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Optimal retrofit design and operation of the steam-supply system of a chemical complex

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Abstract

It is inordinately difficult to optimise the steam-supply system of a chemical complex under the condition that the production capacities of a multitude of products vary temporarily. Any of the available general-purpose methods for optimal design and operation hardly suffices for this purpose; therefore, a specific-purpose method has been developed in the current work. The efficacy of the resultant method is illustrated by optimising the steam-supply system of an existing chemical complex. The complex consists of one power-plant; one boiler station; four production plants operated in batch; one production plant operated continuously; and one pipeline network.

Keywords: Heat integration; Steam-supply system; Process synthesis

1. Introduction

Heat demands of chemical complexes are generally extremely high; often, these demands are met by condensing steam. For any chemical complex, the steam is usually supplied by two sources, the boiler station and the power plant. The distance between any of these sources and the destination of the steam can exceed a mile; thus, the capital and operating costs of the steam-supply system strongly depends on the geometrical and operating parameters (diameter of the pipe, thickness of insulation, pressure drop, etc.).

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The involvement of batch operation and the varying levels of production of multiple products can give rise to a significant variation in the energy or heat-power demand of a chemical complex. Such a variation, in turn, results in immense difficulties in optimising the steam-supply system of the complex; the system must be capable of supplying the maximum demand of the given chemical complex. In the current work, therefore, a novel, specific-purpose optimisation method has been developed to circumvent these difficulties.

Several papers deal with the optimisation of steam-supply systems under variable energy-demand. For example, a multiperiod optimisation framework is presented in [7,6]; a combinatorial optimisation method is proposed in [5]; and the pressure levels in the steam network are optimised in [4].

2. Fundamentals

The major source of difficulties encountered in optimising the steam-supply system of a chemical complex as indicated in the preceding section resides in its combinatorial nature. To drastically reduce the complexity of the algorithm for implementing the optimisation method developed requires thorough understanding of the unique combinatorial properties of the system in terms of process structures. For this purpose, the present work relies heavily on combinatorics and graph-theory [2].

3. Method

The method developed is based on the P-graph representation [1], the decision-mapping, combinatorial algorithms [2], and the accelerated branch-and-bound method [3]. In the first step, the chemical complex is evaluated in terms of the energy requirement, thus revealing the trend of its heat-power demand. In the second step, the resultant trend of the heat-power demand is transformed as follows:

(a) Divide the total range between the maximum and minimum demands into n sections and enclose the original curve depicting the trend by a series of rectangles, whose heights correspond to those of sections, so that each rectangle contains a portion of the curve within a single section. In the example illustrated in Fig. 1a, the curve is divided into the five sections, L_1 through L_5.
(b) Order the rectangles by their heat-power levels corresponding to their heights, and merge the rectangles of identical height.

The above transformation yields the n levels of heat-power demand with the corresponding cumulative periods, $M_1, M_2, \ldots, M_n$, in the power-time coordinate system; as shown in Fig. 1a, $n = 5$ for the example of Fig. 1b.

The heat-power demand of each time period is given by the height of the corresponding rectangle that represents a steam flow. For convenience, each steam flow is considered as a "product" in the P-graph representation. Thus, the n levels of heat-power demand lead to n steam products. On the basis of the transformation, the problem can now be stated as follows:

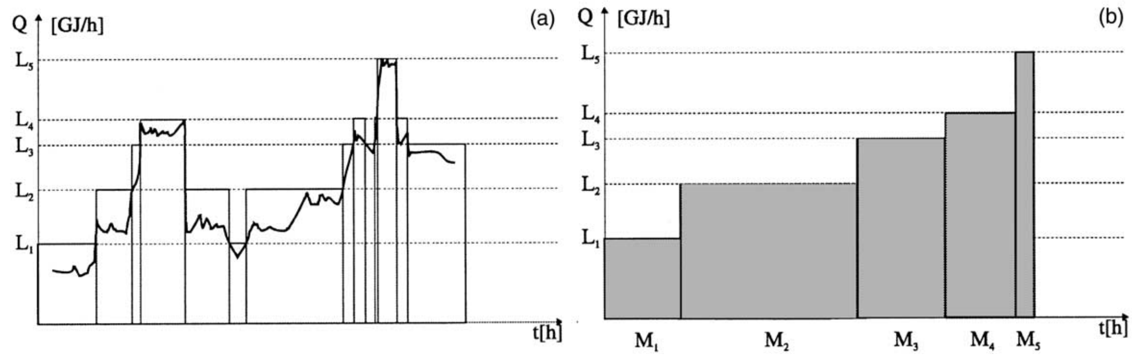

Fig. 1. (a) Temporal trend of heat-power demand, and its discretization with the rectangles, each having the height of one of the resultant sections. (b) The cumulative heat-power demand.

