Operation optimisation of district heating production

District heating systems containing combined heat and power plants

JONAS PREISZ DANIEL GUSTAFSSON

Supervisor: Ulf Ekman Examiner: Erik Ahlgren

Daniel Gustafsson	Jonas Preisz
841020-5952	831122-6230
gustafssd@student.chalmers.se	*preisz@student.chalmers.se*

November 8, 2010

Abstract

With the rising demand of green power many district heating companies are using or consider building combined heat and power plants to increase their competitiveness. This however also creates the need for a way to optimize the production of said power plants. This report will investigate possible solutions for a program that can determine how to best utilize the different boilers available at heat and power plants.

A study of existing methods to analyse district heating systems was conducted in order to evaluate and compare their suitability for optimization of medium sized district heating production systems containing both heat and power production.

A case study of Mölndal Energi is included as an example of how a tool for this kind of analyses can be done. Modelling of the different plants is covered in detail as well as the construction of the optimization software and its interface. Data from Mölndal Energi were used along plant specifications from the contractor to create models for the plants and the heat demand. The resulting program gives a production prognosis for 24 hours and a production distribution over the plants for each hour. It does however not take into account minimum capacity of the plants or start up costs.

The models used in the program are of limited precision and they will need to be fine tuned once data from actual operations of the plant is available. Overall however the program is working as intended and solves the optimization problem.

Acknowledgements

This report is based on work, not only by us, but by many people from Mölndal Energi, Chalmers University of Technology and elsewhere. We would like to give special thanks to Ulf Ekman at Mölndal Energi for his support and guidance through the entire process and for supplying information and rewarding discussions.

For his input on defining the problem and later also in finalizing the report we would also like to thank Erik Ahlgren at the department of Energy and Environment at Chalmers.

For helping us with data for the models and guiding us regarding the needs of the plant operators we would like to thank Göran Lundström at Mölndal Energi.

Sam Boman helped us in an early stage by welcoming us to Eskilstuna Energi to see how they deal with their optimization problems. This information proved critical when deciding how to move on in the project and therefore he deserves our gratitude.

Thank you!

Contents

List of Figures

Chapter 1

Introduction

1.1 Background

With the current energy legislation in Sweden, combined heat and power production is more competitive than ever. The main constituents of this legislation are power certificates, that states that a certain amount of the power produced should come from renewable sources, and the emission fees. Where the district heating production plants before may only have produced heat, there will be more and more power production added when companies see the profit opportunities of the legislation. The increased use of combined heat and power means that more knowledge is needed on the production sites since there will be more aspects to consider when producing both heat and power. Tools to analyse the production situation would help making the necessary decisions needed to be made in order to have a production that is as efficient as possible.

1.2 Purpose

A tool to describe and optimize the daily operations of heat and power plants is needed to gain a better understanding of the production and its coupling to demand. Heat and power producers can with this type of software manage their plants better. This leads to positive effects such as being able to better predict the amount of heat and electricity produced as well as the amount of fuel needed to produce it. This in turn leads to more informed communication with customers and suppliers.

1.3 Goal and scope definition

1.3.1 Goal

The goal of this thesis is to analyse and evaluate some available methods of economically optimising district heating production on a day-to-day basis. The conclusions of this analysis should be usable when recommending a solution for heat and power producers that wants to acquire such a tool.

The goal of the case study is to reccommend a program that can answer a set of questions that will rise in the daily operations of a combined heat and power plant given the specific circumstances at Mölndal Energi. The reccommendation should be based on the analysis made in the previous chapters of the report. The questions are:

- What will the load on the plants be?
- What will the cost for the day be?
- Which fuel mix should be used?
- Which plants should be used?
- Should the district heating link with Göteborg Energi be used?
- Should the power production be maximized or limited?
- Should the flue gas condensation be used?

1.3.2 Limitations

Only programs able to assess the economic aspects of district heating production is to be evaluated. Only costs directly connected to production is included. That means no investment costs, maintenance costs or personell costs. The analysis should be on a rather short time scale to be usable in the day-to-day operations of the plants.

1.4 Disposition of the report

This report consists of five chapters starting with this chapter, the introduction. The introduction explains the motive behind the thesis and limitations that have been set. The second chapter contains theoretical background information available for readers who are not familiar with all the concepts of this report. The third chapter covers methods used to analyse district heating systems and is a basis for the decision regarding the type of tool that should be recommended for Mölndal Energi. The fourth chapter is a case study of Mölndal Energi in which the optimisation tool is created. The fifth chapter contains the conclusions made and gives a short outlook on possibilities for future work connected to this master thesis.

Chapter 2

Theory

2.1 Condensing turbines

In this report we consider the expansion of the steam in the turbine to be a Joule-Thomson process as described in [1] page 132. The maximum theoretical efficiency of such a process can be derived from the work done by the gas during the expansion by dividing this energy with the incoming energy. Using V for volume, P for pressure, T for temperature, R as the ideal gas constant and n the number of molecules we get the following expression where

$$\eta = \frac{P_{in}V_{in} - P_{out}V_{out}}{P_{in}V_{in}} \tag{2.1}$$

Assuming a perfect gas ($PV = nRT$) we can express this in terms of temperature, giving the following efficiency.

$$\eta = 1 - \frac{T_{out}}{T_{in}} \tag{2.2}$$

The in-temperature is the temperature of the saturated steam that has been heated in the boiler and the out-temperature is closely connected to the forwarding district heating temperature via a heat exchanger.

2.2 Optimization

2.2.1 Microsoft Excels solver

The Solver that comes bundled in Microsoft Excel solves nonlinear problems using the generalized reduced gradient method called GRG2. This method will find an optimum as long as the function is continuously differentiable and there are no "numerical difficulties (such as degeneracy or ill conditioning)" [2]

There are some pitfalls that need to be avoided when using a numerical method for finding a local optimum and below a short explanation of the most common ones and how to avoid them will be given.

Non-smooth functions are easily created in excel due to its spreadsheet nature where a multitude of different functions can be used to create the spreadsheet and relations like greater and smaller than and equal to can easily be included inside the normal code. These can give rise to discontinuities which can sometimes cause problems. It is important to make a distinction between the two cases depending on if the discontinuity is dependent on a decision variable in the optimization or not. It is only when the discontinuity is dependent on a decision variable that it can cause a problem for the optimization since if it is independent of decision variables it will appear to the program as smooth. Note also that even if the problem is not smooth, the solver might not take a path to the solution that brings it to the discontinuity which means that even if your problem includes discontinuities the solver can still give a correct answer depending on the starting conditions given and other parameters.

For nonlinear optimization problems the program might encounter local optimums instead of the sought after global optimum. Good modelling practice includes using starting points that are relatively close to the expected optimal values [2].

When deciding on how to implement the optimization we had a number of things to consider.

2.2.2 Optimization limitations

The optimization method used by the solver requires the function to be differentiable, which means that you can only include points that are part of the studied interval in the solution. This makes the solver impractical for including a minimum production of the plants because if it is included as a boundary condition the program will not go outside this boundary and thus will not see the solution where the plant is not used at all. Also the solver will not find a path to that solution even if it is included since the area around the solution is not differentiable.

In non-linear optimization problems, local minima and maxima may cause the solver to stop searching even though the real solution is another point. To avoid this a starting point close to the expected value should be chosen. It is also sometimes possible to use a linear representation of the problem without introducing a too large error.

2.3 Economy

2.3.1 Marginal cost

The marginal cost of a product is the cost per unit for the next unit produced. In mathematical terms it is the derivative of the total cost function with respect to the quantity produced. This derivative can be used to choose which plant should be used for extra production. It is an important figure for district heating companies for when they settle agreements with trading partners and for deciding their district heating prices for their customers. [3]

2.3.2 Cost accounting

When producing several different goods from the same raw materials a problem of accounting these costs to the right product arises. The two main ways of addressing this problem is by either considering one of the products as main product and the other as a by product or if this is not possible to consider them as joint products. In the main product case there is one product that can be considered the most important and in that case all costs are attributed to the main product and the gains from selling the byproduct will benefit the main product. In the case of joint production there are several ways to handle the accounting as discussed in [4] and [5].

Chapter 3

District heating analysis

This chapter aims to explain some of the ways to analyse different parts in a district heating system. It will cover some of the differences between commercial and custom made softwares. As custom made softwares can be very diverse, choices regarding two of the most important functions of the software, load prediction and optimization are compared.

A small market survey was done in order to see how other companies handled the problems that Mölndal Energi will face. We hoped to get enough input to be able to determine what kind of software that Mölndal Energi should use; if there is a suitable commercial program on the market or if a customized program should be made. In order to get this information, we sent an e-mail to the district heating companies in Uddevalla, Gävle, Jönköping, Borås and Göteborg. We also made a visit at Eskilstuna Energi, which has a customized software made by their operation manager, Sam Boman.

3.1 Market survey questions

The questions that we asked were:

- What kinds of heat or power plants do you have? Size, type, and if you have an accumulator.
- Do you use a computer program to plan/optimize your operations? In that case, what program? Commercial or self made?
- Why did you choose the program that you use?
- What are the strengths and weaknesses of your program? Do you miss anything in it?

3.2 Market survey results

Out of the six companies we asked, three uses a in-house made optimization program, one uses a commercial program, one uses no program and we did not get an answer from the last company.

The company that does not use an optimization program is Uddevalla energi, who produce very little electricity in comparison to heat. An important difference in the power production between Mölndal Energi and Uddevalla Energi is that Uddevalla uses municipal waste as fuel. That means that incinerating the fuel serves a purpose of its own, not just an economic purpose. Therefore, Udevalla Energi is not in the same need of an optimization software as the companies that uses biofuel. We did not get any answer from Jönköping Energi.

Gävle Energi, that uses a commercial program made by Vitec, uses their program in a way that is much like the way that Mölndal would use their program. They use it to plan their produced effect as well as choosing the type of fuel they will use. They have accumulators in their plants, something that Mölndal does not have. Their program can model charging and discharging those and that modelling is also an important part of the program that Eskilstuna Energi uses, a customized excel document. While the program solves some of Gävle Energis problems, it is a problem for them that the program is no longer updated since the company that made it has shut down. They also mentioned it being hard to use, something that improved with time though.

