



Market-driven operational optimization of industrial gas supply chains



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ABSTRACT

This paper deals with the operational optimization of industrial gas supply chains. Industrial gas networks differ from other applications and require a rather special and shrewd approach to modeling and optimization issues. Currently in industrial gas plants: (i) the raw material is free; (ii) binding contracts and clauses place tight limits on supplies, production and distribution; (iii) electric energy cost fluctuations wield a greater influence over overall production than in other industrial areas; (iv) market demand is subject to multifaceted fluctuations and uncertainties; (v) long-term market demand is usually regulated by take-or-pay contracts; (vi) main users are on-site or connected via pipeline; and (vii) cryogenic storage constitutes a significant expense and encourages companies to veer toward just-in-time production.

This paper also provides very general guidelines for dealing with the aforementioned peculiarities, and compares plant-wide and enterprise-wide optimizations of industrial gas networks. An existing network is adopted as industrial case study.

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1. Introduction

Supply chain optimization is defined as the ability to create synergies between the vertical administration levels and the horizontal production hierarchy of a company, accounting for interactions between their suppliers and customers, and incorporating them into a well-defined decision-making process. The idea of modeling the decision-making process through feedback systems is not new and can be traced back to the work of Nobel Prize Laureate Herb Simon (Simon, 1957). Nonetheless, the optimization of supply, manufacturing, and distribution operations with the aim of reducing costs and inventories is still an open issue in many industrial fields including fine chemicals, gas and oil processing, and refineries (Grossmann, 2004, 2005). However, a wide and varied set of tools and methodologies is also now available to help tackle certain specific types of supply chain problems. For instance, Ydstie (2004) adapted Helfert's work (Helfert, 2001) to reflect supply chain management objectives in the process industry, by classifying decisions into three categories: investment, operation, and finance. Other classifications have also been proposed by many different authors (Biegler & Grossmann, 2004; Floudas & Lin, 2004, 2005; Shah, 2005; Van Landeghem & Vanmaele, 2002). Shah (2005), for example, distinguished between recipe-based planning (Gupta & Maranas, 2000; Kallrath, 2002a, 2002b; McDonald & Karimi, 1997),

which involves large gross margins, and property-based planning (Moro & Pinto, 2004; Moro, Zanin, & Pinto, 1998; Pinto & Moro, 2000; Pinto, Joly, & Moro, 2000), which is typical of blend sites and characterized by slimmer margins. Floudas and Lin (2004, 2005) classified existing scheduling approaches, involving static, dynamic, predictive, stochastic, reactive, and periodic methodologies. These categories have direct applications in several industrial areas: final distribution networks (Van den Heever & Grossmann, 2003; Van den Heever, Grossmann, Vasantharajan, & Edwards, 2000), strategic investment planning (Cheng, Subrahmanian, & Westerberg, 2003; Varma, Reklaitis, Blau, & Pekny, 2007), campaign scheduling (Busch, Oldenburg, Santos, Cruse, & Marquardt, 2007; Floudas & Lin, 2004), R&D portfolios (Blau et al., 2000; Blau, Pekny, Varma, & Bunch, 2004), and integrated oil networks (Julka, Karimi, & Srinivasan, 2002a, 2002b; Neiro & Pinto, 2004, 2005), to name a few. This work in particular deals with execution (or operational) planning as explained by Van Landeghem and Vanmaele (2002) and thus complements the existing work carried out with regard to industrial gas companies and cryogenic plants, and which focused on detailed mathematical modeling of air separation units (Ierapetritou, Wu, Vin, Sweeney, & Chigirinskiy, 2002), financial planning for energy-intensive businesses (Rodera, Bagajewicz, & Trafalis, 2002), dynamic modeling and the optimization of cryogenic tanks (Rodriguez & Diaz, 2007), and detailed process dynamics along pipelines (Zhu, Henson, & Megan, 2001).

This manuscript aims to investigate mixed-integer modeling and optimization issues by means of a multiscale (plant-wide and enterprise-wide) approach used for an existing network of air

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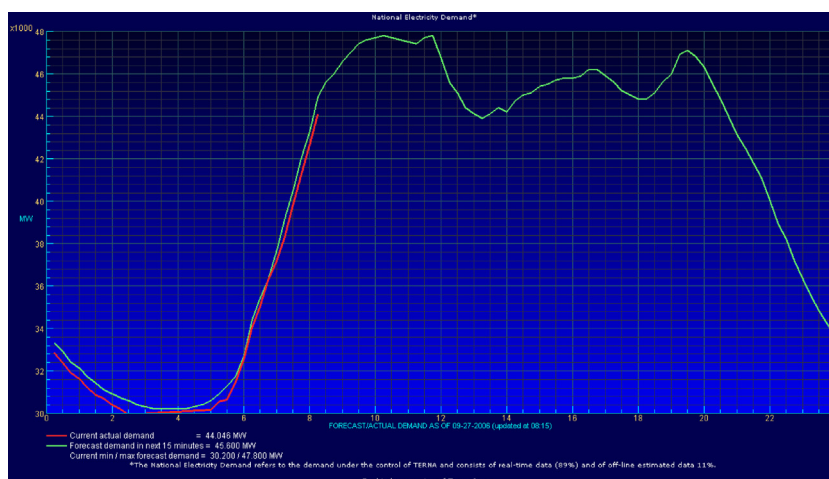


Fig. 1. National daily energy demand.

