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Optimising the Operation of a District Heating System

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A system with several actors will increase the possibilities for collaboration and therefore, in many cases also increase the possibilities to affect the operation with economic and environmental benefits. In this paper a district heating system is studied with purpose to create economic and environmental operation guidelines in favour of the involved actors. The company LuleKraft owns a combined heat and power plant, while the four heating stations together with the DH network are owned by Luleå Energi. District heat is produced from the CHP plant and the four heating stations which are fired with process gases from an integrated steel plant, oil, wood pellets or electricity. The heat demand in the system is strongly depending on the outdoor temperature.
In this paper, the system is modelled with Mixed Integer Non Linear Programming in order to optimise the profit and CO_2 emission. A comparison between actual process data and modelled results is performed. A pareto front is derived to show the trade-off between economic benefits and CO_2 emissions. It is found that the main suggestions, under conditions for optimised profit, are (1) to prioritize effective heat production instead of electricity production at cold outdoor temperatures and (2) redistribution of the accessible process gases between the CHP plant and one of the heating stations. This will lead to an improved operation strategy, resulting in increased profit and reduced energy consumption.

1. Introduction

1.1 Industrial collaboration

Collaboration between two or several actors within one or several system will in many cases increase the possibilities to optimise the operation with economic or environmental benefits. The case of Kalundborg in Denmark is described (Domenech and Davies, 2011), where different types of industries, e.g. heat and power production, chemical industry, plaster board manufacturing and soil remediation are connected to each other and to the municipality, and therefore able to use a product or by-product from another industry or system as a resource in their own production chain. In this way industries could increase their profit while reducing emissions and consumption of virgin materials. Within the forest industry a symbiosis between a chemical pulp mill, sawmill, biofuel upgrade plant and a district heating system has been studied (Karlsson and Wolf, 2008). Many industries could improve their operation with this kind of symbiosis, but due to the increased system complexity this has to be handled carefully to avoid sub-optimisation of the total system. Therefore, a holistic view at the system is essential to make sure a positive system change is made. Such optimisation studies may advantageously be realized by validated process models (Müller et al., 2012).

1.2 District heating system

An optimised system will always be the ideal situation, but for a system with several actors the difficulty to identify and quantify the increase or decrease in profit for a specific process sometimes makes collaboration difficult to achieve. The Swedish district heating (DH) market is under political discussion to establish Third Party Access (TPA) investigated by (Söderholm and Wårell, 2011) and later by (Broberg et al., 2012). This would open the DH market for a third part to deliver heat to the system, e.g. industrial

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excess heat, and therefore increase the possibilities for industrial symbiosis but also for risk of sub-optimisation.

Within the district heating system in Luleå, there are three companies operating: LuleKraft, Luleå Energi AB and SSAB. The Combined Heat and Power plant (CHP) in Luleå is named LuleKraft. It fires excess process gases from the adjacent integrated steel plant SSAB, and oil as peak load fuel. The CHP produces district heating for the municipality, electricity, process steam for the integrated steel plant, and drying gases for a wood pellet plant. The DH system is operated by LuleKraft, but the network and four heating stations are owned by Luleå Energi. The heating stations are fuelled by oil, electricity, or biomass. Collaboration between these companies is a necessity in order to optimise the operation of the system.

1.3 Purpose

The purpose with this article is to show the possible benefits with collaboration between companies operating within the same system boundary. An optimisation model of the system is created in order to identify how changes in production can affect profit, energy consumption, and CO_2 emission. An improved understanding of the system and a more holistic system perspective within each company will contribute to an increased possibility of expanded collaboration.

2. Method

2.1 Optimisation

The system is modelled with a Mixed Integer Non Linear Programming (MINLP) text based interface called GAMS (General Algebraic Modeling System) (GAMS, 2011). The optimisation tool BONMIN is used to solve the problem. Compilation and post processing of the results are performed with Microsoft Excel 2010. The method and modelling work are further described by (Bellqvist and Olofsson, 2012).

2.2 The model

The model is based on and constructed through energy- and mass balances and consists of 40 variables. The district heating system is modelled and simplified to the system shown in Figure 1. The dashed line surrounding the figure defines the boundary for the DH system. Ingoing resources are process gases from the integrated steel plant, oil, wood pellet and electricity, and outgoing product is electricity produced from LuleKraft. HWC (Hot Water Central) in the figure represents a heating station. The heating stations consist of one or several boilers and are modelled with fuel input and boiler efficiency. The total network losses in the system are assumed to be 10 % of produced heat.