The three companies that uses self-produced programs are Göteborg, Borås and, as mentioned before, Eskilstuna. The reason for creating a program on your own is usually the feeling that the commercial programs are not good enough, and that one could make a better model of ones heat and power plant than is possible in the commercial versions. The cons that Gävle experienced with their commercial program could easily be avoided with good planning when making a program and good documentation, so that the program can be improved as new demands on information arise. All these three companies have a similar situation to Mölndal, with several plants and a production of both district heating and electricity.

3.3 Optimization software on the market

In the market survey, one company answered that they use a commercial program. Here, that program and other well known programs for analysing district heating production will be investigated.

3.3.1 Martes

Martes is a software that simulates production of district heating, power and steam in a district heating system. According to the developer, Profu, it can be used as a tool to make decisions regarding investments, choice of fuel, contract negotiations and more. The time resolution for Martes is twelve hours and it is recommended for analyses that have a time span of a week up to several years.[7] For every time point in the studied year, the operation of the available plants are simulated. The plant with the lowest marginal cost is used first up to its maximum capacity and so on until the load demand is met. The program then presents a set of results, such as load duration curves, how much energy that has been produced and the total cost over the time period. This time period is most often a year. [7]

3.3.2 Markal

MARKAL is a model developed to evaluate energy systems at a national, regional or community level over a long period, often 40 to 50 years. It is often used to study the effects of different types of legislation on the system by running several different simulations and comparing them. MARKAL can identify the least-cost energy system given certain restrictions. [8]

3.3.3 Vitec planner

Vitec planner is a program that predicts load demand and plans the production for a district heating producing company. It is meant to be used on a daily basis and has a time resolution of one hour. According to Vitec the program works in two steps. First a load demand prognosis is created and using information about temperature and possibly other data as well. In their information sheet they state that wind, time of the day and time of the year as well as social aspects also is of great importance, but wether the program actually include this or not is uncertain, we can only assume that it does. [9] [10]

The second part of the analysis is the production planning. The Planner can be complemented with a modell of the production plant that includes descriptions of start up costs, minimum and maximum loads, efficiencies and physical limitations. With this information the program will suggest a way to run the plant to minimize the production costs. [9]

3.4 Custom made software

Several companies said that they use custom made programs. In this section, some methods to use when making such a program will be investigated.

3.4.1 Economic analysis

For analysing heat and power plants there are several different methods and tools available. These are all applicable for different areas of analysis with regards to both system definitions and scope of time. Olausson [5] goes through the most common of these methods and lists the areas where they are useful. For our studies the methods described as Engineering economics and Thermoeconomics are the most relevant as they focus on economic aspects.

Engineering economics

According to [5] engineering economics is the tool that together with energy analysis has the largest impact on decisionmaking situations today. It allows the calculation of the total production costs but not how much each product costs if several products are produced. It is possible to include many different costs in the analysis from investment cost to fuel costs. When a longer time span is used discounting is also included in the analysis and for long term planning and investments the availability will also be of great importance.

The exact way of calculating the cost function can vary depending on the goal and scope of the analysis. The analysis will vary depending on if its an economic analysis of a long term investment or if the marginal cost of production is of interest. In [5] Olausson gives an example of a generic function for calculating the cost of producing electricity for a long term perspective and taking construction costs in consideration.

$$Y_{el} = \frac{TCR \cdot \lambda}{P \cdot T_{eq}} + \frac{Y_F}{\eta} + \frac{U_{fix}}{P \cdot T_{eq}} + u_{var} \tag{3.1}$$

$$\lambda = \frac{z}{1 - (1+z)^{-n}} \tag{3.2}$$

In this equations first part TCR is the total capital requirement, λ is the annuity factor dependant on z and n, the discount rate and the amortization period respectively. P is the power output and T_{eq} is the equivalent utilization time. The second part of the equation relates the fuel price Y_F to η which is the average plant efficiency. The last two parts represents the fixed and the varying operation and maintenance costs.

Thermoeconomics

Thermoeconomics is similar to engineering economics in that it uses thermodynamic laws to make an economic calculation. The point where the two methods differ is in the allocation of a cost for each goods produced. This is done by using the concept of exergy as a method of dividing the costs. The drawbacks of using this method is that it requires a reference state and that it requires specific knowledge of all the exergy losses in the processes that are to be modelled. [5]

The reference state involved in this analysis is dependent on the environment in which the plant is operating. Tabulated values are available for common environments but for more uncommon temperature and pressure ranges the values may have to be calculated.

Exergy is often denoted as physical, kinetic potential and chemical exergy with separate equations for each part. The potential and kinetic exergy can be neglected when performing energy analyses of heat and power plants. [5]

$$E_{ph} = (U - U_0) + p_0(V - V_0) - T_o(S - S_0) \tag{3.3}$$

$$E_{ch} = \sum n_i(\mu_i - \mu_{i0}) \tag{3.4}$$

Equation 3.3 gives the physical component of the exergy and equation 3.4 gives the chemical exergy. U is the internal energy of the system, S is the entropy, T is the temperature, V is the volume, p is the pressure and the subscript 0 is used for the reference state.

These equations are then used to calculate the exergy flows of individual components in the plant, like the boiler or the turbine. Adding the different costs associated with running the plant to these equations allows to calculate the costs associated with each process. [5]

3.4.2 Load demand modelling

It is considered well known that the main factor when determining the heat load demand for a district heating grid is the outdoor temperature and the behaviour of the consumers [11] [12]. The ways to model these dependencies are varied though. Two main categories could be identified, top-down models which starts at the total demand data and finds patterns in that, and the bottom-up models, which starts at the consumers and sums the loads in the net to get the total load.

Top-down models

In [11] it is suggested to have the load demand function as two added functions; one that is dependant on outdoor temperature. This function is divided into five linear functions, one for each fifth of the temperature range of the input data. The second component of the function describes the dependency of the hour in the week. It is acquired by subtracting the actual heat demand from the data with the modelled heat from the temperature function for each hour in the week, then creating an average value for each hour. This dependency describes the behaviour of the consumers to a degree, as it can cover the daily routines such as showering, heating of buildings that do not need to be heated all the time, and other things. It does not, however, describe phenomenons that occur over larger time spans, such as holidays. The model created in the article has a relative error that varies between 6.24 and 15.22 per cent for eight scenarios. The scenarios are two different district heating systems for the four quarters in a year.

Bottom-up models

In [12], the author describes a possible way to predict the amount of heat consumed by a building. In the most advanced model, the input data are: outdoor temperature, indoor temperature, wind speed, solar radiation, temperature in the previous 24 hours, mass flow of the heat carrier in the previous 24 hours and hot water temperature. The authors analysis of the results shows that the outdoor temperature is, the most important parameter. The second most important parameter in this model of heat consumption is the flow rate of the district heating water over the last 24 hours, it is more important than the outer conditions such as wind speed and solar radiation. According to the author, this parameter illustrates the behaviour of the consumers.

In [13], the author explores the means to model the heat demand in large district heating grids. The load is suggested to be divided into four parts, which are to be added in order to get the total load. These parts are space heating for buildings, domestic hot-water preparation, distribution losses and finally what the author calls additional work-day loads. In [14], space heating is said to be the most significant factor. It is estimated to contribute with 60 per cent of the total load. Hot-water preparation makes up for 30 per cent, while distribution losses and additional work-day loads makes up for the remaining 10 per cent. The different parts of the load varies with different parameters. The space heating load is mainly dependant on the quality of the housing and the outdoor temperature. The demand for hot-water preparation is mainly determined by the time of the day, week and year. Even events such as holidays affect this load. The distribution losses are rather constant and are determined by the quality of the district heating grid and it's connection to the houses. The last part of the total load, additional work-day loads is not thoroughly explained, but it is connected to the additional need for district heating when people work.

3.5 Discussion

When comparing the available alternatives to each other we see that Martes includes a lot of the features required. It can make an accurate distribution of the production, but it requires that the load prognosis is given. It can also calculate costs for production. Its main drawbacks are that it uses a too long time scale, that certain parameters are constant and that a production prognosis must be given which creates a need for additional tools.

Markal is designed for evaluating energy systems at a national to community level for long time periods. It is often used to study legislation effects but it is possible that it could be adapted to smaller scales and then be used to find the least-cost energy system but this would most likely include some extra work. It also requires the load demand prognosis to be known.

Vitec planner is a software designed specifically to solve problems concerning daily plant operations at district heating plants. When compared to the questions in chapter 1.3.1 we see that it can create a load demand prognosis which is then used to make an optimized production distribution plan. Much is uncertain regarding the algorithm used and which information is included in the model. Gävle energi also claims that it was not as user friendly as they would have preferred and that is is no longer updated. After several unsuccessful attempts to contact Vitec for further information we must conclude that this is the case which makes it a somewhat uncertain option.

When making a custom made program it is possible to ensure that all the questions in 1.3.1 are answered, at least to some extent. Many design choices have to be made regarding aspects such as load demand modelling, time scale and cost accounting.

When creating a load demand model, the available data and time are important to consider. With sufficient time, enough data could be gathered. The ideal model would be created using a bottom-up method since it requires more knowledge of the system, which could be used to model the system in greater detail. This approach demands more information and work than would be needed in comparison to a top-down model. The first parameter that should be included in any load demand prognosis is outdoor temperature. Literature suggests that consumer behaviour is the second most important parameter, although the ways to model it varies from article to article. Parameters of lesser importance is solar radiation and wind properties.

When deciding about the time scope and resolution of a program that plans the daily operations one has to think about how often the program is meant to be used. The scope should at least cover the time period between the executions. There is a certain inertia in the operation of the plant, so a too fine resolution is not really helpful. It would also mean that there might be too much data for the operator to handle. A too rough time resolution would meant that much the load demand prediction and the production distribution would be wasted, and the efficiency of the program would go down. These choices should be made with the operators and their work routines in mind.

