active and informed operational personnel. The financial incentives to use the global optimization strategy is normally found in situations when the company distributing and selling the energy is not the same as the company generating the heat for the district heating system. Another situation when such more complex systems are appropriate is when there is third party access in one district heating system, i.e. when different energy companies compete in the same physical arena. This situation is obviously normal in most power grids but it is not as common in district heating systems.
The presented system combines a production agent with a market agent and numerous consumer agents in order to achieve the desired functionality. The producer agent forecasts the heat load and calculates the optimal operational production levels in relation to the forecast. When there is a difference between the actual heat load levels and the requested optimal levels, or if an external signal such as a pressure drop triggers, the market agent will distribute load control among the consumer agents using an auction mechanism in order to minimize this difference. The consumer agents implements a quality filter in order to secure required quality of service while trying to participate in as much load control as possible. The agent-based architecture of this system ensures a self balancing process which can be used for numerous aspects within operational demand side management.

12.6 Acknowledgments

The authors would like to thank Karlshamn Energi, Dalkia and Veolia Environnement Research & Innovation (VERI) for their support and for letting us use operational data from system installations in Sweden and France, and NODA Intelligent Systems for support regarding server and data access.

This paper was made possible through a grant (Fjärrsynsprojekt 6268) from the Swedish District Heating Association.

We dedicate this article to Fredrik Wernstedt.
Chapter 13

Paper XII - A dynamic simulation of the production, distribution and consumption of district heating systems: A verification study of Dhemos

Simulation tools are regularly used for optimizing the operational and strategic functionality of district heating systems. Normally, the production, distribution and consumption are modelled separately, but by integrating these models several advantages can be achieved, e.g., increased realism. Dhemos is a simulation system that combines different simulation models in order to achieve a system level model of a district heating system. It has been developed and refined during more than a decade and has been used within several projects, e.g. in order to support the development of new control strategies.

In this paper we describe the verification process of Dhemos and discuss its validation process. The current status and capacity of Dhemos is evaluated and the functionality of Dhemos compared to a commercial simulation tool available on the market. The results verify that the computations seem to be correct and indicates that Dhemos is useful for practical applications in real-world settings. Moreover, Dhemos has a number of fundamental design characteristics which
suggest potential also for future development. However, it is noticed that Dhemos currently lacks important functionality regarding the user interface in comparison with commercial alternatives.

13.1 Simulation system overview

Simulation techniques are regularly used in the district heating industry in order to simulate physical, operational and financial processes relating to production, distribution and consumption. By building theoretical models of the real world equivalent a process can be studied without having to invest in costly and time-consuming experimentation (Banks et al., 2001). Traditionally, the simulation tools available focus on single distinct issues within the district heating domain, e.g. long term production planning from financial aspects or short term operational analysis regarding pressure head and temperature levels in the distribution network (Årvestson, 2001).

In most available simulation systems for district heating there is a separation between tools for production, consumption and distribution. Tools for production simulation normally focus on the financial aspects of long to medium term planning, while simulation tools for distribution normally focus on short term planning in relation to operational behaviour of flow, pressure drops and temperature losses with the district heating network. There are not many dedicated tools for modelling consumption behaviour in district heating systems, although simple versions of such models are possible to implement manually in tools like Matlab or its equivalence. However, such systems are usually severely limited in their usability. Most commercially available simulation systems for district heating either handle long term simulation in production or short term planning in distribution.

13.1.1 The Dhemos simulation framework

Dhemos is an framework for combining simulation models for production, distribution and consumption. The basic idea behind Dhemos architecture is that it should facilitate a more modular approach when combining different simulation models. Table 13.1 provides an overview of the framework. For each level of the different module an example of a simulation value relating to that level is shown. Obviously there are many other values on each level, but the example is shown to give an idea of the focus.