Figure 1: District heating system with system boundary, ingoing resources and outgoing product. The different producers (rectangular box) along the network produce heat for the heat consumers (rhombus box)

The heat producers in the system are LuleKraft, HWC1, HWC2, HWC4 and HWC5. The heat produced at LuleKraft and at the different heating stations is consumed by the heat sinks, numbered 1 to 24 (+SSAB) in Figure 1. All the units and different areas are connected with black lines, representing the main distribution lines of the district heating network.

In Figure 2, a schematic description of LuleKraft is shown. The main parts of LuleKraft are the boiler and turbine. The boiler produces superheated steam by firing process gases and oil. The process gases are BLG (blended gas) – a mixture of basic oxygen furnace gas (BOFG), blast furnace gas (BFG) and coke oven gas (COG). The superheated steam is expanded in the turbine which consists of three different stages: TMI – high pressure, TME – intermediate pressure and TML – low pressure stage. The expansion generates electricity in the generator and district heat in the condensers (C1, C2). Steam is extracted from TMI for use within the integrated steel plant. Another alternative to produce heat is to directly reduce steam (extract steam before the turbine) to WC2. This is performed with higher heat production efficiency compared to expanding the steam through the turbine. Though, this alternative will reduce the steam amount for electricity production.

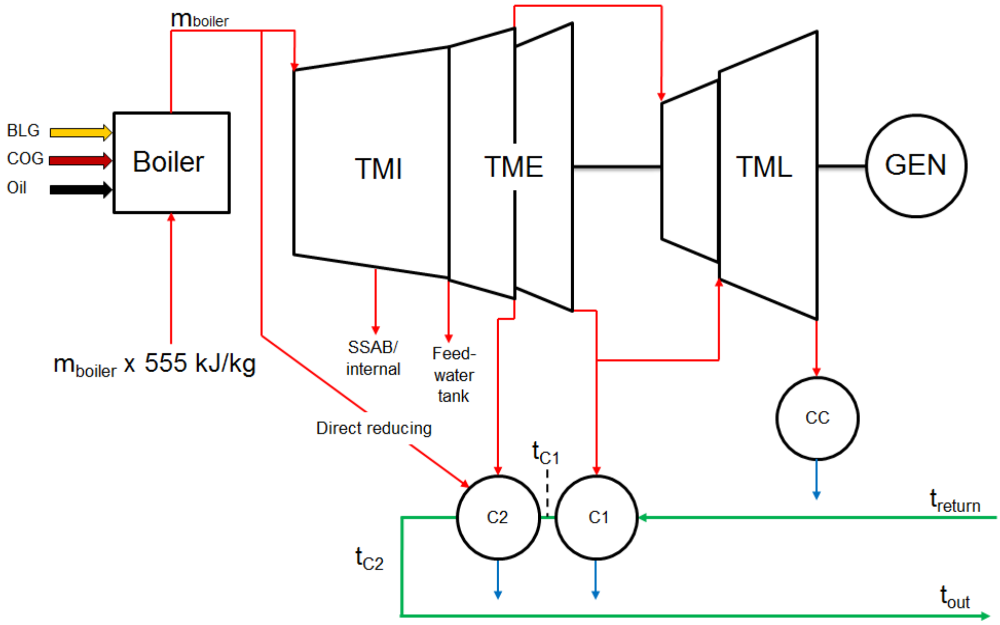

Figure 2: Schematic description of LuleKraft with boiler and turbine. The turbine consists of three different stages, high pressure-, intermediate pressure- and low pressure stage. Superheated steam is expanded to saturated steam in the turbine and generates district heat in two condensers and electricity in the generator

The outdoor temperature, t_{out}, has the greatest impact on the heat demand, $\dot{Q}_{DH}$, in the system. Based on measurement data, an approximation of the correlation between outdoor temperature and heat demand is derived according to Eq (1):

$$\dot{Q}_{DH} = \dot{Q}_{\max}(0.2383 - 0.0139 \cdot t_{out}) \qquad (1)$$

Where $\dot{Q}_{\max}$ corresponds to the maximum heat demand for different heat sinks in the system. The maximum heat demand of the total system is 418 MW, when adding the different heat sinks together. The correlation is derived for temperatures below 0 °C and is used to describe the demand for heating of residential housing. Industrial demand of heating is assumed to be independent of outdoor temperature and a constant demand is used for the consumption of these.

2.3 Boundaries

Fuels used at LuleKraft and the four heating stations, together with production- and fuel capacities are shown in Table 1. The boilers also have lower boundaries for minimum heat produced which is not reported in this paper.