Cost accounting could be done in several ways, and all of them could be considered correct. A simple way would be to account all costs to the main product, which in the case district heating production would be heat. This would mean that selling power would be considered lowering the production cost of district heat. The option would be to allocate some of the cost to power and some to heat. To do this is a delicate matter, how should the two products be valued in comparison to each other? In [5], a method called thermoeconomics is mentioned. It could be used to allocate costs to the two products by calculating exergy flows in the production process. This tool requires large calculations and may not be suited for a frequently used program, but it could instead be used to create a series of cases. The case that is the most similar to the actual operations would then be used to allocate the costs between heat and power.

Chapter 4

Case study: Mölndal Energi

At Riskulla, three different types of plants will we available when the new combined heat and power plant is ready for operation. They are the combined heat and power plant (CHP), the biofuelled hot water boiler (HWB) and an oil fueled HWB. The hot water boilers have a rather simple concept. The fuel is combusted in the furnace and the heat produced in the furnace is used to heat up water that moves in a circulating system around the furnace. The high pressure hot water produced is cooled at heat exchangers where the heat is transferred to the district heating water.

In the biofuel HWB at Riskulla, there is also a flue gas condenser (FGC) which uses the heat that is left in the flue gas after leaving the furnace. It is basically a heat exchanger where the smoke gas heats the return water from the district heating grid. A combined heat and power plant will, as the name implies, produce both heat and electric power. In a CHP plant the steam from the boiler can be led both through a condensing turbine and a heat exchanger, or one after the other. By directing the flows, you can control how much power and heat that will be produced. The condensing turbine uses the heat content in the steam to work. It uses two temperatures, the high temperature of the incoming steam and the low temperature of the outgoing water in the district heating grid to determine its efficiency.

The combined heat and power plant being constructed at Riskulla will generate 70 MW heat from the boiler or 45 MW heat and 23 MW of electricity and it is also able to produce an extra 21 MW of heat from the flue gas condensation.

Most of the data we have used comes from the contract between Mölndal Energi and its suppliers, where calculated performance of the plant and its components is presented. When it comes to the properties of the district heating grid historical data was used. This data was gathered during the period 2 September to 2 December 2008 with measurements nine times per day, resulting in 816 data points.

4.1 Decisions

Based on the discussion in section 3.5 a set of basic decisions about how to proceed with the work at Mölndal Energi can be taken. Based on the experiences of other district heating providers as well as the needs of Mölndal energi it was decided to create a custom made software to solve the optimization problems.

The program needs to be able to do a load demand prognosis since it is the basis around which to optimize the plants. The model used to predict the load demand can be constructed in many different ways. The bottom up method gives good precision but it also requires a lot of data for many different data types such as wind speed, cloud coverage and so on. This data is not available at Mölndal energi so a top down model was chosen utilizing the data available. In [11] a model where each hour in a week has its own weight is used. For the modeling at Mölndal Energi a model with each hour of the day having its own weight and a distinction between weekends and weekdays is also made.

Once the load demand prognosis is complete a way to optimize the way to produce this energy must be found. First the marginal production cost functions of production for each plant needs to be calculated. The method described by Olausson in [5] as Engineering economics was chosen because of its relative simplicity compared to the method described as Thermoeconomics. Calculating reference states and exergy losses for each possible state is more suited for a study of a few specific cases than for a program used over a wide range of states.

The engineering economics method however leaves us with a basic problem of accounting the total production costs to the two different goods. It was decided upon to use a standard method of considering heat as a main product and power as a by-product. This requires power price to be known in advance but this should not be a problem with the current electricity contract model used.

When choosing an optimization algorithm Microsoft Excel Solver was chosen. It is capable of handling nonlinear problems and is widely used and is well documented. It also allows the program to be created in an environment that is familiar to the end users.

4.2 Method

In this chapter the general methods used in the different parts of the project is described.

To be able to answer the questions stated in 1.3.1 and create this tool, a model of the plants and and other parts of the system is needed. These models should describe all the relations needed to answer the questions. Based on these models, cost functions for each plant should be modelled. Aspects that is certainly needed to model are:

- Effectiveness of the plants
- Fuel consumption
- Fuel properties

- FGC performance
- The alpha value of the heat and power plant
- Load demand

The data used in this chapter comes from several sources. Data describing the heat and power plant comes from the contract between Möndal Energi and its contractor. Data describing the FGC comes from specifications on the FGC on the heat only boiler at Riskulla, as no data on the FGC that will be used on the combined heat and power boiler is available. The load demand data comes from measurements done by Mölndal Energi

4.2.1 Load demand modelling

The load demand of the net varies with many parameters. The most obvious one is the outdoor temperature, as discussed in literature [11] [12] [13]. The colder it gets, the more heat is needed to warm the houses. What is not as obvious or easy to model is the behaviour of the demand at different times. The data we have used comes from logs that Mölndal Energi keeps for several relevant data types. We have used data, measured between 2 September and 2 December in 2008 at about nine times every day. The most important dependence is how the demand varies with outdoor temperature. We chose to create a function that describes load demand as a function of outdoor temperature, and try to make all other dependencies multiplicative with that function. The second most important feature that this load demand function must describe is how the demand is distributed over the day. What was done was firstly to make a polynomial extrapolation of the load as a function of the outdoor temperature. This was done for degrees of the polynomial up to six. As we consider this the most vital function, we also calculated the sum of the squared difference between the function and the data points for each model, to get more than visual information when deciding which model that should be used. To distribute the load over the day, the data points were sorted according to which hour of the day they were measured. Then the mean values for each day was calculated and each data point was compared to the daily mean temperature. The fractions of the daily means were sorted according to which hour of the day they were measured, and plotted versus the hour of the day. As the customers behavior changes between weekdays and weekends, two different sets of data were assembled and two separate models were constructed.

4.2.2 Modelling of Riskulla

When making a model over the Riskulla plant data was mainly taken from the contract with the suppliers of the heat and power plant. After studies in literature on heat and power plants, as well as discussions with our supervisor, the most relevant functions to model had been identified. When analyzing the data the Matlab function polyfit, which takes function values and makes a least square fit to a polynomial function from that information, was frequently used. This can also be done in Excel, but the advantage of

MatLab is that one can get far more significant digits and one can also choose any degree for the polynomial. The amount of significant digits is important for the precision of the model, especially when using higher degree polynomials.

Plant efficiency

For plant efficiency, we consider two different efficiencies, boiler efficiency and turbine/heat exchanger efficiency. The data for the boiler efficiency were given in the contract, where five load scenarios were presented. For turbine/heat exchanger efficiency the data were taken from fifteen heat balance diagrams, also included in the contract. When modelling these efficiencies they were found to be close to constant over all the cases. A simple ratio between outgoing and incoming energy was used to find the numerical values of the efficiencies.

Alpha value

The alpha value is the ratio between power production and heat production. Data on both these productions were given in the load scenarios that was also used to model the plant efficiency. Dividing power production with heat production and plotting the quotients versus furnace load gives the following figure.

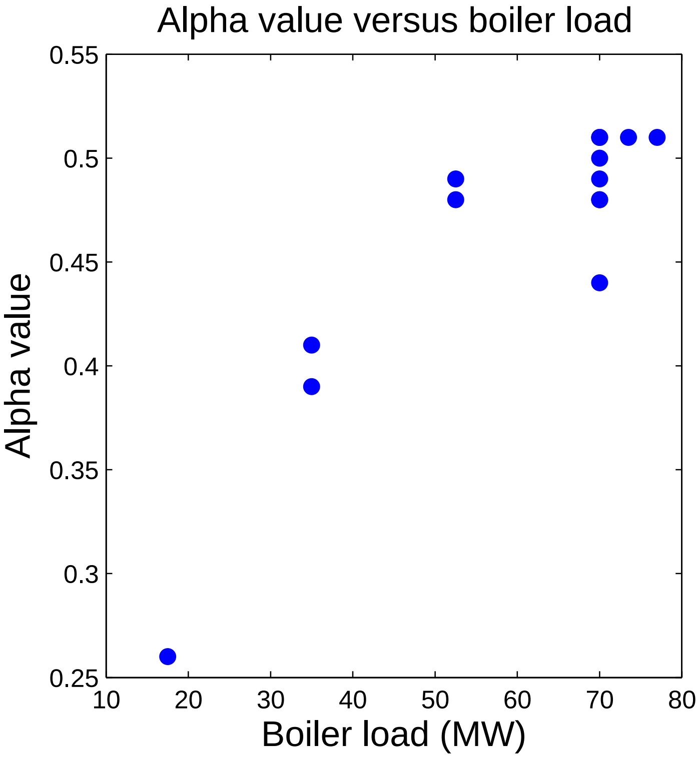


Figure 4.1: Alpha values versus boiler load

What we can see in 4.1 is a rising curve with rather large variance at full load. Using these data we can create a function for the boiler load dependency of the alpha value. Maximum alpha value is attained at low temperatures. Using the lowest temperature values to attain the maximum alpha values at each boiler load case we produced the maximum alpha values function to be combined with the temperature dependency function.

Since the efficiency of the turbine is connected to the temperature of the outgoing district heating water as discussed in 2.1, a relation between the alpha value and the mentioned temperature was investigated. The temperature data was also provided in the load scenarios. The investigation was done at a single load level, to single out the temperature dependency. The chosen load was full load, where the most data was available. The resulting plots can be seen in 4.2.

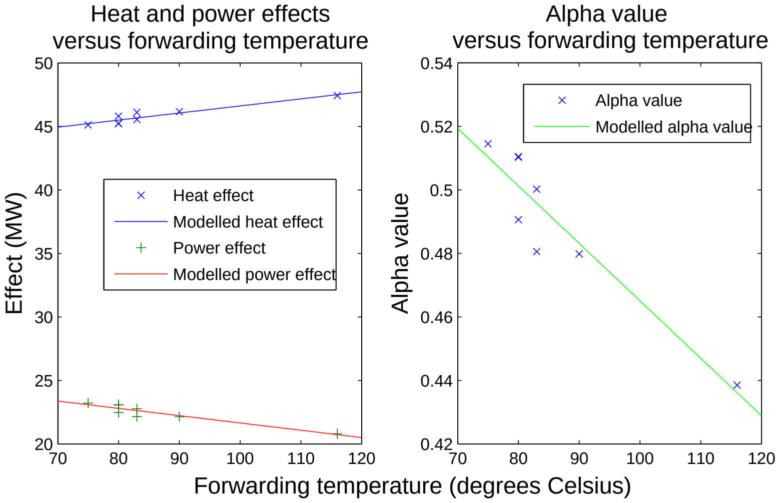


Figure 4.2: Alpha values at full furnace load versus forwarding temperature

The alpha values dependency on the outgoing temperature at full boiler load was approximated as a linear function as seen in right part of the figure above. We have assumed that the alpha value follows the same linear temperature dependency at all loads. By multiplying a normalized version of this function with the previous maximum alpha value function we have a function for the alpha value depending on outgoing temperature and boiler load.

