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Operation of Utility Systems: Optimisation –Based Decision Making

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Utility systems provide heat and power to industrial sites. The importance of operating these systems in an optimal way has increased significantly due to the rising prices of fossil fuels and the need for reducing greenhouse gas emissions. In this contribution we deal with operator decision-making under conditions of variable steam demands from an industrial site. Thus, an optimisation model has been developed which accounts for the costs of running the utility system as well as the costs associated with starting up the operating units. This is illustrated on a realistic case study.

1. Introduction

Chemical plants operate in existing industrial sites, where a number of production processes are grouped together and are supplied with power and heat by a site utility system. Combined Heat and Power (CHP) production, also called cogeneration, is typical for modern utility systems. However, startups, shutdowns and load variations are common in utility systems due to the changes in process demands (Halasz et al., 2002). When the steam demands of the supplied processes change, the common question arises whether it is worth activating or stopping certain devices. Currently, utility system operators still lack optimisation-based tools for making such decisions. The presented work addresses this issue. In the remaining sections, the utility system model and the employed optimisation procedure are described. In order to illustrate the applicability of the developed approach, an industrial case study is presented.

2. Utility System Model

The main components of the utility system are boilers and steam turbines. Steam boilers are modelled with a constant efficiency model, which has been accepted as providing sufficient accuracy. Steam turbines are modelled using Willan's lines with fixed coefficients. This ensures a good balance between modelling simplicity and precision. The complete system model has been built following the methodology presented in Varbanov et al.(2003).

3. System Optimisation

3.1 Changes of the operating state

A common situation when running utility systems is that the steam supply and demand rates change with time. This occurs on a regular basis due to shutdowns/start-ups of processes linked to the system. As a result of changing the overall steam supply-demands pattern, it usually becomes necessary to respond with changes in the operating specifications of the utility system.

For example, an increase of the process steam demand leads to augmented steam generation. However, steam can be produced by different devices and it is to be decided which is the most advantageous way to operate i.e. whether to increase the mass flow rate in a boiler and/or to switch on other devices, and if required, which of them. Furthermore, increased steam generation may also be an opportunity to produce additional power by expanding the steam through steam turbines.

On the other hand, a decrease of the steam requirements means an excess of steam in the utility system. It may be most cost-effective either to save fuel by switching off some steam generator units, or to generate additional power by increasing the steam mass flow rate through an active steam turbine. Another option might be to switch on another steam turbine.

In order to evaluate the effect of changing the operating state and take into account the costs of possible startups of operating units, a binary variable y_{CHANGE} has been defined for each operating unit. Its value is related to two other binary entities – $y_{CURRENT}$ (a parameter) and y_{NEW} (a variable). $y_{CURRENT}$ refers to the unit operation state for the current steam demand, y_{NEW} designates the operation state for the new demand. The binary variable y_{CHANGE} is used for estimating the startup costs incurred when the device changes its operation state from idle to working. Therefore, y_{CHANGE} assumes the value of 1 only if the unit (e.g. a boiler) features a transition from idle to an active state. The logic of setting the value of y_{CHANGE} is illustrated in Table 1.

Table 1. Possible combinations for the binary variables

$y_{CURRENT}$	y_{NEW}	y_{CHANGE}
1	0	0
0	0	0
1	1	0
0	1	1

By these means, it can be judged if it is worth switching on a device or whether there might be a better operation alternative. The defined equations (1-3) allow implementing this logic in the model. The current operating status $y_{CURRENT}$ is given as a parameter and the new status, as well as the operation change are represented by the variables y_{NEW} and y_{CHANGE}, respectively.

$$y_{CURRENT} \cdot y_{CHANGE} = 0 \tag{1}$$

$$y_{CHANGE} - y_{NEW} \leq 0 \tag{2}$$

$$y_{CHANGE} + y_{CURRENT} - y_{NEW} \geq 0 \tag{3}$$

3.2 Estimation of the device startup costs

Starting up a unit requires some time to heat up the device and to make it operational. Some fuel or steam will be consumed and this involves some additional cost. This fact constitutes the basis for the proposed startup cost estimation procedure.