Determine the optimal steam-supply system that is capable of generating the n products with minimal overall cost. Obviously, the number of products, n, is five for the example illustrated in Fig. 1a and b.

First, the determination is made of the technically possible alternatives that can meet the heat-power demand. Second, the maximal structure is generated from these possible alternatives. Naturally, existing operating units are available for retrofit design. Such operating units may appear in more than one possible alternative; nevertheless, it can be considered only in one feasible solution. The maximal structure contains all such operating units.

Because of the definition, the products in reality are generated sequentially and independently. They are, however, interrelated through the capital costs of the operating units: the investment made in one period is carried over to any other later periods.

The maximal structure of the overall system is considered to comprise the layers of the maximal structures of the systems for generating individual products. Thus, the number of layers in the maximal structure of the overall system is identical to the number of products.

4. Application

The method developed is illustrated with the optimal retrofit design and operation of the steam-supply system of an existing chemical complex. The schematic of the original steam-supply system is given in Fig. 2. The complex contains five plants ($A, B, \dots, E$) whose heat-power demands are supplied by a power plant and a boiler station linked to the opposite ends of pipelines $S2$ and O. Plants A, B, D, and E are operated in batch; in contrast, plant C is operated continuously. Plant C is unusual in that it needs to be heated during servicing, and it produces a sufficient quantity of high-pressure steam during normal operation due to the highly exothermic nature of the reactions involved. After pressure reduction, this steam is fed to the steam-supply system. In addition, pipeline $S1$ starts at the power plant and is connected to pipeline $S2$ in the vicinity of the branching point to plant A. The branching points are relatively close to each other. The length of pipeline $S1$ is approximately 1800 m, and those of pipelines $S2$ and O are approximately 2000 m.

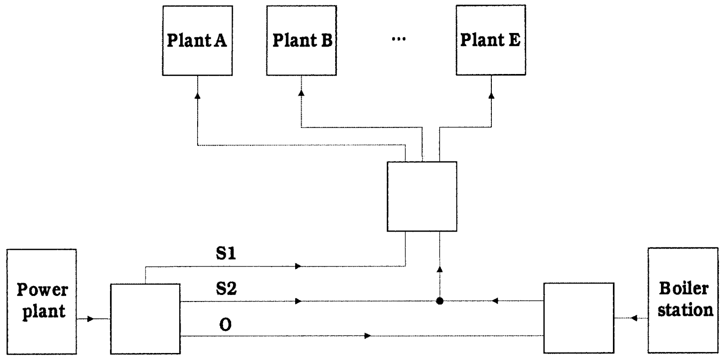

Fig. 2. Schematic of the original steam-supply system.

Currently, pipeline O lays idle; nevertheless, it can be reactivated if to do so is proved to be optimal.

4.1. Alternative schemes for retrofit

An analysis of the original system suggests that the following technically possible alternatives be considered.

(1) Excluding the boiler station (steam demands are met only by the power plant).
  (a) Increasing the cross-sectional area for the flow. It can be implemented by reactivating pipeline O and/or additional pipelines.
  (b) Increasing the pressure drop in the steam-supply system.
    (i) Increasing the starting pressure of the steam.
    (ii) Decreasing the end pressure of the steam.
(2) Including the boiler station.
  (a) Changing the source of the water for the boiler station.
  (b) Operating the boiler station periodically.

4.2. Models of operating units

The models provide the values of the outputs as functions of the inputs and the cost functions. The classes of operating units included in the system are pipelines, steam injectors, and reducers. The models are nonlinear; therefore, they are linearized by discretization for computational simplicity. Nevertheless, the discretization significantly magnifies the combinatorial complexity of the problem.

4.3. Generation of the maximal structure

The maximal structure contains the technically possible alternatives represented by a P-graph. The method developed generates the optimal solution structure and the corresponding values of the parameters from the maximal structure. The arcs in the P-graph representation link any operating units to other operating units through materials whose symbols are solid circles. The flows of steams with various pressures and prices at the sources are regarded as the raw materials. The amounts of the available raw materials are limited by the capacities of the entities supplying the steam. The products are the steam flows capable of meeting the demands at the sites of consumption.

Fig. 3 exhibits a single layer of the maximal structure corresponding to one product. The feeds to the pipelines at level I, $S1$, $S2$, O, 200, and 300, are supplied by the power plant at the pressure, P_E^+, which is higher than the original pressure, P_E^n. The pressure of the steam is to be reduced to P_0^- at the site of consumption; thus, reducer $R1$ need be installed at level II.