FGC modelling

There was very limited data available in the contract specifications regarding the FGC. An estimation had to be done on data on another FGC. This other FGC has a worse performance, and that is all that is known except for the data. Here, the FGC maximum effect is presented as a fraction of the furnace load that is dependant of the return water temperature and moist content of the fuel. A plot was made where effects were plotted against moist content for several return water temperatures.

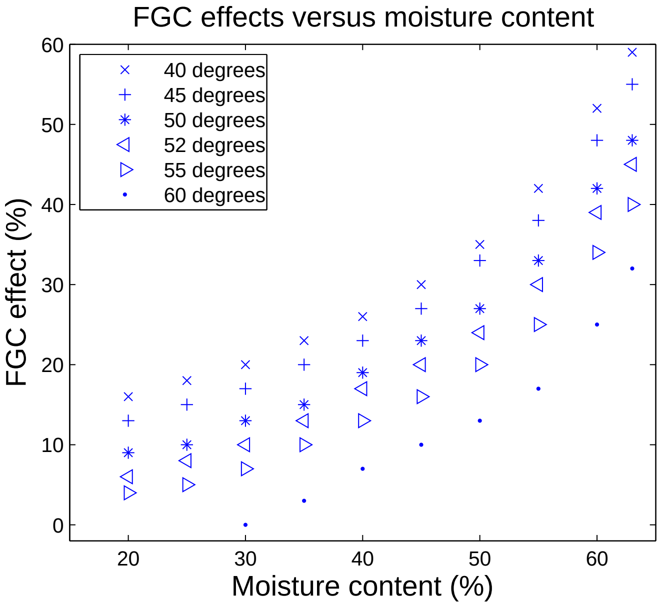


Figure 4.3: FGC maximum effect for several return temperatures versus fuel moisture content

What can be seen in 4.3 is that the curves behave similarly as the moist content raises and the shape of the curves seem exponential. In order to study the moisture content dependency of the plant efficiency, independent of the temperature, a comparison was made between the 50 degree curve and the others, respectively. A plot of each of the curves divided by the 50-degree curve 4.4 shows what looks like linear functions. The choice to divide with the 50-degree data was arbitrary. 50 degrees is in the middle of the temperature span.

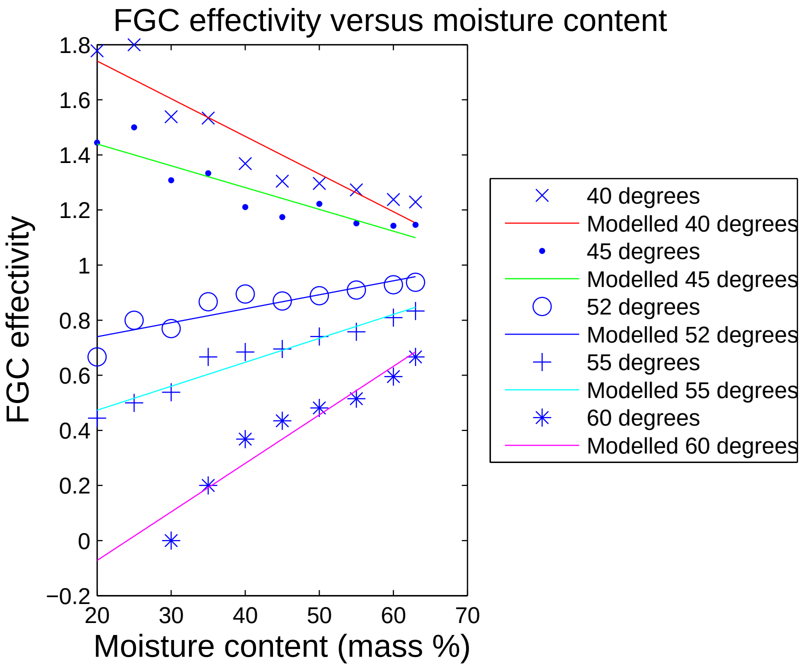


Figure 4.4: FGC effectivities as compared to 50 degrees return temperature for several return temperatures versus fuel moisture content

To unite these linear functions into one function, that function would be a linear function where the parameters vary as the moist content changes. The constant and the linear coefficient of the linear functions in were plotted as functions of the moisture content.

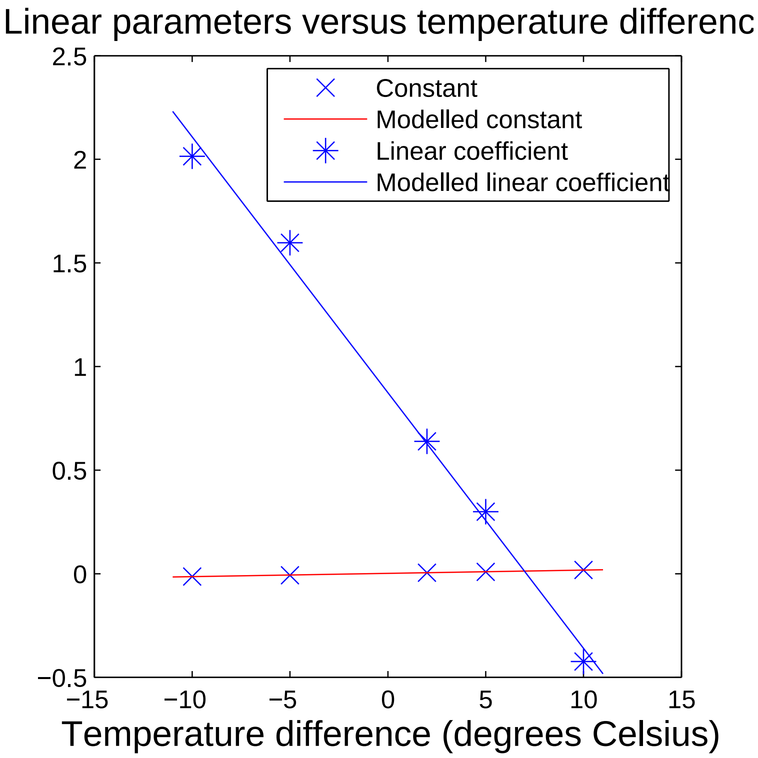


Figure 4.5: FGC linear parameters versus fuel moisture content

Even in 4.5, the dependency seem to be linear. This gives us the ability to model the efficiency curves for varying moisture content for return water temperatures in a wide temperature range.

What is left is to determine the 50-degree function. After testing polynomials and exponential functions, the exponential model was found to be the most suitable in a least square sense. The exponential function can be seen in 4.6

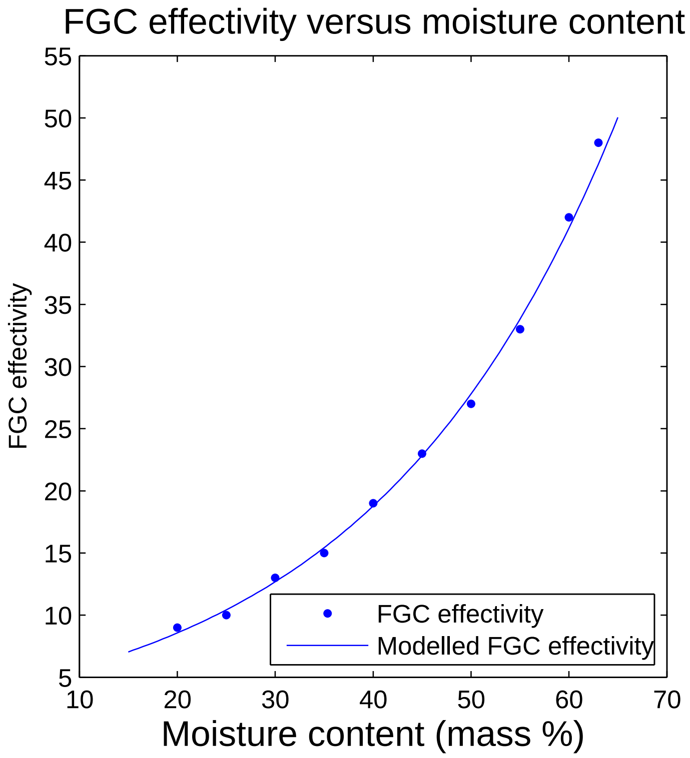


Figure 4.6: FGC efficiency at 50 degrees return temperature versus fuel moisture content