The first version of Dhemos was developed in 2002 and implemented a distribution model based on equations compiled and adapted by Pall Valdimarsson (Valdimarsson, 1993). At the time, most distribution models were based on aggregation models in which the components of the network are bundled together.
The Valdimarsson model, on the other hand, was based on a microscopic approach in which each individual network component was explicitly modelled. The distribution network is modelled through the use of graph theory, which provides a smooth framework for representing the geographical layout of a district heating system. The network is viewed as an electrical circuit in which the flow and pressure head in the district heating network are calculated according to Kirchhoff’s laws for current and potential difference (Chua & Lin, 1975). The network is represented in matrix form which enables the use of powerful mathematical tools for manipulating the data (Anton & Rorres, 2005). However, as the original distribution model only calculated the steady state of flow and pressure head throughout the network, dynamic capabilities were added in the framework. Also a temperature loss model was added, which in combination with the flow and pressure head calculations provided a complete distribution model (Larsson, 1996).

One of the benefits of a modular design is that it is relatively easy to switch between different simulation models. The basic production model in Dhemos only considers the fundamental physical properties at the interface between a production plant and the distribution network, i.e. the supply temperature and pressure head. Correspondingly, the basic consumer model only calculates the flow at each consumer node. In this way the producer and consumer nodes act as boundary conditions for the distribution calculation. Also more complex production and consumption models have been implemented in the Dhemos package, but the basic interface towards the distribution model is still the supply temperature, pressure head and flow.

The production model uses a linear temperature program to calculate the supply temperature while the pressure head is set for each time step. However, it is also possible to simulate the actual pump functionality, for example in order to study the pumping costs. Normally a pump station will act based on the differential pressure level at some specified point in the network. Although the interface towards the distribution model are the same physical boundary conditions there are several different alternatives for calculating these. Dhemos also has the ability to model more complex processes within the production unit in order to study the financial ramifications of different operational behaviour (C. Johansson et al., 201

<table>
<thead>
<tr>
<th>Table 13.1: Overview of Dhemos framework with examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
</tr>
<tr>
<td>Physical level</td>
</tr>
<tr>
<td>Component level</td>
</tr>
<tr>
<td>System level</td>
</tr>
</tbody>
</table>

201
The consumption model is used to calculate the flow value for each consumer in the network. These flow values are boundary conditions for the distribution model, just as the temperature and pressure head values are production boundaries. In the basic consumer model the flow is modelled based on the energy signature of the building in relation to the current outdoor temperature and an estimated cooling ability of the heat exchanger at the specific customer model. By combining these values it is possible to estimate a flow value which then acts as a boundary value for the distribution model. In this study the basic model consumer model has been used since a predictable behaviour was required in order to facilitate a comparison with the existing simulation model. However, if a more complex behaviour is required it is possible to use an option which separates the consumer model into two different models, one for the heating system and one for the tap water usage (Arvastsson & Wollerstrand, 1997). The heating system consists of an energy balance model for calculating the indoor temperature and a substation component which calculates the energy transfer into the building. The substation component uses the outdoor temperature as input when calculating the energy usage of the substation, which is the way most district heating substations work in real life. The substation component basically builds a simple model of an actual heating system starting with the heat exchanger package itself. This is modelled as a parallel-coupled substation since this provides a good description of the relations between flow rate and temperature (Arvastson, 2001). Based on the input from the substation component the energy balance model will calculate the indoor climate. An energy balance model is based on the fundamental form of energy input minus energy output in order to estimate if the energy content of the building is stable or deviating in any way.

Two different energy balance models are implemented in Dhemos. The basic version uses a fundamental formula based on an estimate of the time constant of the building (Österlind, 1982). In the original form, the time constant is calculated based on a total loss of heat load input. However, in an operational setting this is rarely the case. Therefore the time constant is changed based on the supplied heat load levels in relation to the building characteristics (Selinder & Zinko, 2003). A more thorough description of this process has been presented in a previous article (C. Johansson & Wernstedt, 2005).

