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Optimal Scheduling of Combined Heat and Power

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1 INTRODUCTION

In combined heat and power (CHP) plants conversion of up to 90% of primary energy to electrical power and heat takes place. If there is a demand for heat sufficiently close to the location of an electrical power plant, then it is for this reason desirable to use a CHP plant rather than separate electrical power and heat plants.

In Denmark more than 40% of the demand for space heating is supplied from district heating plants. Of this, more than 40% is supplied by CHP plants. There is therefore in the power supply system a need for operational planning of the production of heat and electrical power. In this paper we describe the problem of optimal unit commitment and economic dispatch in a system with CHP plants. We describe the modeling of the system, the optimization method and computational experience.

In the English language literature few descriptions of combined heat and power systems scheduling are found. No survey of the international literature exists. We shall therefore briefly mention the relevant literature that is known to us, so that this may serve as the first survey in the field.

A description of the CHP technology and the international development of district heating is found in Tourin (1978). A description of the physical and technical aspects of cogeneration is given in Diamant (1970). Palmer (1981) describe four energy conversion systems. Dobbs (1982) describes pricing and investment decisions in connection with CHP. Jeffs (1983) surveys the status of district heating in Denmark.

Simulation models are described in Larsen and Christensen (1983) and Pedersen (1983). Description of cogeneration units and mathematical models of them, suitable for optimization purposes, are given in Bengiamin (1983), Jenkins and Fietz (1982), Marchand & al. (1983), Püttgen and MacGregor (1989) and Verbruggen (1979). These papers are concerned with development of optimal schedules for a single cogeneration system, under the assumption that electrical power can be bought or sold unlimited at known prices. Bengiamin (1983) and Verbruggen (1970) use a load curve technique, Bengiamin (1983), Püttgen and Macgregor (1989) and Marchand & al. (1983) use linear programming models and techniques. Jenkins and Fietz (1984) use a variety of techniques but conclude that only heuristics and linear programming are practical. In these studies little emphasis is given to the development of the unit commitment schedule.

In Beune (1990) the problem of simultaneous scheduling of the cogeneration and the electrical power units is addressed. In this study, the optimization method is a decomposition method. The optimization takes plase in an interplay between the electrical power system (excluding cogeneration units) and the cogeneration system. The coordination between the subsystems is attained by the interchanges of information about marginal production costs.

Harhammer (1982) and Rabensteiner (1987) describe a similar problem, i.e., the optimal unit commitment and economic dispatch in a system containing CHP plants. The modeling contain combinations of linear and integer elements, and the optimization method is mixed integer programming.

Olesen (1990) and Pedersen (1990) also describe versions of this problem. The modeling is nonlinear, while the optimization is based on Lagrangean relaxation. The present paper is based on the same research project as these two papers.

2 DESCRIPTION OF THE UNITS

In the system under consideration there are two kinds of units: cogeneration unit, i.e., units producing both electrical and heat power; and electrical power units, producing electrical power only. We shall now specify mathematical models of these units.

In time period t electrical power unit i produces p_{it}. This production is constrained to be either zero (i.e., the unit is *off*) or to be between the positive lower limit $0 < \underline{p}_{it}$ and the upper level $\overline{p}_{it}$ (in which case the unit is *on*). Thus, we require $p_{it} = 0$ or $\underline{p}_{it} \leq p_{it} \leq \overline{p}_{it}$.

The cost of production of one time period at level p_{it} of this unit is $PCOST_{it}(p_{it})$. This cost function is assumed to be a piecewise third order polynominal for $\underline{p}_{it} \leq p_{it} \leq \overline{p}_{it}$, and to have $PCOST_{it}(0) = 0$. A typical example is indicated in Figure 1.

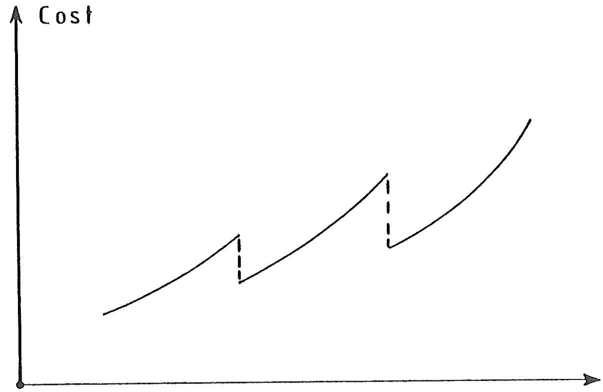

Figure 1. Production cost as a function of total energy production

As seen we do not assume that $PCOST_{it}$ is convex, nor do we assume that it is continuous. The reason for discontinuity is that the unit uses both oil and coal as fuel. The basic fuel is coal, but at low production levels oil is added in order to secure a good burning process. At high production levels oil may be added to increase production. Due to price differens between coal and oil this implies discontinuities.