4.2.3 Optimization software

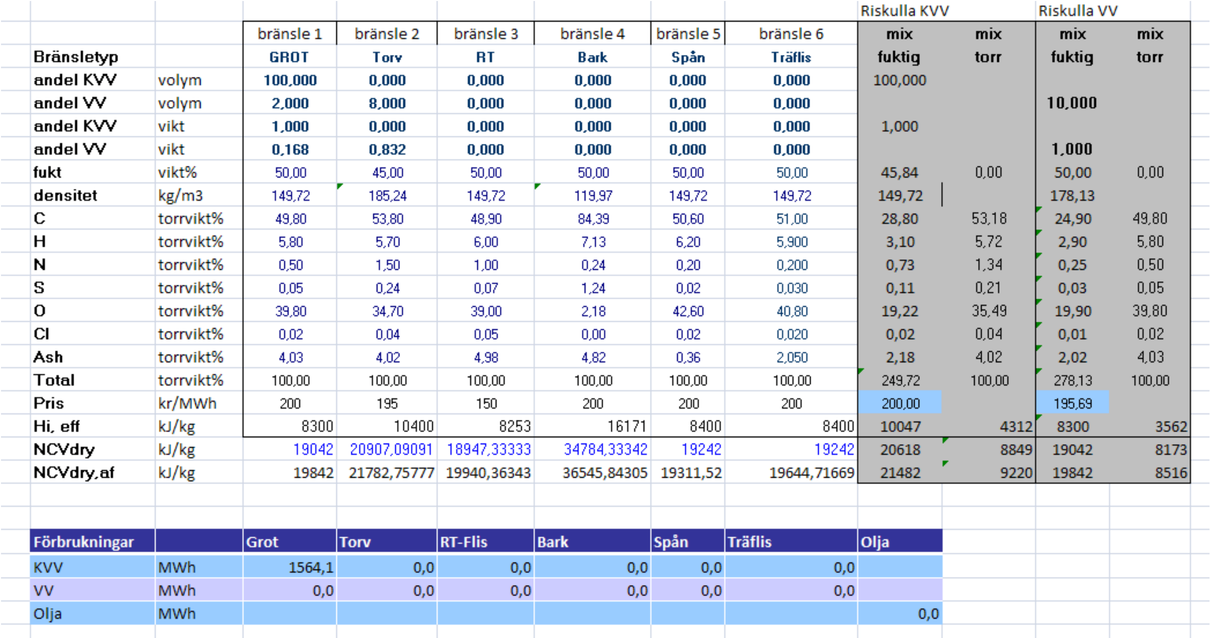
The optimization program was made in Excel using Visual Basic and the spreadsheets of an usual Excel document. The basic algorithm used is the generalised reduced gradient method implemented in the solver that come bundled with Excel. This algorithm is then used for every hour separately to create the final result which is a production prognosis together with a production distribution recommendation.

Platform

The program is made in an Excel sheet. The main argument for this is that the plant operators are allready proficient in Excel and all the required software is already available. For a more detailed discussion on the choice of platform and its implications see chapter 4.4.3.

Interface

The sheet consists of seven tabs that together with an optimization algorithm and an input interface make up the basis of the optimization program. The program generates a production plan for the day and delivers it through the results sheet. The different tabs represent one of the tasks that the program performs: modelling of the plants, economic information, district heating grid prediction, fuel mixing and the main tab; the optimization and results tab. The price information tab is probably the most simple one. It contains typical market prices of consumption goods that is used in the plants. These goods are both fuels and other things that are used in the production, such as sand and ammonia. Here, the marginal cost of Göteborg Energi, the electricity price and the heat price is also presented.

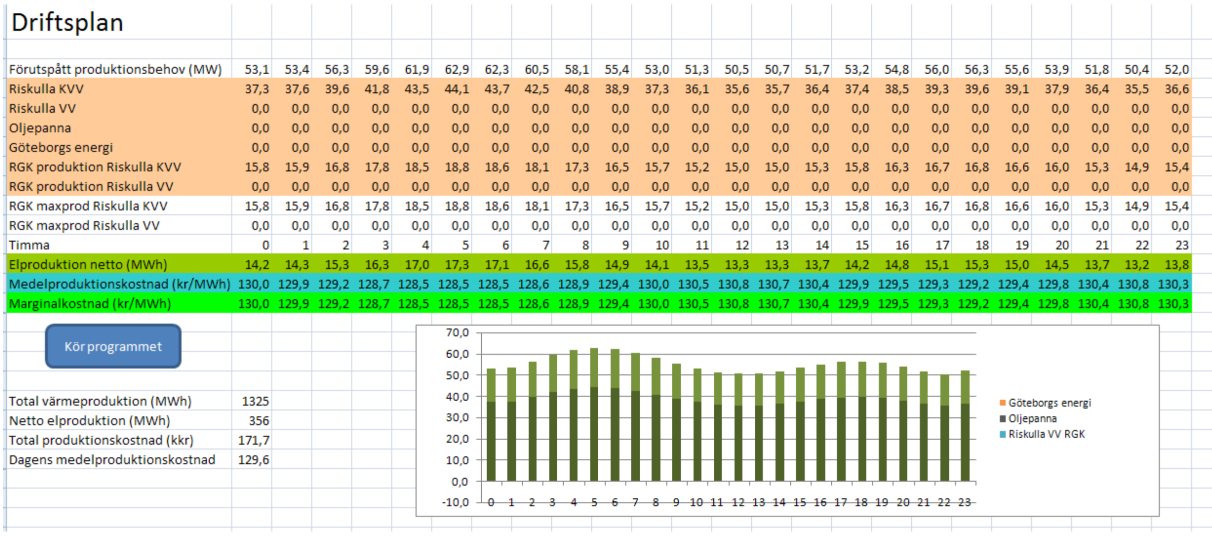


								Riskulla KVV		Riskulla VV	
		bränsle 1	bränsle 2	bränsle 3	bränsle 4	bränsle 5	bränsle 6	**mix**	**mix**	**mix**	**mix**
Bränsletyp		**GROT**	**Torv**	**RT**	**Bark**	**Spån**	**Träflis**	**fuktig**	**torr**	**fuktig**	**torr**
andel KVV	volym	**100,000**	**0,000**	**0,000**	**0,000**	**0,000**	**0,000**	100,000			
andel VV	volym	**2,000**	**8,000**	**0,000**	**0,000**	**0,000**	**0,000**			**10,000**	
andel KVV	vikt	**1,000**	**0,000**	**0,000**	**0,000**	**0,000**	**0,000**	1,000			
andel VV	vikt	**0,168**	**0,832**	**0,000**	**0,000**	**0,000**	**0,000**			**1,000**	
fukt	vikt%	50,00	45,00	50,00	50,00	50,00	50,00	45,84	0,00	50,00	0,00
densitet	kg/m3	149,72	185,24	149,72	119,97	149,72	149,72	149,72		178,13	
C	torrvikt%	49,80	53,80	48,90	84,39	50,60	51,00	28,80	53,18	24,90	49,80
H	torrvikt%	5,80	5,70	6,00	7,13	6,20	5,900	3,10	5,72	2,90	5,80
N	torrvikt%	0,50	1,50	1,00	0,24	0,20	0,200	0,73	1,34	0,25	0,50
S	torrvikt%	0,05	0,24	0,07	1,24	0,02	0,030	0,11	0,21	0,03	0,05
O	torrvikt%	39,80	34,70	39,00	2,18	42,60	40,80	19,22	35,49	19,90	39,80
Cl	torrvikt%	0,02	0,04	0,05	0,00	0,02	0,020	0,02	0,04	0,01	0,02
Ash	torrvikt%	4,03	4,02	4,98	4,82	0,36	2,050	2,18	4,02	2,02	4,03
Total	torrvikt%	100,00	100,00	100,00	100,00	100,00	100,00	249,72	100,00	278,13	100,00
Pris	kr/MWh	200	195	150	200	200	200	200,00		195,69	
Hi, eff	kJ/kg	8300	10400	8253	16171	8400	8400	10047	4312	8300	3562
NCVdry	kJ/kg	19042	20907,09091	18947,33333	34784,33342	19242	19242	20618	8849	19042	8173
NCVdry,af	kJ/kg	19842	21782,75777	19940,36343	36545,84305	19311,52	19644,71669	21482	9220	19842	8516

Förbrukningar		**Grot**	**Torv**	**RT-Flis**	**Bark**	**Spån**	**Träflis**	**Olja**
KVV	MWh	1564,1	0,0	0,0	0,0	0,0	0,0	
VV	MWh	0,0	0,0	0,0	0,0	0,0	0,0	
Olja	MWh							0,0

Figure 4.7: The fuel tab of the software

The fuel tab 4.7 contains data on the fuels that are probable to be used. Information such as carbon content and dry heating values are constants. There are also variables used in the optimization here, such as the moisture content of the different fuel types and the fuel mix shares of each fuel. Each of the different plants also have their own tab where plant specific data is stored for use in the optimization. Maximum production capacity, generator and boiler efficiencies and more is found here.



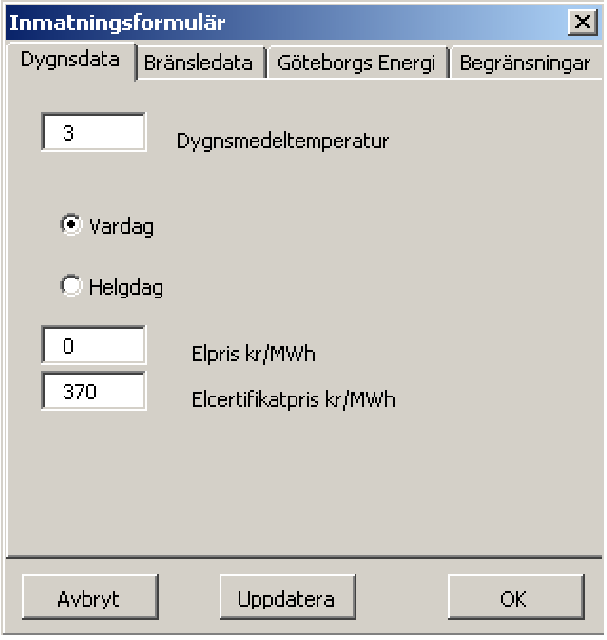
Driftsplan

Förutspått produktionsbehov (MW)	53,1	53,4	56,3	59,6	61,9	62,9	62,3	60,5	58,1	55,4	53,0	51,3	50,5	50,7	51,7	53,2	54,8	56,0	56,3	55,6	53,9	51,8	50,4	52,0
Riskulla KVV	37,3	37,6	39,6	41,8	43,5	44,1	43,7	42,5	40,8	38,9	37,3	36,1	35,6	35,7	36,4	37,4	38,5	39,3	39,6	39,1	37,9	36,4	35,5	36,6
Riskulla VV	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Oljepanna	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Göteborgs energi	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RGK produktion Riskulla KVV	15,8	15,9	16,8	17,8	18,5	18,8	18,6	18,1	17,3	16,5	15,7	15,2	15,0	15,0	15,3	15,8	16,3	16,7	16,8	16,6	16,0	15,3	14,9	15,4
RGK produktion Riskulla VV	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RGK maxprod Riskulla KVV	15,8	15,9	16,8	17,8	18,5	18,8	18,6	18,1	17,3	16,5	15,7	15,2	15,0	15,0	15,3	15,8	16,3	16,7	16,8	16,6	16,0	15,3	14,9	15,4
RGK maxprod Riskulla VV	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Timma	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Elproduktion netto (MWh)	14,2	14,3	15,3	16,3	17,0	17,3	17,1	16,6	15,8	14,9	14,1	13,5	13,3	13,3	13,7	14,2	14,8	15,1	15,3	15,0	14,5	13,7	13,2	13,8
Medelproduktionskostnad (kr/MWh)	130,0	129,9	129,2	128,7	128,5	128,5	128,5	128,6	128,9	129,4	130,0	130,5	130,8	130,7	130,4	129,9	129,5	129,3	129,2	129,4	129,8	130,4	130,8	130,3
Marginalkostnad (kr/MWh)	130,0	129,9	129,2	128,7	128,5	128,5	128,5	128,6	128,9	129,4	130,0	130,5	130,8	130,7	130,4	129,9	129,5	129,3	129,2	129,4	129,8	130,4	130,8	130,3