At level II, the pipelines are fed by the steam from the power plant with the original pressure of P_E^n. The pressure of the steam also is to be reduced to P_0^- at the site of consumption. The pressure, P_0^-, is too low to meet the demand; hence, this steam must be fed to the suction end of steam injector G at level III to elevate its pressure.

Level III representing steam injector G can be operated by the high-pressure steam from plant C, the power plant or the boiler station. For this operation, the high-pressure pipelines, denoted as

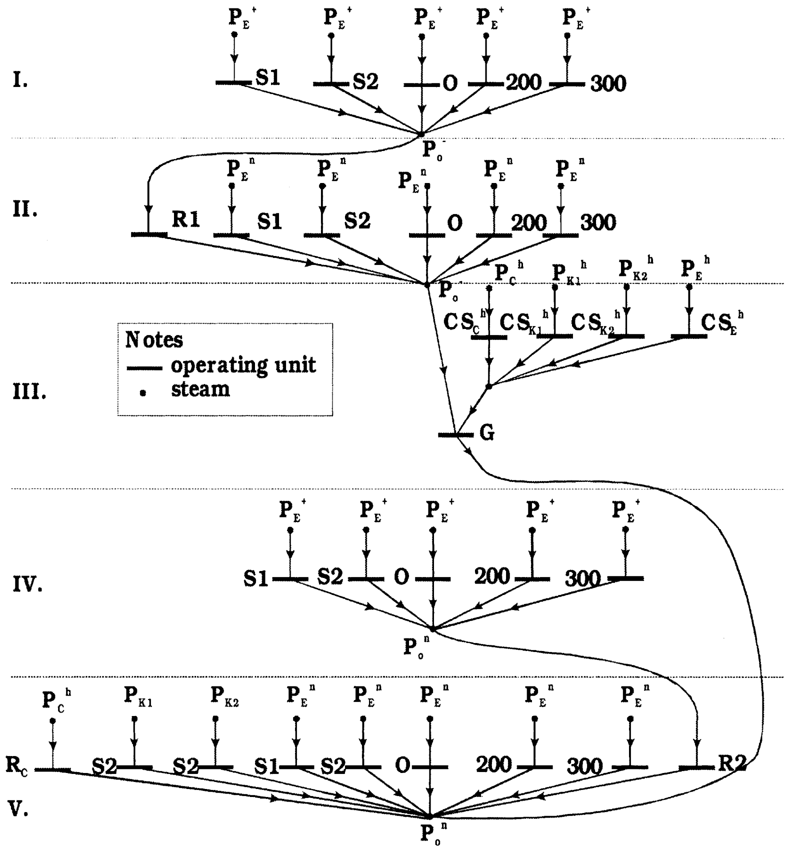

Fig. 3. Single layer of the maximal structure corresponding to one product.

CS_C^h, CS_{K1}^h, CS_{K2}^h, and CS_E^h, are required. The output from steam injector G is capable of satisfying the demand.

At level IV, the pipelines are fed by the steam from the power plant with the pressure of P_E^+, which is to be reduced to P_0^n at the site of consumption. Reducer $R2$, therefore, must be installed at level V because P_E^+ is higher than P_0^n.

At level V, the pipelines are fed by the steam from the power plant with the original pressure of P_E^n, which is to be reduced to P_0^n at the site of consumption, to meet the demand. At this level, reducer R_C is fed by the high-pressure steam from plant C and the steam at the pressures of P_{K1} and P_{K2} from the boiler station.

The pressures, P_E^+, P_E^n, and P_0^-, vary within certain ranges. For simplicity, each of them is assumed to take three discrete values in the mathematical models.

4.4. Input parameters

In addition to the maximal structure, the parameters pertaining to the raw materials, products, and operating units need be specified for the optimisation. Referring to Fig. 3, these are the following.

4.4.1. Raw materials

Table 1 contains the values of parameters pertaining to the raw materials.

4.4.2. Pipelines

Only the fixed part of capital cost is considered due to discretization. Tables 2 and 3 list the maximum capacities and operating costs of pipelines.

4.4.3. Steam injector

Only the fixed part of capital cost is considered due to discretization. Table 4 contains the capacities of the low-pressure input steam when the pressure of high-pressure input steam is 20 bar, and the output pressure is 4 bar.