Two types of cogeneration units are included in the system. In the extraction-condensing units steam is bled off along the turbine body to heat up circulating water, which is then transported to the district heating network. In the backpressure units the steam is let out from the turbine at a temperature which is higher than in a condensing unit, and then used for heating up the district heating network water. The thermal efficiency of such units may be 80 - 90%.

The coproduction unit i can in any time period t produce p_{it} (electrical power) and q_{it} (heat power). The production modes, i.e., the set of possible combinations of p_{it} and q_{it}, is denoted by PMO_{it}. In Figures 2 - 3 typical PMO_{it} are indicated. Figure 2 illustrates a backpressure unit. This is characterized by the fact that there is a unique relationship between p_{it} and q_{it}. Figure 3 illustrates an extraction unit. As seen, here there is no fixed relationship between p_{it} and q_{it}.

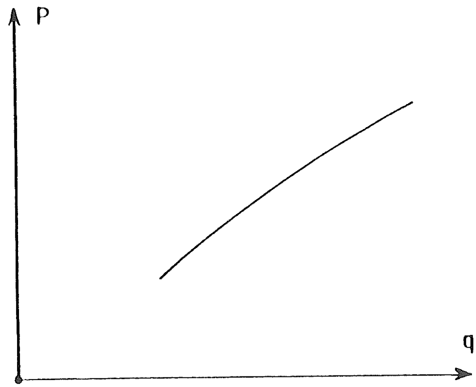

Figure 2. Production mode for a backpressure unit

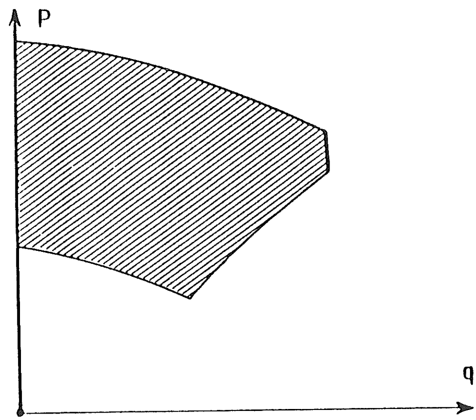

Figure 3. Production mode for an extraction unit

Observe that for coproduction units the maximal electrical power is not a fixed number. Rather, it depends on the heat production q_{it}. Therefore we indicate this maximum as $\overline{p}_{it}(q_{it})$.

The PMOs are characterized as follows. For q_{it} there holds $0 \leq \overline{q}_{it} \leq q_{it}$. For p_{it} there holds either $p_{it} = 0$ (in which case also $q_{it} = 0$) or

$$\underline{\alpha}_{it}^{0} + \underline{\alpha}_{it}^{1} q_{it} + \underline{\alpha}_{it}^{2} (q_{it})^2 \leq p_{it} \leq \overline{\alpha}_{it}^{0} + \overline{\alpha}_{it}^{1} q_{it} + \overline{\alpha}_{it}^{2} (q_{it})^2 \tag{1}$$

where the α's are given parameters.

We shall in the notation which follows consider the electrical power units as special cases of cogeneration units. Thus, an electrical power unit has $PMO_{it} = \{(p_{it}, q_{it}) \mid (0 = p_{it} \text{ or } \underline{p}_{it} \leq p_{it} \leq \overline{p}_{it}), q_{it} = 0\}$, with $\underline{p}_{it}(q_{it}) = \underline{p}_{it}$ and $\overline{p}_{it}(q_{it}) = \overline{p}_{it}$.

By suitable specification of PMO_{it} we can indicate if unit i must be *on* in a specific time period t; in this case the point $(p_{it}, q_{it}) = (0, 0)$ is not included in PMO_{it}. If conversely PMO_{it} consists of only the point $(0, 0)$, then unit i is not available at time period t. Finally, if PMO_{it} includes both $(0, 0)$ and some other points, its unit commitment in time period t remains to be determinated by optimization.

For a given value of $(p_{it}, q_{it}) \in PMO_{it}$, the production cost can be calculated as follows. On the set PMO_{it} we have defined a number of socalled iso-fuel curves. These curves represent point (p_{it}, q_{it}) where the total fuel consumption is the same. We represent these curves by second order polynomials. Thus, for a total fuel consumption of, say k, the values of (p_{it}, q_{it}) that give this satisfy the equation

$$p_{it} = \alpha_{it}^{0k} + \alpha_{it}^{1k} q_{it} + \alpha_{it}^{2k} (q_{it})^2 \tag{2}$$

Here $\alpha_{it}^{0k}, \alpha_{it}^{1k}$ and α_{it}^{2k} are given parameters.