Dhemos also uses a more complex indoor model in order to describe a more detailed behaviour relating to small deviations in the heat load supply. This model is based on a system of differential equations which describe the indoor temperature and the average temperature within the building structure. Normally these type of models require a large set of input data relating to physical characteristics of the individual building which makes it hard to use such models in practical settings. The model used in Dhemos is based on the same type of
equations but has been reformulated in order to avoid the problem with parameter input. This was done by transforming the physical model into a black box simulation model (Cauer, Mathis, & Pauli, 2000). In the black box model only two simulation parameters needs to be set, and they are derived from the time constant and energy signature of the building. Finding these values involve using successive runs of steady state simulations in relation to the time constant and the energy signature. However, in order to facilitate the use of the model in practical settings a set of building templates have been developed. By using the templates it is easy to estimate usable input values for the simulation based on the generic size of different building types. The theoretical background of this black box model is thoroughly described in a previous paper (C. Johansson et al., 2012b).

The non-temperature dependent part of the heat load is primarily due to tap water usage. This can be calculated based on a statistical analysis of historical measurement data. Dhemos uses a model based on measurement data relating to bath, wash and kitchen usage of tap water (Holmberg, 1981). Based on this it is possible to calculate the probability of tap water usage as a function of the time of day. The tap water usage can also be used as an indicator for social behaviour, i.e. by assuming there is a correlation between how much tap water people use and if they are awake and active.

The Dhemos package uses an event list to handle the input parameters for the dynamic simulation. This list contains events that trigger during the simulation. Each event consist of an identifier, a time stamp and a description string. The identifier is predefined value that is connected to different types of input data that the simulation models use. Examples of this include the outdoor temperature or status changes at individual components. The description string can contain arbitrary data given that the ability to parse the string has been added to Dhemos. For each simulation time step Dhemos will inspect the event list and check if the current time step has any related events, in which case the event description will be parsed as input for simulation step.

Dhemos also contains a pre-processing stage which can be used to populate the event list. An obvious example of such functionality is if the simulation system is connected to a weather forecast provider. The event list can also be used for simulations based on heat load forecasts within the district heating system. The total consumer heat demand is primarily related to the outdoor temperature but it is also influenced by social behaviour, especially when studying data on short time frames. If Dhemos is equipped with a heat load forecasting system, the event list can be used to set actual heat loads throughout the simulation run. This would override the normal simulation process in which the heat demand is calculated dynamically in relation to the outdoor temperature. The event list can also be used to evaluate non-standard component specific behaviour such as
fault analysis or operational demand side management. The general idea behind the event list is to be able to introduce behaviour which is not related to the basic physical equations of each component type.

During the course of this project there has also been some development of the core distribution model. The distribution module in Dhemos has two basic equation models, i.e. the special case model and the general model. The special case model handles a distribution situation where the supply side of the district heating network can be modelled as a tree structure. This implies that only one production unit and no storage tanks are allowed in the system. This leaves a model that is very easy to solve analytically. However, most district heating networks feature several production units in combination with distribution loops and possibly storage tanks. For such situations the general model is used. Handling this requires using a Newton algorithm for iterating towards an approximate solution (Mathews & Fink, 2004). In the latest version of Dhemos a new general distribution model was added in order to achieve an increased robustness compared to the original model (Hassine & Eicker, 2011). The current model is easier to implement and handle in relation to larger networks which also benefits the scalability of the system.

13.1.2 Implementation of the Dhemos software package

The first version of the Dhemos simulation tool was developed during 2002-2003. The original purpose of the system was to aid in the development of agent-based system optimization tools for district heating systems. In order to do this the system needed to combine simulation models relating to production, distribution and consumption into one coherent package. This first version was implemented purely in Java and featured a graphical user interface for building and maintaining models of district heating systems. All the core simulation functionality was also developed in Java, including all required mathematical functionality. As the project developed it became apparent that this was not an optimal solution due to performance issues. In order rectify this situation a new version of the core simulation tool was developed in C++ which was able to use the Matlab application programming interface for matrix handling capabilities. Although technically sound this solution was in conflict with the aim of developing a free open source simulation tool since this set-up required each user of Dhemos to also have a commercial licence for Matlab. In the current version of Dhemos a transition has been made from Matlab to the Octave framework. Octave is an open source Matlab clone, with much of the original functionality found in Matlab. The current version is developed and run on the Linux operation system, but it can also be compiled and packaged in order to run on Microsoft Windows.