In order to calculate boiler startup cost, the fuel necessary to reach steam generation conditions for the water volume in the boiler is used to estimate the startup cost. Thus, for a given startup duration (note – different from the new demands duration), the boiler start up cost is determined by the following equation:

$$STupC_{BOILER} = m_{STup,FUEL} \cdot \mathrm{Pr}ice_{FUEL} \cdot t_{STup} \tag{4}$$

In the case of steam turbines, the startup cost is estimated using the mass flow-rate of steam passing through the turbine to heat it up from cold state. The price of the steam consumed for this purpose is obtained from a financial balance through the complete utility system. The turbine startup cost is then calculated as:

$$STupC_{ST} = m_{STup,STEAM} \cdot \mathrm{Pr}ice_{ST,IN} \cdot t_{STup} \tag{5}$$

Start up costs are charged only if the unit changes its operating status from idle (OFF) to active (ON). Thus, the introduced binary variable y_{CHANGE} is multiplied by the device start up cost (a parameter) to account for it only in if this transition takes place. Hence, the equation for the total start up cost is expressed as follows:

$$STupC = \sum_{UNITS} (STupC_{UNIT} \cdot y_{CHANGE,UNIT}) \tag{6}$$

3.3 General optimisation procedure

Due to the bilinear terms in the enthalpy balances, in general a MINLP formulation will be necessary for the optimisation. Nevertheless, MILP is commonly used for this purpose by simplifying the model. The main simplifications include fixing the steam enthalpies in the system components and optimising the flowrates. However, for better precision, the MILP is usually followed by rigorous simulation. This procedure is iteratively repeated until no enthalpy variations occur. The resulting successive MILP optimisation procedure is described in detail in (Varbanov, 2004).

4. Case study

4.1 Problem description and assumptions

Consider the utility system in ***Figure 1***. This includes a gas turbine working at full load with a heat recovery steam generator, two steam boilers, two special heaters, two steam turbines for electricity generation and four direct drive steam turbines. The driver steam turbines are turbocompressor TC and turbopumps 1, 2 and 3 (TP1, TP2, TP3). When the turbines are off, electric motors are used to drive the corresponding machines. On the one hand, activating the turbines involves additional steam generation with the corresponding fuel consumption and startup cost. On the other hand, the power to run the electric motors is saved and some additional power may be sold to the power grid increasing the income.

"*Current demand*" reflects the state before the change in the demands occurs. "*New demand*" denotes the situation after the change has occurred.

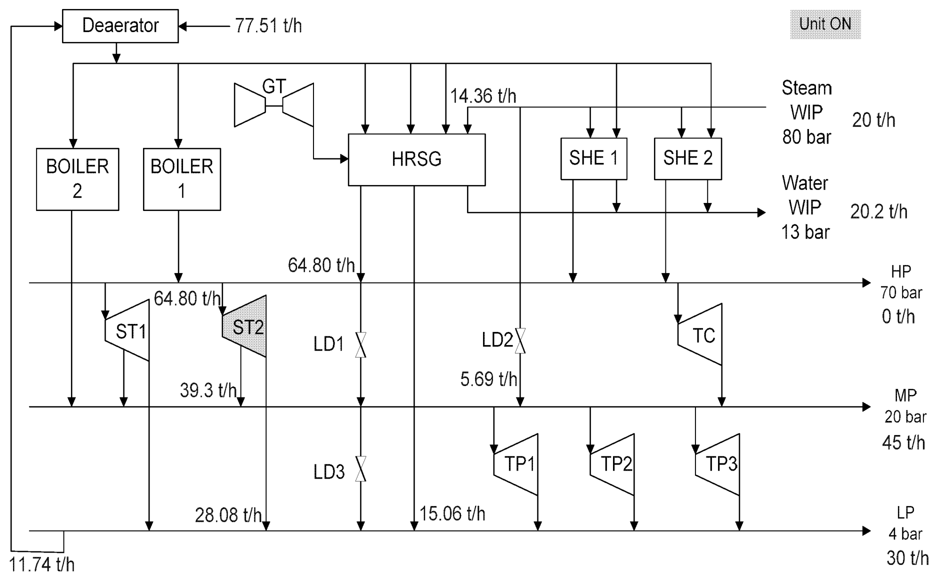

Figure 1. Initial State

The costs in the initial ("current") state are given in €/h, which means that the duration of this state is not considered in the cost calculation. On the other hand, the objective function in the optimisation problem involves the expected duration of the new steam demands. Therefore the costs for the new optimal state are given in € and.concern the period of operation for the new steam demands.