The iso-fuel curves are given for a certain number of different total fuel consumptions. A fine grid will consist of maybe 10 curves, while a coarse grid will consist of maybe 2 or 3 curves. The first curve corresponds to the lower borderline of PMO_{it}, while the last curve corresponds to the upper borderline of PMO_{it}, (see (1) and Figure 3).

For any given $(p_{it}, q_{it}) \in PMO_{it}$ we can now find the cost as follows. First, find the relevant iso-fuel curve (i.e., the relevant k and the coefficients

$\alpha_{it}^{0k}, \alpha_{it}^{1k}$ and α_{it}^{2k} in (2)). Second, find the socalled equivalent power production from (2) by setting $q_{it} = 0$. Third, calculate costs as in a electrical power unit by using the equivalent power. If the total fuel consumption does not correspond to an iso-fuel curve, we use linear interpolation between the two adjacent iso-fuel curves.

Apart from the production cost also a start cost is considered. This cost is dependent on the unit commitment for unit i. If at time period t $(p_{it}, q_{it}) = (0,0)$ (i.e., the unit is *off*) then no start cost occurs on unit i. If $p_{it} > 0$ then a positive start cost occurs if and only if $p_{i(t-1)} = 0$. The magnitude depends on the number of consecutive time periods the unit was *off* before start. This magnitude is an increasing function up to a specific number of time periods (the cooling time), after which it gets constant. Cooling times are typical between 6 and 24 hours. We indicate the start costs for unit i by $SCOST_i(p_i)$.

3 DESCRIPTION OF THE SYSTEM

There are three types of restrictions which link the N units together. These are the electrical power balance, the electrical power reserve constraint and the heat power balance:

$$\sum_{i=1}^{N} p_{it} = d_t^p, \qquad t = 1, T \tag{3}$$

$$\sum_{i=1}^{N} \overline{p}_{it}(q_{it})\delta(p_{it}) \leq r_t^p, \qquad t = 1, T \tag{4}$$

$$\sum_{i=1}^{N} q_{it} = d_t^q, \qquad t = 1, T \tag{5}$$

Here d_t^p is the demand for electrical power in time period t, and r_t^p, where $d_t^p \leq r_t^p$, is the electrical power spinning reserve requirement in time period t. The expression $\delta(p_{it})$ takes the value 0 if $p_{it} = 0$ and the value 1 if $0 < p_{it}$. T is the number of time periods.

In restriction (5) d_t^v is the demand for heat power in time period t. We have by the notation only indicated one district heating network, but it is straightforward to model several district heat networks (and this has been implemented).

Finally we have the expression for the total costs, to be minimized

$$\sum_{i=1}^{N} SCOST_i(p_i) + \sum_{i=1}^{N}\sum_{t=1}^{T} PCOST_{it}(p_{it}, q_{it}) \tag{6}$$

The problem then is to minimize (6) subject to restrictions (3) - (5), $(p_{it}, q_{it}) \in PMO_{it}$, and conditions on the units' initial state (*on*, or *off* for a specified number of time periods).

We see that the problem distinguishes itself from the classical electrical power optimal unit commitment and economic dispatch problem. First, because of the inclusion of cogeneration units and the constraints (5) and $(p_{it}, q_{it}) \in PMO_{it}$. This is the qualitatively new feature of the model. This has also consequences for constraint (4). Second, we work with more complicated models of the units. Not only because they are two dimensional for cogeneration units, but also because we do not make any assumptions of convexity or continuity of $PCOST_{it}$.

4 SOLUTION METHOD

The problem defined in the previous sections has some similarity to the classical unit commitment and economic dispatch problem. It therefore seemed natural to apply methods which would be applicable to that problem.

We settled for Lagrangean relaxation because it seemed suited for the additively separable constraints (3) - (4) - (5) and criterion (6). Moreover, a number of articles reported on application of this method, and as the project evolved, more appeared. See e.g. Muckstadt and Koenig (1977), Bertsekas & al. (1983) and Merlin and Sandrin (1983).

The general idea in Lagrangean relaxation is well described in the literature just referred to. We shall therefore only briefly sketch this technique.