Table 1: Upper boundary for heat production and fuel input at LuleKraft and at the four heating stations of the system. The heat producers use process gases, oil, wood pellet and electricity

	Fuel	*Heat capacity, MW*	*Fuel capacity, MW*	*Electricity production capacity, MW*
LuleKraft	*Process gases or oil*	≤ 215	≤ 320	≤ 97
HWC1	*Oil*	≤ 60	≤ 67	
	Electricity	≤ 80	≤ 82	
HWC2	*Oil*	≤ 80	≤ 89	
	Process gases or oil	≤ 80	≤ 87	
HWC4	*Wood pellet*	≤ 22	≤ 24	
HWC5	*Oil*	≤ 20	≤ 22	
	Electricity	≤ 8	≤ 8	

2.4 Objective function

The process gases availability together with the outdoor temperature influences the cost for heat production; deficit of process gases will require heat production from wood pellet, oil or electricity. Due to the continuous flow of process gases from the integrated steel plant and a limited storage capacity, it is important to utilize the excess of process gases in the CHP, which otherwise have to be flared. Thus, the process gases will always be the primary fuel, regardless when optimising the profit or CO_2 emission. The oil price for LuleKraft is depending on the ratio between electricity and heat production, the oil used for electricity production has been privileged with reduced tax. The lower boundary for electricity production is 50 MW, due to practical production limitations for the generator. LuleKraft has lower oil price compared to Luleå Energi, due to taxes and fees. The cost to run an electricity boiler is the current electricity price plus operational costs. The cheapest fuel is wood pellet, if the electricity spot price is above 20 €/MWh.

3. Results

3.1 General production guidelines

The system has been analysed to develop cost optimal production guidelines. Figure 3 shows a graphic view of general production guidelines at a temperature range of -35 °C to 0 °C. The process gases availability is assumed to be 252 MW based on production data from previous years, and the electricity price is 58 €/MWh. Based on the modelling result LuleKraft covers maximum 160 MW heat with process gases as fuel, when the objective is to optimise the profit. The rest of the energy from the process gases are losses and used for electricity production. For temperatures below -6 °C the wood pellet plant at HWC4 is powered up and for temperatures lower than -10 °C the heat production should be supported by oil at LuleKraft. The model result shows that, at temperatures below -18 °C, heat production should be started at HWC2 with process gases as fuel. The electricity boilers at HWC1 and HWC5 are powered up at very low temperatures.

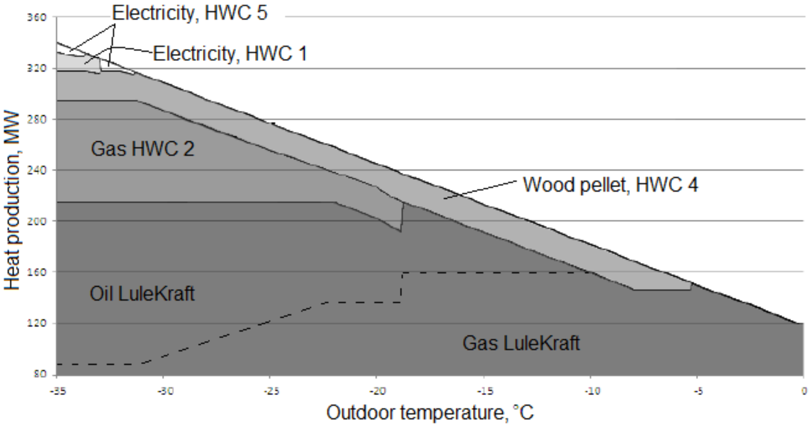

Figure 3: The result from the model indicates where and how heat should be produced in the system for different outdoor temperatures for optimal overall system profit.

3.2 Comparison with production data

With the understanding from Section 3.1 for the most profitable way of producing heat inside the system, the current production system is investigated economically. The results are shown in Table 2 by a comparison between process data and modelled result, during 1st of February 2012. The process gases availability this day was 268 MW. The main differences are that the model results indicate an increased heat production at LuleKraft, whilst decreasing the electricity production. In this way, Luleå Energi does not have to power up their electricity boiler at HWC1. HWC2 should be fuelled with process gases and not oil, which is the current situation. In this way the total system profit can be increased by 33 k€ during this single day. It should be noticed that LuleKraft reduces their profit while Luleå Energi and the system as a whole, increases their profit.