4.2 Demand changes

Since the optimisation outcome depends on the duration of the new demand, two different scenarios of the steam demand duration have been used to investigate this influence. In the initial state only steam turbine ST2 is ON and the operation costs are 1183 €/h. As a consequence of the increase of the steam demand in the MP (middle pressure) main from 45 t/h to 60 t/h and in the LP (low pressure) main from 30 t/h to 60 t/h for 5 hours, Boiler 2 and turbines ST1, TP1 and TP3 have been turned on and turbine ST2 has been switched off. Figure 2 shows these changes of the operation status in the different devices obtained in the optimisation. The cost of the operation during these hours adds up to 11228 €. This operation state can be compared with other operation states. For example, if the steam is expanded through the letdowns instead through the steam turbines, despite of the start up cost savings, power for internal consumption should be bought from the power grid increasing the total cost to 12828 €, which means a cost reduction of 12% obtained by optimisation.

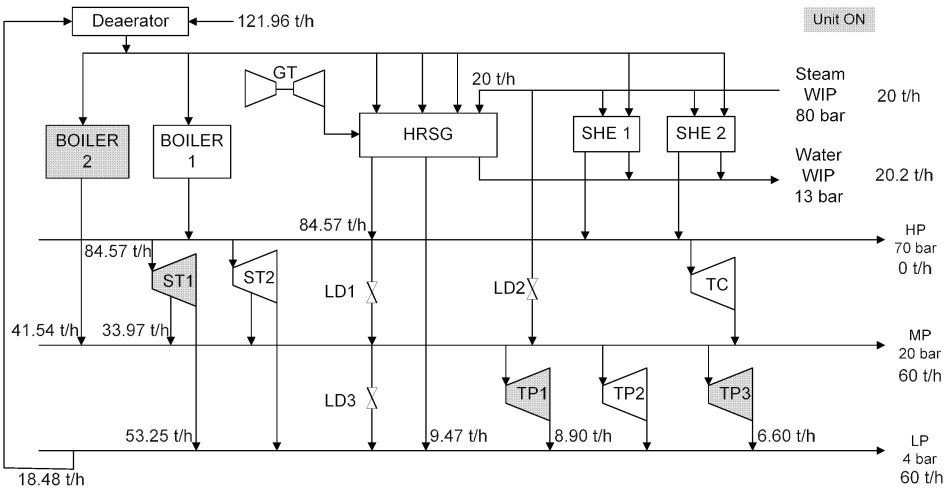

Figure 2. Optimal new state (5 hours demand horizon)

Another scenario with duration of the new demands of 30 minutes is analysed. In this case the optimal configuration shows that turbine ST1 has been switched on and ST2 - off. The shorter duration of the demand increase and the smaller number of devices involved in the status change result in the cost to having a lower value of 1415 €. If an expansion through the letdowns is considered the total cost is then 1704 €, a 16% cost reduction is achieved by the optimisation.

The results of the case study are summarised in Table 2, where the optimal states for the different scenarios with the corresponding total and start up costs are shown.

Table 2. Optimisation results for the considered scenarios

Device	Initial state	Optimal new status (5 h duration)	Start up cost (€)	Optimal new status (0.5 h duration)	Start up cost (€)
Boiler 2	OFF	**ON**	527.54	OFF	0
Boiler 1	OFF	OFF	0	OFF	0
Steam turbine 1	OFF	**ON**	167.81	**ON**	167.81
Steam turbine 2	**ON**	OFF	0	OFF	0
Turbocompressor	OFF	OFF	0	OFF	0
Turbopump 1	OFF	**ON**	1.788	OFF	0
Turbopump 2	OFF	OFF	0	OFF	0
Turbopump 3	OFF	**ON**	1.192	OFF	0
Cost	1183 €/h	11.228 €	698.33 €	1.415 €	167.81€

The presented case study obtaines the optimal configuration of the utility system when an increase of the demand occurs. Similar analyses can be performed for reduction in steam demands. The longer the duration of the new demand is, the worthier it is to switch devices on because the start up costs are distributed over a longer time period and compensated by the device production income.

5. Conclusions

In this work an optimisation tool has been developed for supporting the operators to operate utility systems in the most cost-efficient way. The developed tool provides the optimal utility system configuration when a demand change occurs. The optimal solution is found by minimising the sum of the costs for running the system and the involved component start-up costs.

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