Since the early Java version the file system of Dhemos has changed in order to
increase computational efficiency and scalability. Due to this the original graphical user interface is no longer compatible with the current version of Dhemos. At the moment a Dhemos session is managed through a text-based terminal, but in the future some form of graphical user interface will be developed in order to facilitate a greater user base.

Dhemos uses files with comma separated values. This is done in order to ease the conversion to spreadsheet tools such as OpenOffice Calc or Microsoft Excel. The basic input file for Dhemos is the map file which specifies how all the components in the network are connected. The file also contains the individual parameter values for all the components. In addition to this Dhemos also uses a set of different files specifying specific simulation scenario parameters. The simulator file contains data relating to the current simulation to be calculated, such as simulation length, time step length, log frequency and choice of calculation model. Each calculation model has its own configuration file since the models tend to require quite a diverse set of input parameters. Thus, depending on the choice of calculation model in the simulation file, a different model configuration file will be used. The final file that Dhemos uses is the event file which contain the event list previously described. The event list can be populated either automatically by the pre-processor or manually. Either way, Dhemos requires an event file at least containing at least the outdoor temperature for the current simulation run.

When Dhemos is started a sub-folder is automatically created in the designated log folder. The sub-folder is named by the system time at the start of the simulation. This makes it easy to keep track of different simulation runs. During the simulation this folder will be populated by files correlating to the components specified in the district heating network. It is possible to specific what type of components should log data or not in order to keep the data set more easily manageable. A simulation run of a large district heating network can easily generate several gigabytes of data with full logging an all components if the simulation has a long simulation length in relation to the size of the time step.

13.1.3 Related simulation studies

The basic theoretical background for the Dhemos platform has been described in previous papers (Wernstedt et al., 2003), (C. Johansson & Wernstedt, 2005). In addition to this the functionality of Dhemos has been studied and verified in two projects funded by the Swedish District Heating Association over the years 2010-2012. The first of these projects compared the functionality of Dhemos with a commercially available simulation tool in order to verify the correctness of the output of the Dhemos system (C. Johansson & Wernstedt, 2010a). The focus of the project was the modelling of the distribution network. In this project, data from the Ale network in Gothenburg was used. This network was previously
modelled in an existing tool which eased the verification process. The study concluded that Dhemos produced correct output when compared to the existing model. There were minor differences in the results but it was concluded that this was more likely due to differences in network representation and simulation input rather than any deviation in the actual simulation calculations. The fundamental equation models describing pressure losses, flow and temperature changes in incompressible fluids within piping systems are generally known. However, there are likely differences in the way the network is represented internally in the simulation models and how the the equation models for the different components are combined. In the study it was concluded that calculations governing the pressure loss throughout the piping system were most likely to vary between the two models. This is due to the many variables influencing the calculation, such as water velocity, roughness of pipe walls, approximate methods for calculating the friction factor and temperature dependent values for the viscosity and density of the water.

The second project focused mainly on further development of the production models in the Dhemos package (C. Johansson & Wernstedt, 2012). One of the primary goals was to handle the foundations of production analysis in relation to financial and environmental factors. During the project, production analysis was based on a fuel mix of biomass for the base load with oil for peak load production. However, the Dhemos framework facilitates the addition and manipulation of financial and environmental variables. Additional support for event-driven and algorithm-based processes was also added during this project, which facilitates the process of adding new functionality. The second goal of the project was to develop and analyse methods for identifying system wide energy efficiency measures in smaller district heating networks. In the project the process of configuring and calibrating Dhemos for a specific district heating system was also further developed, and how by using the event list and algorithm-based functionality additions potential measures can be identified and dynamically studied. The third goal of the project was to describe a method for evaluating the impact of such measures from financial and environmental perspectives. To this end three different energy efficiency schemes were described. The schemes all focused on active demand side management and were based on group coordination, market coordination and market coordination with predictive capabilities respectively.

During the project the issue of a dedicated graphical user interface has been discussed, and interviews with potential users has been performed. One very apparent conclusion of the interviews was that Dhemos has to be able to run on a stand alone computer with Microsoft Windows in order to get any traction at all among the user base. Another part of the system that was deemed crucial was the ability to add functionality for operational production optimization on hourly basis. Overall the continuous transition from stationary and long-term simulation
scenarios to operational management simulation has been a consistent trend in the Dhemos development effort throughout the years.