We introduce Lagrange multipliers λ_t (to (3)), ρ_t (to (4)) and ω_t (to (5)) for $t = 1, T$. Relaxing (3), (4) and (5) and appending these constraints to the criterion (6) we then have to solve, for given $\lambda = \lambda_1, ..., \lambda_T$, $\rho = (\rho_1, ..., \rho_T)$ and $\omega = (\omega_1, ..., \omega_T)$ the socalled relaxed problem:

$$\min \sum_{i=1}^{N} SCOST_i(p_i) + \sum_{i-1}^{N} \sum_{t=1}^{T} PCOST_{it}(p_{it}, q_{it}) \tag{7}$$

$$- \sum_{i=1}^{N} \sum_{t=1}^{T} (\lambda_t p_{it} + \rho_t \delta_t(p_{it}) \overline{p}_{it}(q_{it}) + \omega_t q_{it})$$

$$(p_{it}, q_{it}) \in PMO_{it}, \qquad i = 1, N, \qquad t = 1, T$$

If we denote the optimal criterion value in (7) by $D(\lambda, \rho, \omega)$ the socalled dual problem is the following in the variables (λ, ρ, ω):

$$\max D(\lambda, \rho, \omega) \tag{8}$$

$$\lambda \text{ unconstrained}$$

$$\rho \geq 0$$

$$\omega \text{ unconstrained} .$$

For any (λ, ρ, ω), $D(\lambda, \rho, \omega)$ is a lower bound on the optimal criterion value in (3) - (6). The solution of (8) is performed by an iterative procedure, see the references on Lagrangean relaxation cited, or e.g., Shor (1985).

We now turn to the solution of (7). We see that for fixed (λ, ρ, ω) this problem is decomposable, such that it can be solved by solving for each of the N units independently of all the $(N-1)$ others.

For an electrical power unit i the solution takes place in two phases. First the optimal production level $p_{it}(\lambda_{it})^*$ in period t for given λ_{it} is found under the assumption that the unit is producing. This can be done as follows. Given λ_t the optimal positive production level is

- at $\underline{p}_{it}$, or

- at $\overline{p}_{it}$, or
- at a point where $PCOST_{it}$ is non-differentiable, or
- at a point where the gradient of $PCOST_{it}(p_{it}) - \lambda_i p_{it}$ vanishes.

Since we assumed $PCOST_{it}$ to be a piecewise third order polynomial the last case can be examined analytically. Therefore, $p_{it}(\lambda_{it})^*$ can be found by a systematic examination of the finite number of all point satisfying any of these criteria.

The second phase consists in finding the unit commitment. If unit i is *off* at time period t, the contribution to (7) is zero. If the unit is *on*, the contribution is $PCOST_{it}(p_{it}(\lambda_t)^*) - \lambda_t p_{it}(\lambda_t)^* - \rho_t \overline{p}_{it}$; additionally, there may be a start cost. The optimal unit commitment is found by a systematic search. To this, we use dynamic programming; again we refer to the quoted literature on Lagrangean relaxation for a description of this.

For a cogeneration unit the idea is essentially the same. The first phase is more difficult, though, since we have two variables, p_{it} and q_{it}, for each unit in each time period.

The difficulty is resolved as follows. For each iso-fuel curve (see section 2) it is possible to find the optimal (p_{it}^*, q_{it}^*) this way. The expression to minimize is

$$PCOST_{it}(p_{it}, q_{it}) - \lambda_t p_{it} - \rho_t \overline{p}_{it}(q_{it}) - \omega_t q_{it} \tag{9}$$

By using the expressions (1) and (2), (9) can be written

$$\begin{aligned} PCOST_{it}(p_{it}, q_{it}) - \lambda(\alpha_{it}^{0k} + \alpha^{1k} q_{it} + \alpha_{it}^{2k}(q_{it})^2) \\ -\rho_t(\overline{\alpha}_{it}^{o} + \overline{\alpha}_{it}^{1} q_{it} + \alpha_{it}^{2}(q_{it})^2) - \omega_t q_{it} \end{aligned} \tag{10}$$

The first term is a constant, which is irrelevant for determination of the optimal q_{it}. The optimal q_{it} can now be determined by comparing value at the points $q_{it} = 0, q_{it} = \overline{q}_{it}$ and any stationary points of (10). Thus we find the optimal q_{it} on this particular iso-fuel curve, and by using (2) then also the optimal p_{it}.

By comparing optimal values of (10) for all iso-fuel curves, we find the global optimum.

The second phase, in which the optimal unit commitment is found, is exactly the same as for the electrical power units.