Source: www.grtn.it.

separation units (ASUs). A general overview of the peculiarities of industrial gas supply chains is given in the Section 2. Plant-wide modeling and optimization issues are discussed in Sections 3–5. Specifically, the operational planning of a single ASU for different demand scenarios is discussed in Section 5. Enterprise-wide modeling and optimization issues are described in Sections 6–9. Specifically, Section 9 compares market-driven operational planning of plant-wide and enterprise-wide optimizations.

2. Peculiarities of industrial gas manufacturing

The industrial gas market and the manufacturing of industrial gas are subject to specific conditions that make their optimization slightly different from the other areas mentioned above:

- (i) Air is the only raw material required by an ASU: it is free and supply is unlimited.
- (ii) Power supply is regulated by complex agreements and contracts, signed by the National Electric Energy Supplier (NEES) and each ASU. These contracts ensure a supply of electricity to the ASU and set out possible penalties and discount opportunities for the resulting monthly/yearly energy bill. For instance, so-called blackout clauses can prove a source of significant discounts: when national power consumption peaks (see Fig. 1), the NEES may be forced to temporarily interrupt energy supply to the most energy-intensive ASUs either at very short notice or none at all. This could happen at any time. As a result, the NEES generally give ASUs a relatively large discount on their monthly energetic bill.
- (iii) The abovementioned binding contracts are closely tied to oscillating trends in daily national power consumption, with high consumption during the day and lower consumption at night as well as during the weekends and holidays. Average Italian energy demand, for instance, varies between 41 GW in the daytime and 28 GW during the night (Fig. 1). Moreover, the seasonal gap between daily energy consumption peaks is in the order of several GW. Thus, electric energy costs closely reflect national energy consumption (high cost daytime; reduced cost at night).
- (iv) Market demand for final products is also subject to strong and multifaceted fluctuations. Daily oscillations are in particular to end-consumer demand which is null at night and positive in the daytime. Positive market demand on workdays and null demand throughout weekends generate certain weekly

- fluctuations. Moreover, the main users of ASU products, such as steelworks, tend to display batch behaviors (i.e. casting times), which may significantly increase demand uncertainty.
- (v) Long-term market demand is generally regulated by trade agreements and sale and purchase contracts. Several authors have discussed this key point and also proposed the possibility of optimizing the nature, duration, and flexibility of long-term contracts (Bansal, Karimi, & Srinivasan, 2007; Park, Park, Mele, & Grossmann, 2006). With respect to point (iv), trade agreements define a priori the future minimum amount of industrial gases to be supplied to end-users. This strategy stabilizes long-term market forecasts and allows the future demand for final products to be at least partly defined. Thus, we can assume that the market is steady-state in the long-term and the bullwhip effect can be ignored (Manenti, 2009; Moyaux, Chaib-draa, & D'Amours, 2007; Ouyang, 2007).
- (vi) As often happens for oil refineries and natural gas plants, the main industrial gas commodities customers are connected via pipeline. In this case, the pipeline is available for gaseous oxygen only and all other products of air liquefaction are delivered by cryogenic trucks.
- (vii) Cryogenic storage in industrial gas manufacturing is quite expensive and sharper market competition is forcing enterprises to veer rapidly in the direction of just-in-time production.

3. Plant-wide case

In the case of large-scale plants, air separation via cryogenic processes is one of the most efficient technologies currently available (Smith & Klosek, 2001). A typical ASU receives energy as input, and separates air components into gas and liquid oxygen (GOX and LOX), gas and liquid nitrogen (GAN and LIN), and liquid argon (LAR). There is no market for gaseous argon. This section deals specifically with the single-site modeling of an ASU. In line with the definition provided by Narahariseti, Adhitya, Karimi, and Srinivasan (2009), we will refer to the single-site case as a plant-wide case and to the multi-site case as an enterprise-wide case in the remainder of this paper.

3.1. ASU layout

Compression capacity, refrigeration capacity and separation efficiency are the main parameters used in ASU design. Separation efficiency (also called *oxygen production capacity*) quantifies

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