Table 2: Comparison between process data and optimised model result for the district heating system during 1st of February 2012

	Unit	Process data		Model	
Outdoor temperature	°C	-20.2		-20.2	
Electricity price	€/MWh	65.0		65.0	
		Output	Input	Output	Input
LuleKraft	MW	DH: 187.2	Gas:268.0	DH: 204.5	Gas: 239.1
	MW	El.: 73.6	Oil: 33.0	El.: 50.0	Oil: 57.6
HWC1	MW	DH: 18.6	El.: 19.8	DH: 0.0	0.0
HWC2	MW	DH: 22.8	Oil: 27.9	DH: 24.0	Gas: 28.8
HWC4	MW	DH: 20.0	Biomass: 22.8	DH: 18.2	Biomass: 20.4
HWC5	MW	DH: 0.0	0.0	DH: 0.0	0.0
Profit system	**k€/day**	**45**		**78**	

3.3 Pareto Front

A pareto front is in this case a correlation that defines the best possible profit with a specific CO_2 emission. Figure 4 shows a pareto front for three different outdoor temperatures. The slope of the correlations indicates how the profit is influenced by a specific change in CO_2 emission. The operation point for -20 °C represents the actual profit and CO_2 emission of the system one hour during 1st of February 2012. Three different alternatives (i, ii and iii) indicate potential improvements compared to the current operating point. The objective in alternative (i) is to maximize the profit, which is done with the production configuration in Figure 3. Alternative (ii) indicates an optimised profit with the CO_2 emission at constant level. In alternative (iii), the CO_2 emission is minimized, but this will still increase the profit compared to the operation point.

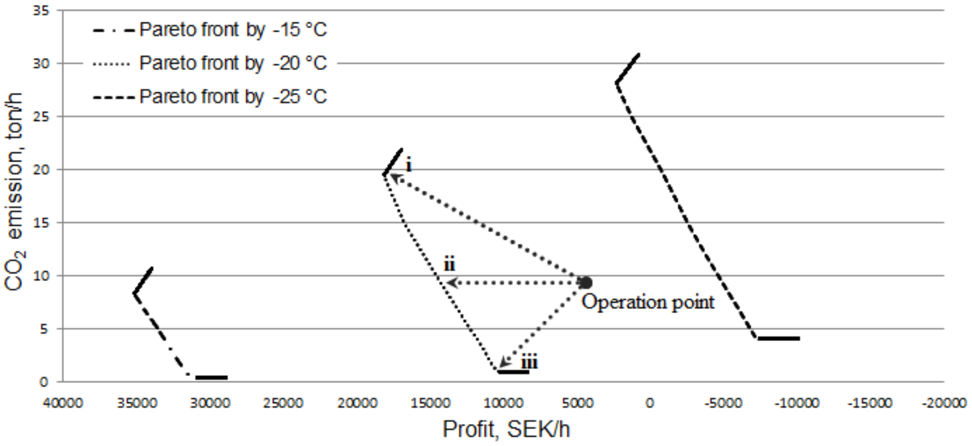

Figure 4: Pareto front from the model result for three different outdoor temperatures, displaying the best possible profit for a specific CO_2 emission. Proposed actions are marked with i, ii, and iii from the operation point for one hour during 1st of February 2012 at -20 °C

4. Conclusions

Eq (1) is a representative correlation for the heat demand in the system, but could be further developed by including more parameters like wind speed, humidity, daily heat demand variations and dynamic behaviour of the network. This equation is the main contribution to the modelling work within the network design area. The model results provide guidelines regarding heat and electricity production within the DH system. The understanding when oil should be used at LuleKraft rather than at HWC2 due to more favourable oil price is important. Changed pricing or prerequisites for the oil will affect the choice of fuel, and therefore also the result. It is never profitable to use oil for electricity production with an electricity spot price at 58 €/MWh, which is lower than the oil price. Less process gases at LuleKraft will therefore be synonymous with less income from electricity production. The above mentioned, together with higher heat production at LuleKraft are the main differences between production data and modelling results. The profit of the system is increased, but this requires fairly distribution of the benefit through systematic planning and strategy development. This study has contributed with a holistic system perception, which has encouraged an increased collaboration among the involved companies.

In this paper, the importance of collaboration within systems of several actors is proven. The utilization of industrial excess heat is possible to enhance with system analysis. To further develop the collaboration between the companies involved, it is particularly important to pinpoint the optimisation possibilities. Future modelling work should be to study process changes within the system, e.g. extended DH-network, variations in process gases availability and profitability of new investments such as an accumulator tank.

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