Total värmeproduktion (MWh)	1325
Netto elproduktion (MWh)	356
Total produktionskostnad (kkr)	171,7
Dagens medelproduktionskostnad	129,6

Figure 4.8: Figure caption

The main tab 4.8 presents information about how much heat that is expected to be needed and an option to calculate the optimal way to produce that heat with the currently available plants. To be able to calculate these values the program needs a few data from the user and these are filled in in the window shown before the optimizer starts. This window is divided into 4 tabs by which activity they are connected to. The first tab 4.9 named Dygnsdata contains information related to the current 24 hour period such as temperature and if its a holiday or a workday.



3 Dygnsmedeltemperatur

● Vardag

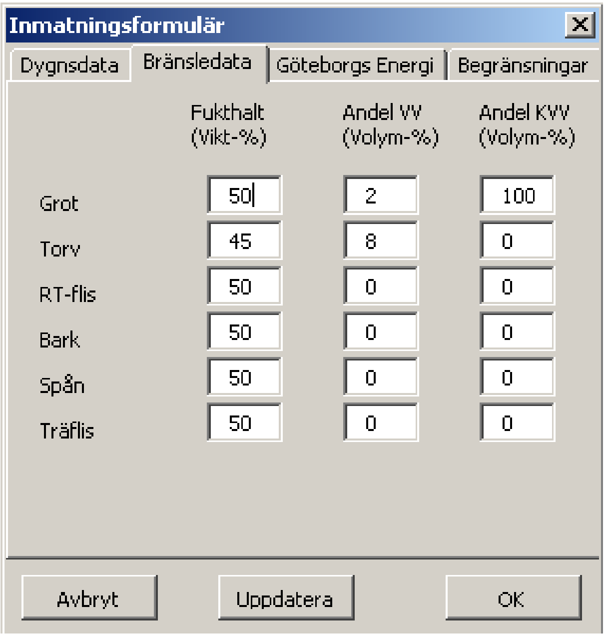
○ Helgdag

0 Elpris kr/MWh

370 Elcertifikatpris kr/MWh

Figure 4.9: The main tab of the input window

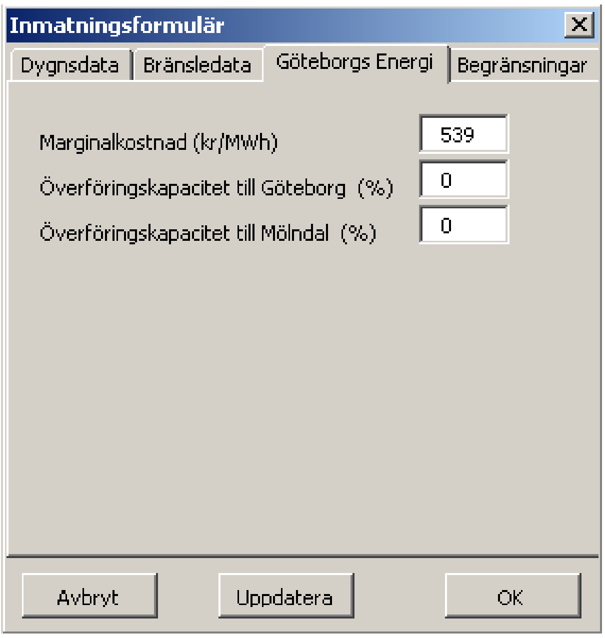
The second tab 4.10 contains information about the fuel data and more specifically the share of the fuel that is of a certain type and the moisture content of each fuel type.



	Fukthalt (Vikt-%)	Andel VV (Volym-%)	Andel KVV (Volym-%)
Grot	50	2	100
Torv	45	8	0
RT-flis	50	0	0
Bark	50	0	0
Spån	50	0	0
Träflis	50	0	0

Figure 4.10: The fuel tab of the input window

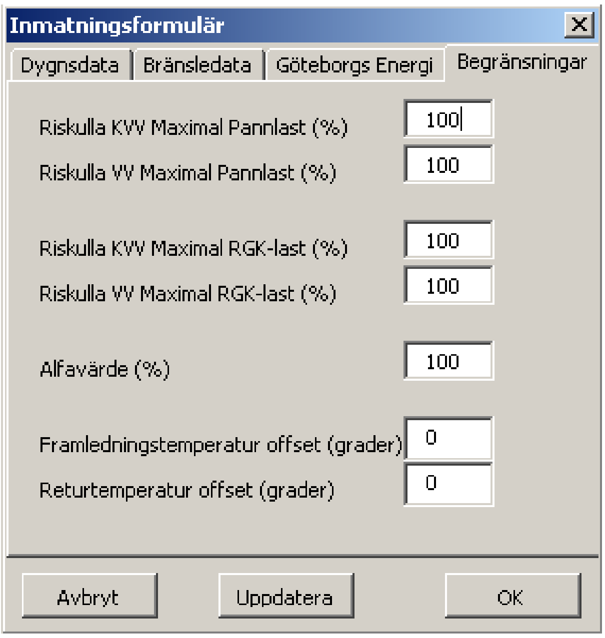
The third tab 4.11 contains information regarding the cooperation with Göteborg energi, transportation capacity and their marginal production price.



Marginalkostnad (kr/MWh) 539
Överföringskapacitet till Göteborg (%) 0
Överföringskapacitet till Mölndal (%) 0

Figure 4.11: The Göteborg energi tab of the input window

The fourth and last tab 4.12 contains information about limitations on the plants in question. This is mainly for using when a plant needs to be turned off or if it can not run past a specific capacity for some reason like maintenance or damaged parts.



Riskulla KVV Maximal Pannlast (%) 100
Riskulla VV Maximal Pannlast (%) 100
Riskulla KVV Maximal RGK-last (%) 100
Riskulla VV Maximal RGK-last (%) 100
Alfavärde (%) 100
Framledningstemperatur offset (grader) 0
Returtemperatur offset (grader) 0

Figure 4.12: The limitations tab of the input window

Algorithm

The first step of the program is to, from the data given by the user, calculate a prognosis for the heat demand. This will later serve as a boundary condition for the optimization process. In its current form this prognosis is rather crude and based on the outdoor temperature averaged over 24 hours and if it is a weekday or a holiday. For more information on these calculations, see 4.2.1.

Before starting the optimization several costs are calculated from the different fuel mixes used, the amount of water in the fuel, the heating values and the costs of these fuels. These fuel prices together with several other costs then make up the basis of the function that will later be optimized.

When making the model we have tried to keep the parts that depend on the decision variables linear if it is feasible. This is because the nonlinearities can give rise to local optimums that are separated from the global optimum that we seek. We have however included some nonlinearities where we have deemed it necessary. Specifically this is for the alpha value where a linerarisation would have introduced such a large error on the final price since the electricity incomes makes such a large impact on the optimization.

When the constraints and costs have been calculated we use the solver for each hour to get an hourly optimization of the operations. The internal workings of the solver has been described in 2.2.1 and will not be further discussed here. Once each hour has been optimized the results will be displayed in a spreadsheet detailing each plants production for each hour as well as in a diagram over the same data.

Related data such as marginal cost for each hour and electric production is also displayed. Several other details can also be shown, but these are not visible by default. An example of a result presentation is shown in figure 4.8. We have also chosen to treat the electricity production as a byproduct to the heat and are thus using the accounting method described in 2.3.2.

Grid specifications

There is no accumulator in the system at Riskulla, so the only real storage for heat is the distribution system itself. The temperature of the distribution grid can not be controlled since it needs to be adapted to energy outtake which is dependent on the outdoor temperature and other parameters and thus cant be used as a accumulator in a large scale. This means that we need to predict almost momentarily how much heat we need to produce. Due to uncertainties in weather forecasts however it is not meaningful to have a too small time scale. This is why we have chosen to optimize the system hourly.

Limitations

The alpha value used for determining the amount of electricity produced is determined by the district heating forwarding temperature from the plant. Currently it does not account for the ability to connect the plants as a series so that the output temperature for the specific plant can be lowered and thus the alpha value increased. The result of this is that for very low temperatures where several plants are used the marginal cost will be calculated as too high and the amount of electricity produced will be displayed as a lower value than what is the optimal.

The output temperature of the whole system is approximated from operational data over one year and is not a physical optimum in any way. It is merely a way to predict the output temperature from a given temperature based on previous data. Since the heat of the circulating water determines the maximum possible heat transferred to the houses it is obvious that these values are connected, however the circulation flow is also a determining factor of the energy transfer. Given that Mölndal Energi does not change their preferences for circulation speed and output temperature the given values should be correct.

An important part of the marginal cost of the heat and power plant at Riskulla is the revenue from the electricity sales. The program in its current form does not take into account the possibility of changing prices during the 24 hour period. To circumvent this it is possible to just run the program with the different costs and compare the results.

Another limitation is the temperature interval for which the program can be used. Data was available for temperatures ranging from -8 degrees Celsius to +25 degrees Celsius and thus the predictions made outside this interval ranges from unreliable to obviously wrong and thus the program should not be used outside this interval.