Lagrangean relaxation does not in general provide an optimal solution, and not even a feasible one. Therefore, after convergence of (λ, ρ, ω) to within predefined tolerances, a feasible solution is constructed. This is done by keeping the unit commitment fixed at the terminal value and then modifying the production levels until (3) and (5) are fulfilled. In order for this to be possible, the iterations in (λ, ρ) are not considered converged before simple checks have ensured that it will be possible to find a feasible solution with the given unit commitment. In particular, it is checked that (4) is fulfilled.

With fixed unit commitment the feasible solution is found as follows. For (λ, ρ) kept at their terminal values, (p_{it}^*, q_{it}^*) are found to solve optimally the following problems for $t = 1, T$:

$$\min \sum_{i=1}^{N} PCOST_{it}(p_{it}, q_{it}) - \lambda_t p_{it} - \rho_t \overline{p}_{it}(q_{it}) \tag{11}$$

$$\sum_{i=1}^{N} q_{it} = d_t^q$$

$$(p_{it}, q_{it}) \in PMO_{it}, \qquad i = 1, N$$

Then with q_{it} fixed at q_{it}^* the following problems are solved for $t = 1, T$ to determine a new p_{it}^*:

$$\min \sum_{i=1}^{N} PCOST_{it}(p_{it}, q_{it}) \tag{12}$$

$$\sum_{i=1}^{N} p_{it} = d_t^p$$

$$(p_{it}, q_{it}^*) \in PMO_{it}, \qquad i = 1, N$$

As seen we partially decouple the heat and the electrical production, but coordinate the two problem by the Lagrange multipliers (λ, ρ, ω).

The two problems (11) - (12) are solved by dynamic programming, discretizing production levels.

5 IMPLEMENTATION AND EXPERIENCE

The modeling and solution methods were developed at The Institute of Mathematical Statistics and Operations Research (IMSOR) at the Technical University of Denmark in close cooperation with the two major electrical power cooperations in Denmark, ELKRAFT and ELSAM. The project was initiated in 1984. In 1987 a prototype of the system was finished, since 1989 two real implementations have been in operation. One at ELKRAFT, used for weakly scheduling and one at ELSAM, used for long term planning, with a time horizon of up to one year. These implementations include additional features, such as several district heating areas, interchange of electrical power with neighboring countries, and simplified representations of the electrical network. We refer to Pedersen (1990) and Olesen (1990) for descriptions of and experiences with these implementations.

In general it is difficult to solve the dual problem (8). The method used relies on subgradient methods. Although a firm theoretical basis exists for these, see e.g. Shor (1985), we found that it was necessary to include a good deal of experimental results in the updating formulas.

One of the specific points observed was that it was expedient to use a two level updating structure for the Lagrange multipliers. In the outer loop (λ, ρ) were updated with fixed ω. Then, with fixed (λ, ρ) we iterated ω in the inner loop.

A heuristic argumentation for this can be given as follows. The number of coproducing units is significantly smaller than the number of electrical power units. Therefore the change in the optimal values of the left hand sides at (3) and (4) is much more smooth, relatively, than the change in the left hand side of (5) for the same changes in (λ, ρ, ω). In other words, the solution was much more stable in relation to (3) and (4) than in relation to (5).

The observed dual gap is defined as the cost of the feasible solution minus the optimal value of the lower bound $D(\lambda, \rho, \omega)$. The observed dual gap is measure of the "closeness" of the found solutions criterion value to a theoretical lower bound. An observed dual gap of zero would indicate that the optimal solution was found.

We observed a dual gap of 1-3%, relative to the lower bound. This might be expected from the literature quoted on Lagrangean relaxation. In particular, when there are few units, the gap may be relatively bigger, see Bertsekas & al. (1983). In our case we have few coproduction units (down to 2 or 3 in some of the runs).

As seen from Section 2 the model formulation of the individ units is very detailed. In particular, we nowhere assume convexity. This was felt necessary, in order to get realistic models. The disadvantage of this is that computation times may be high. However, it will be fairly easy to simplify the models by making suitable assumptions. We have implemented a solution procedure based on quadratic, strictly convex cost curves, which is much faster than the implementation for non-convex curves.

6 SUMMARY AND CONCLUSIONS

We have described a modeling and optimization scheme which handles combined heat and power production. The basic idea on optimization is the application of Lagrangean relaxation. This method is well established for electrical power systems only. It is shown how Lagrangean relaxation can be extended to handle also the heat production.

The basic modeling is fairly detailed in order to be able to handle realistic systems. However, the basic optimization can benefit from a simplified modeling, assuming convex production costs.

There are at present two fullscale implementations of our prototype in practical operation. This shows that the basic idea is sound and that practical requirements can be met under this scheme.

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