13.2 Experimental set-up

This study used data from Gothenburg Energy concerning the district heating system in Ale, a small town close to Gothenburg. The Ale network is part of the larger Gothenburg district heating network, although it is geographically separate from Gothenburg. For this network there existed a simulation model using commercial simulation software, and data from this system was used as reference for this study. In order to model the Ale network in Dhemos, the available component and network layout data were compiled and analysed.

The district heating system in Ale has a general layout like a tree structure starting in the south at Angered which then moves north for a split between Kungälv and Heljered. Angered, Eka, Perstorp and Heljered are production nodes in the network. In Angered the Ale network is connected to the rest of the district heating network in Gothenburg. In the simulation model this is considered to be the primary production node since most of the heat demand is covered through this flow.

There exists a range of simulation systems aimed at different aspects of district heating. In this study the primary goal has been results relating to distribution analysis.

13.3 Results

Table 13.2 shows the mass flow at different consumer clusters. The values are calculated by Dhemos and the reference system. All the results relate to a simulation scenario with an outdoor temperature of -16°C.

Table 13.3 shows the pressure loss along the distribution pipes in the system. The pipe D1 is the longest pipe at more than 3.8km which obviously translates to a higher pressure loss than the other shorter pipe sections.

Table 13.4 shows the pressure head at different production points in the network. The pressure head is highest at Angered (P1) where the Ale-network receives flow input from the Gothenburg district heating network. From P1 the pressure head drops as the water propagates throughout the network, except in P6 where there is a production unit with a pumping station.
Table 13.2: Mass flow at consumption clusters [kg/s]

<table>
<thead>
<tr>
<th>Consumer cluster</th>
<th>Reference</th>
<th>Dhemos</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>14.8</td>
<td>14.4</td>
</tr>
<tr>
<td>C2</td>
<td>25.2</td>
<td>24.5</td>
</tr>
<tr>
<td>C3</td>
<td>3.7</td>
<td>3.6</td>
</tr>
<tr>
<td>C4</td>
<td>10.6</td>
<td>10.4</td>
</tr>
<tr>
<td>C5</td>
<td>20.8</td>
<td>20.3</td>
</tr>
<tr>
<td>C6</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>C7</td>
<td>7.9</td>
<td>7.7</td>
</tr>
<tr>
<td>C8</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>C9</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>C10</td>
<td>10.5</td>
<td>10.2</td>
</tr>
<tr>
<td>C11</td>
<td>9.9</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Table 13.3: Pressure drop in distribution pipes [m]

<table>
<thead>
<tr>
<th>Distribution pipe</th>
<th>Reference</th>
<th>Dhemos</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>26.6</td>
<td>30.3</td>
</tr>
<tr>
<td>D2</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>D3</td>
<td>8.6</td>
<td>9.9</td>
</tr>
<tr>
<td>D4</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>D5</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>D6</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>D7</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>D8</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>D9</td>
<td>3.7</td>
<td>3.8</td>
</tr>
<tr>
<td>D10</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>D11</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>D12</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>D13</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>D14</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>D15</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>D16</td>
<td>2.4</td>
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<tr>
<td>D17</td>
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<tr>
<td>D18</td>
<td>7.7</td>
<td>7.6</td>
</tr>
<tr>
<td>D19</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>D20</td>
<td>3.0</td>
<td>3.2</td>
</tr>
<tr>
<td>D21</td>
<td>4.0</td>
<td>4.1</td>
</tr>
<tr>
<td>D22</td>
<td>8.0</td>
<td>8.3</td>
</tr>
</tbody>
</table>
Table 13.4: Pressure head throughout the network