The program also neglects costs for start and stop, which means it will recommend running a plant for a very short period of time even if it is probably best to use another way of producing this energy. It also does not handle minimum production capacities, which means it may recommend using a plant at levels below what is possible. Such situations should be easy to recognise for the user of the program, as a warning will show when they arise.

Göteborg Energi

Mölndal Energi have a connection to Göteborg Energis grid over which they can transfer a limited amount of heat every hour. The two companies compare their marginal production costs to determine if and in what direction such a transfer should be done. This possibility to transfer heat to Göteborg is a possible way for Mölndal Energi to keep their new CHP plant running at a higher efficiency for a longer period of the year and should lead to economic benefits for both companies. This puts an extra requirement on the optimization program however since it will need to be able to handle these cases.

4.3 Results

In this chapter our results will be presented.

4.3.1 Load demand modelling

Presented in 4.13 are the resulting models for polynomial of degrees two, five and six, presented together with the raw data.

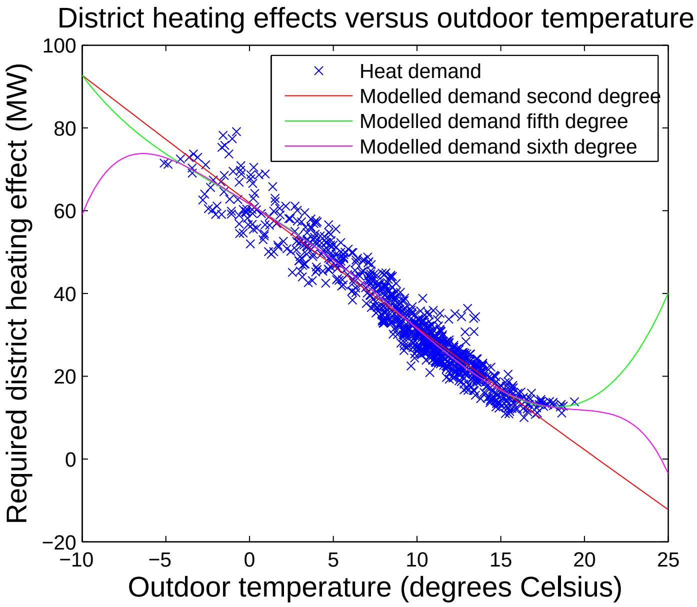


Figure 4.13: The heat demand of the district heating grid versus outdoor temperature

We can see that all the models act nicely within the temperature ranges where there is data available. The calculated square difference was lowest for the polynomial of the sixth degree. We chose that model, not only because of the low square difference, but also because of the unrealistic behavior of the other models at high temperatures.

4.3.2 Modelling of Riskulla KVV

Here the results of the modelling of the CHP at Riskulla is presented.

Boiler and turbine efficiency

A simple ratio between input energy and output energy showed that there is little variation between the data points. The only difference was when the air that is blown into the furnace is humidified, the efficiency goes up by a small amount. The efficiency is 0,905 without humidification and 0,907 with humidification. The case with humidified air was chosen to be used in the program due to the desired high efficiency.

The data for the turbine and heat exchanger system efficiencies were given in heat balance diagrams and were also provided by the supplier. Several scenarios were presented and we could see clear linear relations between the total efficiency, heat and power output with respect to the energy provided from the boiler. 4.14

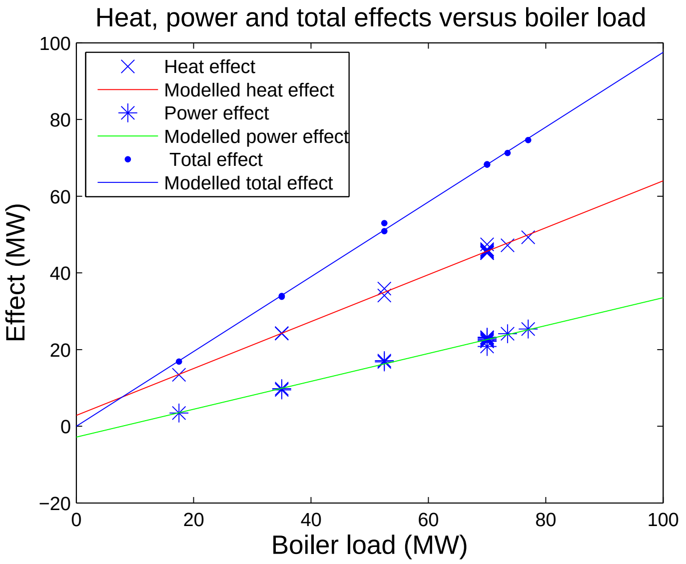


Figure 4.14: Outputs versus furnace load

One would think that the functions would be zero at zero load, which probably is the case in reality. Negative electricity production is of course not realistic, but the furnace is never operated at those loads.

Alpha value

The alpha value modelling resulted in a function that is dependant on two variables; boiler load and temperature on the outgoing district heating water. The boiler load sets a potential maximum for the alpha value, while the outgoing temperature sets how many percent of that maximum that will be the actual value.

FGC modelling

The model of the amount of heat extracted in the FGC contains three variables: fuel moist content, return water temperature and boiler load. The heat effect is a faction of the boiler load, where that faction is a function of the fuel moist content and the return water temperature. That function consists of two parts, one exponential function that describes how effective the FGC is when the return water temperature is 50 degreesand the moist content changes, and one linear function, multiplicated with the first, which describes how large share of the 50 degree curve that is used, depending on the actual temperature.

4.3.3 Optimization software

The final program and its creation was described in the method chapter. In this chapter we will focus on the output from the program.

In the main tab a large number of data is displayed concerning the load required for the hours of the day. First the total load required for each hour is displayed and then the optimized loads needed for each plant to produce the given amount of heat. The total amount of heat required is calculated from temperature measurements, time of the day and if it is a weekday or weekend. The uncertainty of the load demand prediction for the entire 24 hour period is fairly low while the exact distribution over each hour is not so precise as discussed in 4.3.1.

The optimized way to produce a given amount of heat each hour is calculated with the generalized reduced gradient method described in 2.2.1 and uses a set of costs derived from different cost functions for the plants. The method in itself will give the optimal solution with a very high precision but it is of course limited by the functions it is optimizing and how well they relate to reality.

The costs of production for each plant is calculated using prices for fuels and other materials consumed in the production as well as the sales price for electricity in the case of the combined heat and power plant. Based on previous experiences at Mölndal Energi we decided that these data could be approximated as fixed consumptions per MWh.

Fuel consumption and electricity production are the main constituents of the cost functions and these have been given extra care. Plant efficiency at different levels of utilization have been used to give a more correct representation of reality. It must however be noted that the data used to create these cost functions are not from the real plant and may require some tuning once the plant is up and running.

As long as the plant works close to the way it was described in the data sheets however the cost functions should not differ greatly from the true behaviour of the plants. There are a few situations however where even small variations in the cost function give greatly varying results. This occurs when the cost of production of two plants are very close to each other. A small error in the cost function can then give rise to a large change in the suggested production. Visually this will have a large impact on how the production looks, but in these cases where this arises the actual deviation from minimum cost is still low due to the small differences in costs.

The optimization handles all but one of the questions that Mölndal Energi wanted answered. The load distribution prognosis is used to calculate the costs over the day and it optimizes electricity production and FGC usage. The only question not answered is that of which fuel mix should be used. The program can be used to test how fuel mixes impact the production price, but there is no optimization that finds the best fuel mix. This is because the best fuel mix depends on how the plants are run and how the plants are run is somewhat dependent on the fuel mix. This can of course be solved, but it would lead to a much slower program, so much that we felt we had to take it out.

4.4 Discussion

4.4.1 Load demand modelling

This is the weakest link in the model. As there were only outdoor temperature, time of day and time of week to use as independent variables, the model is limited to those input data. Other factors that would have an impact on the load demand is probably rain, wind, cloudiness and incoming solar radiation. All these should be studied to create a better load model. A simpler version of such a model could be to create a model for each month or so, as the months at least have similar weather each year. The load demand model is limited in its temperature range. At temperatures that are not in the interval -5 to 20 degrees, one should not use this model, but rather use some other sort of prediction.

Comparison to literature

Unlike the heat demand models described in [11] [12] [13], the heat demand model in the case study is created using a black-box method, i.e. it is done without detailed knowledge of the district heating grid but rather with an interpolated function that describes the measured data. The reason for this is that the available data at Mölndal Energi is not enough to model the Riskulla plant as done in the literature. The only weather data that is stored is the outdoor temperature. However, the same two parameters that are considered the most important in predicting load in the literature are also the ones that are used in the case study. These are the outdoor temperature and the consumer behaviour, which is represented by the time of the day and week, as suggested in [11] and [13]. Even though the model in the case study is less advanced, its performance still is comparable to the other models. The average relative error between the model and its data points are 10.5 per cent in the case study, while in [11], the same error varies between 6.24 and 15.22

per cent. When comparing it to the performance in [12], the model created here performs better than the best one in the article does in 3 cases out of 7. The author uses a measure called correlation coefficient which is defined as

$$R = \sqrt{1 - \frac{\sum_{n=1}^{N}(y_i - yc_i)^2}{\sum_{n=1}^{N}(y_i - \bar{y})^2}} \tag{4.1}$$

and is a measure of how much the model differs from the data points in comparison to how much the data points varies from the mean of the data points. y_i is the data points, yc_i is the modelled value and $\bar{y}$ is the mean data value. The correlation coefficients varies between 0.91 and 0.98 in [12], while it is 0.95 in the model created in the case study.

4.4.2 Modelling of Riskulla KVV discussion

Alpha value

The alpha value, which equals the amount of electricity produced divided by the produced heat, depends on the efficiency of the generator turbine. The turbine in Riskulla KVV converts the heat energy in the steam into kinetic energy. Since it is a back pressure turbine, which works between two temperatures, the high before the turbine and the low after, its efficiency is dependant on those two. The data used in the modelling is taken from the contract specifications from the supplier.