Table 1
Parameters pertaining to raw materials

Raw materials	P_E^+	P_E^+	P_E^n	P_E^h	P_c^h	P_{K1}^h	P_{K2}^h
Pressure (bar)	5.0	6.0	4.3	8.0	20.0	8.0	8.0
Cost (HUF/t)	3211	3870	3073	4073	3073	3900	4073
Upper limit (t/h)	–	–	–	–	5.0	20.0	20.0

Table 2
Maximum steam flow rate of $S2$, O (t/h)

		Starting pressure (bar)		
		4.3	5.0	6.0
End pressure (bar)	3.0	4.4	5.6	7.3
	3.5	3.6	5.1	6.8
	4.0	2.2	4.2	6.2

Table 3
Operating costs of pipelines of $S2$, O

Steam feed pressure (bar)	4.3	5.0	6.0
Operating cost (HUF/h)	618	643	772

Table 4
Parameters pertaining to steam injectors

Pressure of low pressure input stream (bar)	Flow rate of low pressure input steam (t/h)	Flow rate of high pressure input steam (t/h)	Output flow rate (t/h)
3.0	0.59	0.41	1.0
3.5	0.62	0.38	1.0

4.4.4. Reducer

Only the fixed part of capital cost is considered due to discretization.

5. Mathematical model

With the sets of materials $M = \{1, 2, \ldots, m\}$, products $P \subseteq M$, and raw materials $R \subseteq M$ given, and, the operating units indexed as $\{1, 2, \ldots, N\}$, the mathematical model of the system can be formulated as given below.

Constraints:

$$\sum_{j=1}^{n_i} y_{ij}^k \leqslant 1, k \in P, \quad i = 1, 2, \ldots, N \tag{1}$$

$$z_{ij} \leqslant \sum_{k \in P} y_{ij}^k, \quad i = 1, 2, \ldots, N, \ \ j = 1, 2, \ldots, n_i \tag{2}$$

$$y_{ij}^k \leqslant z_{ij}, \quad i = 1, 2, \ldots, N, \ \ j = 1, 2, \ldots, n_i, \ \ k \in P \tag{3}$$

$$x_{ij}^k \leqslant y_{ij}^k u_{ij}, \quad i = 1, 2, \ldots, N, \ \ j = 1, 2, \ldots, n_i, \ \ k \in P \tag{4}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{n_i} s_{il} x_{ij}^k = 0, \quad l \in M \setminus R \setminus P, \ \ k \in P \tag{5}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{n_i} s_{ik} x_{ij}^k \geqslant p_k, \quad k \in P \tag{6}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{n_i} -s_{il} x_{ij}^k \leqslant q_l, \quad k \in P, \ \ l \in R \tag{7}$$

Annual cost function:

$$\sum_{i=1}^{N}\sum_{j=1}^{n_i}\left(\frac{a_{ij}}{E}z_{ij}+\sum_{k\in P}\left(c_{ij}t^k+d_{ij}x_{ij}^k t^k\right)\right)+\sum_{l\in R}\left(r_l\sum_{k\in P}\sum_{i=1}^{N}\sum_{j=1}^{n_i}-s_{il}t^k x_{ij}^k\right) \tag{8}$$

where,

y_{ij}^k binary variable signifying the existence of segment j of discretized operating unit i in the given structure for product k,
x_{ij}^k variable signifying the capacity of segment j of discretized operating unit i in the given structure for product k ($x_{ij}^k \geqslant 0$),
z_{ij} binary variable in calculating the fixed cost of segment j of discretized operating unit i,
u_{ij} capacity limit of segment j of discretized operating unit i,
n_i number of the segments of discretized operating unit i,
a_{ij} fixed capital cost of segment j of discretized operating unit i,
c_{ij} fixed part of the operating cost of segment j of discretized operating unit i,
d_{ij} slope of the linearized variable part of the operating cost of segment j of discretized operating unit i,
r_l unit cost of raw material $l \in R$,
q_l upper limit of raw material $l \in R$,
p_k steam-flow demand of product $k \in P$, t/h,
t_k period for manufacturing product $k \in P$, h,
s_{il} steam flow $l \in M$ provided ($s_{il} > 0$) or consumed ($s_{il} < 0$) by operating unit i for unit capacity, t/h. ($s_{il} = 0$ indicates that operating unit i is not linked to steam flow l),
E payback period, year.

This model contains 530 binary variables for the problem under consideration. The method developed has yielded the optimal solution within 550.41 s (≈9 min) on a PC (PIII 1 GHz); it involves the solutions of 134,515 LP problems. The resultant annual cost is 143,905,000 HUF (≈580,000 EURO); it is 8% less than the actual cost.

6. Concluding remarks

A novel combinatorial method has been developed for the optimal retrofit synthesis and operation of the steam-supply system of a chemical complex. Its application to an existing chemical complex has amply demonstrated the efficacy of method.

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