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Operational optimization of the utility system of an oil refinery

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Abstract

The objective of this work is to develop a mathematical programming model applied to the operational planning of the utility plant of the RECAP Refinery (São Paulo, Brazil), as well as its interconnections with the process units. The problem is formulated as a mixed-integer linear programming (MILP) model where the mass and energy balances, the operational status of each unit, and the demand satisfaction are defined in multiple time periods. The model determines the operational configuration of the plant by minimizing utility costs, and identifies steam losses as well as inefficient units by comparing the optimal solutions with the current operation. The MILP is able to accurately represent the topology and optimize the operation of the real-world system under different utility demands and abnormal situations in single and multiperiod scenarios, achieving up to 10% cost reduction. The MILP is currently integrated with the plant database and used for the planning of the refinery utility system.

Keywords: MILP; Utility plant; Thermoelectric plant; Planning; Refinery; Optimization

1. Introduction

Demand fluctuations are typical of utility or thermoelectric plants in petroleum refineries. Among the major causes are changes in the oil feed properties, multiple operational campaigns, maintenance of process units, interruption of electric energy supply, and cost variations of fuels and electric energy. On the other hand, utility systems are essential for the operational feasibility of refineries and must continually adapt their production levels to satisfy such dynamic demand patterns. Therefore, the designs of utility plants tend to present a high level of flexibility, thus allowing multiple operational configurations that satisfy the same demand targets, sometimes with significantly different operating costs.

It is important to note that the operational management of electric energy and steam systems is a complex process that benefits from the use of the optimization technology. Optimization techniques drive the systematic selection of configurations and operating conditions to satisfy utility process demands at minimum cost. Optimization models can be further used for the development of operating procedures for situations in which there is a steep variation in demands for utilities, since their costs represent a significant component of the refinery operating cost. Furthermore, such models can be extended for the analysis of the impact of new designs in the utility demand and operational cost of the plant.

There are important contributions that address problems in design and operation or utility systems within the optimization framework, both in academia and in industry (see Hobbs, 1995, for a review). Papoulias and Grossmann (1983) proposed an MILP framework for the design and synthesis of chemical plants, including utility systems; this framework was later extended to an MINLP representation in Bruno, Fernandez, Castells, and Grossmann (1998). Kalitventzeff (1991) presented an MINLP approach for the optimal energetic planning of chemical plants. More recent applications include Chang and Hwang (1996), Iyer and Grossmann (1997), Papalexandri, Pistikopoulos, and Kalitventzeff (1998), Strouvalis, Heckl, Friedler, and Kokossis (2000), Cheung and Hui (2004), and Shang and Kokossis (2004); an interesting industrial application of MILP planning

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to a petrochemical plant was developed by Hui and Natori (1996).

The above-mentioned works address the development and application of mathematical models for the optimization of utility plants with distinct purposes, such as synthesis and design, production planning, maintenance planning, long-term contract negotiations, emission control, feasibility studies for retrofitting the plant, and real-time optimization. Most papers rely on the optimization of an economical (profit, capital cost, operational cost, maintenance cost or combinations thereof) objective or a performance criterion. Moreover, most models are formulated as mixed-integer linear programming (MILP) models with single or multiple time periods, and results show that the linear approximations do not present a significantly negative impact in the solution of real-world examples. Another important feature of the models is the need to customize the utility plants according to their multiple configurations, operating conditions and capacities and performance of the units involved. In this sense, modeling frameworks such as the ones developed in Pinto, Joly, and Moro (2000) and Neiro and Pinto (2005) in the context of petroleum refineries facilitate the representation of production plants. Moreover, the acquisition and validation of data is an arduous task due to inadequate and insufficient instrumentation in real-world utility plants.

Despite the above challenges, the development of models for utility systems in optimization-based modeling and solution platforms present several advantages over the use of commercial packages, as the flexibility in introducing additional configurations and unit performance to the models, at relatively low cost and little knowledge of the mathematical programming algorithms.