<table>
<thead>
<tr>
<th>Distribution pipe</th>
<th>Reference</th>
<th>Dhemos</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>162.2</td>
<td>162.2</td>
</tr>
<tr>
<td>P2</td>
<td>133.4</td>
<td>129.5</td>
</tr>
<tr>
<td>P3</td>
<td>124.8</td>
<td>119.6</td>
</tr>
<tr>
<td>P4</td>
<td>122.8</td>
<td>117.0</td>
</tr>
<tr>
<td>P5</td>
<td>110.0</td>
<td>102.1</td>
</tr>
<tr>
<td>P6</td>
<td>123.7</td>
<td>123.7</td>
</tr>
<tr>
<td>P7</td>
<td>112.7</td>
<td>112.6</td>
</tr>
</tbody>
</table>

13.4 Discussion

In relation to the comparison performed in this study it is important to realize that Dhemos as well as all similar systems are simulation tools and as such they are only capable of delivering a simplification of reality. Furthermore, no matter the accuracy of the model itself, it is still heavily dependent on correct input and parameter values. The simulation system used as reference during this study has been considered correct on the basis of its thorough market penetration.

In general it is possible to state that Dhemos "does the math" correctly in relation to the reference system. There are some differences in the end results but they are most likely due to different was in representing the network and differences relating to input data and simulation parameters. The basic equation models for calculating pressure, mass flow and temperature variations for incompressible fluids in pipe system are commonly known. However, there is most likely some difference in how the the network is represented internally in the simulation systems and how the basic equation models are connected.

It can be noted that it is the calculation of the pressure drop that is most likely to vary between Dhemos and the reference system. This is most likely due to the fact that these calculations are dependent on a large range of variables, such as water velocity, roughness of pipe walls, approximate methods for estimating the friction factors and temperature dependent values for the viscosity and density of the water. However, it can be concluded that Dhemos in general produces results close to the reference data even in relation to pressure drops.

The result section relates to the verification of the functionality of Dhemos. In addition to this several interviews have been performed in parallel during the course of the Dhemos development in order to validate the project. These interviews indicate that there is indeed a need for a coherent framework for combining simulation models of distribution, production and consumption from an academic as well as market perspective. During the development of Dhemos it has been used in several simulation projects with among others Gävle Energi,
13.5 Conclusions

Dhemos forms a basic foundation for simulating district heating networks. During the study the functionality of Dhemos has been verified and shown to be correct. However, at the moment the system is not mature enough to be used as a replacement for commercial alternatives due to lack of an easy to use graphical user interface. The system has a scalable design which provides a framework for further development, especially in relation to simulation studies combining production, distribution and consumption.

When comparing Dhemos to commercial alternatives it should be noted that many existing simulation tools primarily are used as tools for consultants working together with district heating companies. In other words they are normally not sold as stand-alone products, but rather in a packaged deal consisting of both the simulation system itself and consulting hours. However, there is nothing in the open source license of Dhemos preventing people from using it as a tool in such a context.

The focus of this paper has been to evaluate simulation models in relation distribution calculations. However, Dhemos also incorporates models for simulating production and consumption behaviour. The ability to combine such models into one framework is considered to be one of the strong points of Dhemos. This is especially true due to the increased academic interest in research combining market related, societal and technological aspects.

13.6 Acknowledgements

The author would like to thank Göteborg Energi for providing measurement data and access to the existing simulation system.
Bibliography


Concrete for energy efficient buildings the benefits of thermal mass. (2007). Irish Concrete Federation Ltd.


Gustafsson, J. (2011). Wireless sensor network architectures as a foundation for efficient district heating. Luleå University of Technology.


Tekniska Högskolan.


Rossing, O., & Johnsson, J. (2005). Samverkande produktions- och distribu-


Svensk Fjärrvärme.


ABSTRACT
Intelligent district heating is the combination of traditional district heating engineering and modern information and communication technology. A district heating system is a highly complex environment consisting of a large number of distributed entities, and this complexity and geographically dispersed layout suggest that they are suitable for distributed optimization and management. However, this would in practice imply a transition from the classical production-centric perspective normally found within district heating management to a more consumer-centric perspective.

This thesis describes a multiagent-based system which combines production, consumption and distribution aspects into a single coherent operational management framework. The flexibility and robustness of the solution in industrial settings is thoroughly examined and its performance is shown to lead to significant operational, financial and environmental benefits compared to current management schemes.