We investigated the temperature dependency of the turbine in the different scenarios of full load production. These full load scenarios covered by the contract all have the same temperature before the turbine, so that leaves the lower temperature as a variable. The lower temperature that the turbine works against is that of the water sent to the district heating grid. That temperature has already been modelled as a function of the outdoor temperature. A plot was made of the calculated alpha values versus the furnace load, to see if there was any relations there. In general, most efficiencies in a heat and power plant are connected to the furnace load.

We saw that the alpha value is strongly related to the furnace load, and that there is a variation even on the same load level. Using the data points on full load level (70 MW), we tried to describe the dependency of the temperature of the sent water as a fraction of the maximum value of that specific furnace load. Even though there is limited data available and the data that was used are not from actual operation, the model describes the data quite accurate. The boiler load dependency is described as a maximum function as it was extracted from the data points with the highest alpha value. This does not mean that it in any way describes the maximum alpha value at any given forwarding temperature, but rather that we do not know how the alpha value behaves at lower temperatures. The weakness in the model is the temperature dependency, as the data points there did not describe a clear function, but rather a general sloping tendency.

Flue gas condensation

The resulting function that we use to describe the FGC at Riskulla actually describes another type of FGC. This, of course, makes the model less than optimal. However, it contains a type of function that could be applied to the real FGC when data is available. The function will suggest lower effects than the actual ones, which at least will not lead to too little heat delivered to the customer.

The general shape of the modelled function looks reasonable; more moisture in the fuel would create more smoke gas and a higher heat recovery in the FGC. Also, the heat exchanger in the FGC will be more efficient when there are large heat differences, so lower return water temperatures would lead to higher efficiencies, as is shown in the function. This, of course, means that one could easily get a better model of the FGC by measurements on the real FGC and doing the same modeling. The data that would have to be measured is then FGC effect, furnace effect, fuel moist content and return water temperature.

Limitations

When making the models we continuously had to consider their applicability in a future optimization program and also which parameters would be available to the operator.

A major limitation when it comes to create a model of Riskulla KVV is the amount of data available. The plant is not operational yet, and has therefore not generated any real measured data. What we have had to rely upon is calculated data from the supplier of the plant, and not actual data from the real operation. While these data might be accurate, there is no room for the massive data sheets a operation log can produce. Therefore, in many cases, we have just a few data values to work with. In some cases, as few as three data values were used.

The program takes into account the fuel mix used in each plant but it does not include a way to optimise the fuel mix. The best way to optimise the fuel mix with the program in its current form is to manually change the fuel mixes in the interface.

Accounting

Another critical design choice was the valuing of the two products produced in the process and the division of the costs between these two products. We chose to treat heat as the main product and electricity as a byproduct. This is reasonably correct since Mölndal Energis main business can be considered to be producing heat and they have a heat demand they must meet. This may change over time however and then another way of accounting might be more practical.

This way of accounting the entire cost but also the sales of the electricity to the heat production price can for example give a negative cost for heat production. In this case it could be argued that even though the heat production is greater in terms of quantity the electricity production is of greater monetary value.

For the purpose of finding the lowest production cost or greatest profit potential this way of accounting serves its purpose well. The implications of this choice is that we have an easy way to find the minimal production price for heat, as long as we know the sales price of electricity. The downside is that we can not use the program to calculate a marginal production cost for the electricity. To do this we would instead need to set the sales price for heat and from that calculate the marginal cost of electricity.

Grid specifications

The program handles most of the situations that can arise with regards to the transmission to Göteborg Energi but there are a few situations which it can not handle. For example it presumes a fixed marginal price from Göteborg Energi for the entire amount sold or bought. This may not be the case at all times if for example Göteborg has a small amount of cheap heat and then their marginal cost rises. In these cases the operator will need to use his knowledge about the system to interpret the results and correct them thereafter.

4.4.3 Optimization software

The optimization softwares main function is to calculate a production need prognosis and to optimize the production of the required heat. In its current form though optimization is mainly limited by the models it uses to describe the system, but some of the design choices have a certain impact on the result.

User interface

The program is made in an Excel sheet, a familiar environment to work in for most people, and an environment that is easy to change so that it suits the end users needs better. Most people have a basic knowledge in Excel which helps reduce time spent on education for the operators of the plant. Care has been taken to use a layout that is self explanatory and uses terms that are familiar to the operator.

When making the decision to use Excel to work in, a few key attributes were considered. Firstly no new software will need to be installed since Excel is already available on Mölndal Energis computers. Moreover most of their plant operators are proficient in the use of Excel which should then reduce the need for further education. Another positive effect of this was that any changes to the program would be possible to do in house if need arises.

The choice to use Excel as a basis for the program for example makes the optimization slower than what it could have been with a different program. This in turn influenced the precision that could be used since more advanced calculations make the program run even slower. Depending on your computer the run time of the program will be between 5 and 20 seconds and thus the relative time loss from using a slower software is low since the program will not be used more than a few times a day.

Therefore we concluded that the positive effects of using an interface familiar to the user and the time savings when changing and understanding the program outweighted the drawbacks.

Chapter 5

Conclusions and outlook

To conclude we will go through the different goals as stated in the Goal and scope definition and compare to the results and the discussion of those results to see how well they correspond to eachother.

5.1 Discussion

The goal of this thesis was to analyse and evaluate some available methods of economically optimising district heating production on a day-to-day basis and then to apply this knowledge to recommend a solution for Mölndaö energi.

We decided to recommend a custom made program. This program answers most of the questions listed in section 1.3.1. It gives a prediction of what the load on the plants. It gives a cost estimation for the 24 hour period and it optimises which plants to use. It also makes sure that the link to Göteborg Energi is used to its fullest. The greatest benefit is that it can easily calculate the complex cost function of the CHP-plant and thus make decisions regarding FGC-use and power production, something that is otherwise hard to do manually. The program does however not solve the fuel mix problem. Different fuel mixes can be tested manually using the program, but there is no optimisation done by the program itself.

Overall the program serves its purpose well. It is also constructed in a way to be easily updated once more and better data is collected. This helps ensure that the program can be kept up to date.

5.2 Conclusions

The survey gave us useful information regarding what tools other companies use and how they use their tools. Sam boman at Eskilstuna Energi proved an invaluable source of information and inspiration as he gave us a clear picture of what could be done and how it could be done. All in all the survey gave us a good picture so that we could plan the specifics of our later work. We decided to create our own optimization program that should be easy for Mölndal Energi to update in the future.

Given the available data the models are fairly accurate but more work in this area is adviced. Starting by evaluating which parameters could influence the models and then specifically gathering those data to be able to improve the models would be a good way to address this. The alpha value model may need to be adjusted when data from actual plant operation is available. The FGC model is based on a similar type of FGC and thus needs to be updated with data from operation of the used FGC. One could also differentiate the FGC of the CHP and the HWB. The load demand model would improve by gathering data in a larger temperature range and also measuring other parameters that may be of use, like wind speed and wind direction, cloudiness et cetera.

The program as it is structured fulfills the required user friendliness and gives results that are as exact as they can be with the given models. If more utility is required it should be fairly simple to implement it and also to expand its user interface to handle more input data.

We concluded that the positive effects of using an interface familiar to the user and the time savings when changing and understanding the program outweighted the drawbacks of having a slightly slower optimization.

The program solves the basic optimization problem but some special cases needs to be adjusted by the operator. For example the minimum production of each plant is not taken into account and neither are start up costs.

5.3 Outlook

In this chapter we aim to find the most likely and or rewarding ways in which our work could be taken further with regards to different aspects of the project. Further development of the program will be covered as well as suitable model refinements and appropriate measurements for data collection for further improvements.

5.3.1 Future development of the program

One area where the program could be improved is the input data quality and the general user interface as well as refining the models used in the program further. The program uses a rather basic interface and as the operators use the program there is a chance that a need to change it will arise to be able to use newly available data for example.

The first step of improving the program would probably be to refine the models used in the optimization program. This would in turn require data to be gathered from the new plant to create an updated model.

One of the weakest part of the program is currently the production capacity prognosis, which is dependent on time of the day, weekday and the temperature. To improve this further, more data will be needed and examples of such data is weather data such as wind speed and wind direction as well as the general cloudiness during the day. Including these connections into the model would most likely result in a better model, but in the end the quality of the production prognosis will never be better than the weather forecast that is being used to determine it.

5.3.2 Plant optimization in the future

As combined heat and power plants will continue being used more and more an increasing need for optimization software will arise. Commercial software is available but companies seem wary of using them or prefer creating their own alternatives tailored to their own situation. This is something that can change over time and might also vary with the size of the companies. Moreover as the electricity production changes and more and more energy is tied to sources that vary over time, like CHP's but also other sources like wind and wave power, grid stability becomes an ever increasing problem that must be taken into consideration when planning new plants.

Bibliography

[1] F. Mandl, *Statistical Physics, second edition*, John Wiley & Sons, 1988

[2] D. Fylstra, L. Lasdon, J. Watson, A. Waren, *Design and Use of the Microsoft Excel Solver*, http://www.utexas.edu/courses/lasdon/design3.htm 2008

[3] http://www.econmodel.com/classic/terms/mc.htm, March 2010

[4] S. Waldo Specthrie *Basic Cost Accounting*, 1963

[5] P. Olausson, *On the selection of Methods and Tools for Analysis of Heat and Power Plants*, Lunds University, 2003

[6] http://molndalenergi.se/ 2008

[7] http://www.profu.se/martes1.pdf, February 2010

[8] http://www.etsap.org/markal/main.html, February 2010

[9] Vitec *Planner - Lastprognoser och produktionsplanering* http://www2.vitec.se/Delade dokument/Planner.pdf, march 2010

[10] J. Johnsson, O. Rossing, *Samverkande produktions och distributionsmodeller*, Svenska Fjärrvärmeföreningens Service AB, 2003

[11] E. Dotzauer, *Simple model for prediction of loads in district-heating systems*, Applied energy 73, 277-284, 2002

[12] D. Popescu et al, *Simulation models for the analysis of space heat consumption of buildings*, Energy 34, 1447-1453, 2009

[13] A. J. Heller, *Heat-load modelling for large systems*, Applied energy 72, 371-387, 2002

[14] S.E. Werner, *The heat load in district-heating systems*, Chalmers University of Technology, 1984