In this context, the objective of this work is to develop and implement a mathematical programming model applied to the utility plant of the Capuava Refinery (RECAP, São Paulo, Brazil) as well as its interconnections with the process units, which solves the structural and process optimization and satisfies demand and allocates utilities at minimum cost. Besides presenting the optimization model and its results, this paper aims to describe the necessary steps for achieving satisfactory results from a real-world problem.

This paper is organized in five parts, including this Section 1. Section 2 describes the complete configuration of the utility central of a real-world refinery as well as the utility production, purchase and distribution feature of the plant. The mixed-integer optimization model is presented in Section 3, whereas Section 4 shows the computational results from plant data and analyzes several operational scenarios. Conclusions and future extensions of this work are given in Section 5.

2. Description of the utility system

2.1. General features of the system

Fig. 1 presents the simplified flowchart of the RECAP central utility (or thermoelectric) system in which each unit connected to utility header *UT* is represented by a rectangle that contains its identification; this configuration considers only the systems that are subject to optimization. The initials *J* are used to identify pumps and ejectors; *GV* or *L* denote furnaces and boilers; *M* represent heat exchangers, *O* or *P* indicate vessels, *TF* designate valves and *V* specify blowers and compressors.

The utilities that are considered in the optimization problem are superheated steam at 30 kgf/cm^2 or 29.4 bar (*V30S*), saturated steam at 30 kgf/cm^2 (*V30*) and its condensate (*CV30*), 5 kgf/cm^2 or 4.9 bar steam (*V5*) and condensate (*CV5*), 1 kgf/cm^2 or 0.98 bar steam (*V1*) and condensate (*CV1*); there are also two other headers for condensate that are *CVV* and *CM*, which originate from the vacuum system of the process condensation turbines. The water utilities are denoted by *Ax*, where *x* indicates *A* = feed to boiler, *C* = clarified, *D* = deaerated, *G* = make-up to boiler, *Q* = cooling from process, *T* = cooling to process, *U* = untreated; moreover, *PG* represents the water purge (blowdown) streams from the boilers. Electric energy (*EE*) is partially produced by the refinery from the effluent gas of the catalytic cracking unit, *U570*, in the turbo-expander/electric generator (*S-571TE*) and some of the energy is acquired from the local concessionary. In this case, a contract for the acquisition of this utility defines costs that depend on demand; for instance, consumption above 4 MW increases its cost by 20%. The fuel gas and natural gas network is denoted by *GC_GN*; it receives fuel gas from the catalytic cracking unit and natural gas from the desulphurization unit (*UDS*) and pipeline *GASAN*.

The headers, which collect and distribute utilities, are denoted *CL_UT* (*UT* given by the specific utility name). The steam headers may also transfer their utilities to a lower pressure level steam network, through pressure reduction valves. In this case, the quality of the steam is controlled through the temperature by injecting water. Hence, for the purpose of planning, pressure and temperature in each network can be assumed constant and with values that are the same as those obtained from data acquisition systems. Unit *UT_Dr2* is a pseudo-unit that indicates the difference between calculated values and acquired data from the material balance of the real unit *ut*; hence, the flow rate value of inlet stream of *UT_Dr2* incorporates the measurement errors as well as the errors in utility consumption/production estimates.

The units of the utility plant present either fixed or variable operation. The former either comprise units that present a single type of driver and have always the levels of utility consumption or production that are defined by the process or do not belong to the utility plant and their flow rates are pre-defined; hence, utility levels of the drivers are given by fixed parameters. In practice, the parameter values of the units with fixed operation are either provided from the data acquisition system or manually (based on their average values). In this case, decisions involve the type of driver to be used, as a function of utility availability and costs. The units under variable operation are either composed of alternative multiple drivers (turbine or electric motor), whose selection must be made, or those that must satisfy directly the demands and therefore their utility production and consumption levels must be determined by the planning system.