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A general modular framework for the integrated optimal management of an industrial gases supply-chain and its production systems

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ABSTRACT

A general modular methodology for the simultaneous optimization of the supply-chain network and the production systems of a general industrial gas producer is developed and implemented in a C++ program. The formulation and solution algorithm are specifically designed to be able to work on-line and to determine the optimal assignments of production site output to customer demand in the supply-chain and the corresponding optimal operating conditions for the production plants in integrated fashion. Here, the production network is not simply modelled as a set of product sources, rather the model is detailed enough to allow effective and feasible optimization of the entire system. Moreover, the proposed approach can be easily combined with the rolling horizon technique to mitigate the uncertainties in demand. The modelling strategies, employed for the supply-chain network and the production sites, along with the solution approach, adopted for the resulting optimization problem, are detailed. BzzMath library classes are used to meet the computational efficiency requirements for on-line applications. The effectiveness of the proposed methodology is demonstrated on a case study involving a portion of the real supply-chain and network of production facilities of Linde Gas Italia S.r.l.

1. Introduction

Supply-chain management refers to the handling of raw material restocks and supplies, the delivery of final products to the customers and the mutually beneficial economic interactions between the company and its competitors. In simplest terms, the supply-chain can be considered as a coupling of material logistics and competitor-company interactions. The production level management refers to the determination of the operating conditions of the production sites. By looking at these two definitions, it is evident that these two operational levels are directly and strongly interconnected with each other and their main connection is through the product storage facilities.

Since the global profitability of any company strongly depends on the management policies adopted for both its supply-chain network and its production level, a number of authors have studied how these two areas can be optimized as a function of market factors, such as product demands, raw materials availability and cost, energy/utility prices fluctuation, other production costs and delivery expenses. Even though much research has been published in this area, especially in the last fifteen years, most papers only address specific cases. General methodologies have been studied but limited to certain classes of problems. For instance, several income-based scheduling strategies, for a single production plant, are analysed in (Busch et al., 2007; Floudas, 2005; Maravelias, 2012; Yue and You, 2013), some methods for the income-based optimization of the production subsystem at the corporate level are studied in (Grossmann, 2004, 2005; Manenti et al., 2013a,b; Varma et al., 2007) and a comprehensive knowledge on how to model and solve scheduling problems for single and multiple entities can be found in (Floudas and Lin, 2004; Méndez et al., 2006; Harjunkoski et al., 2014). Moreover, a few algorithms for the supply-chain network and alike optimal management are described in (Bansal et al., 2007; Neiro and Pinto, 2004; Ng and Lam, 2013; Park et al., 2006; Shah, 2005) while some applied studies, on the same topic, can be found in papers like (Bowling et al., 2011; Julka et al., 2002). Finally, planning approaches have been investigated in many papers such as (Kallrath, 2002; Timpe and Kallrath, 2000), with the additional aim of finding ways to quantify the impact of uncertainties on the achieved results (Cheng et al., 2003).

Within the last five years, new formulations and solution strategies, which integrate regulatory control and planning, have been

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conceptualized and developed. In these studies objective functions, similar to those used in planning problems, are employed within a model-predictive control scheme (MPC). However, all these strategies are highly computational demanding and thus they have only been applied to batch plants, modelled by means of low dimensional systems of linear equations (Subramanian et al., 2014).

All the above-mentioned supply-chain/production optimization approaches lead to very large-scale optimization problems which are linear or non-linear and might also include discrete variables, depending on the modelling strategies employed. However, generally some assumptions are introduced such that the resulting optimization problem is LP or MILP in order to be able to guarantee the global optimality and to keep CPU times at a feasible level. Since the logistics portion of the supply-chain networks can be typically modelled with linear equations, it is most convenient to use linear models to represent the operation of the production plants in the supply chain. As a consequence, some form of reduced order linear models must be used (Buzzi-Ferraris and Manenti, 2010a,b). The solution of the resulting large-scale optimization problem can then be attacked using several different direct or decomposition algorithms. The literature provides a considerable amount of information on this topic in many papers, such as (Biegler, 2007; Biegler and Grossmann, 2004).

While the problem of supply-chain/production level optimization has been and still is extensively studied in literature, fully-integrated strategies, which allow the simultaneous optimization of supply-chain and production levels, have only been reported in recent years (Maravelias and Sung, 2009; Muñoz et al., 2013; Grossmann et al., 2008; Phanden et al., 2011). In addition, the examples of these strategies that can be found in the literature often model the production facilities as a set of simple product sources, without incorporating the operational details of these sources. This simplification can lead to infeasibilities when it comes to applying the optimization-derived results in actual practical situations. It must be reported that the very recent tendency is to move towards a better (model-based) description of the production sites. Nevertheless, there is still no general strategy for the simultaneous optimization of supply-chain and production networks that fully realizes this goal.

Among the possible sectors where supply-chain/production optimization might be of relevance, the one involving the industrial gas producers (IGPs) is the focus of our interest since only a limited number of studies have been reported and none of them can be considered to be sufficiently general (Ierapetritou et al., 2002; Mitra et al., 2012, 2014; Manenti et al., 2013a,b; Manenti and Rovaglio, 2013).

For these reasons, the current paper proposes an integrated approach for the simultaneous optimal management of both the supply-chain network and the production level of a generic IGP, at the entire company level. This novel approach consists of several main components:

- a general, hybrid modelling approach for the production plants (air separation units or ASU), which uses both first principles models and correlations developed from experimental data and/or rigorous simulations;
- a general model of the supply-chain network and storage system;
- a complete formulation of a cost-based objective function;
- a suite of numerical methods to reduce the resulting optimization problem dimensions and solve it efficiently.

The rolling horizon technique can also be easily employed in order to handle the uncertainties in the demands and make the method suitable for real industrial applications. The proposed methodology is implemented into a C++ tool, exploiting BzzMath classes (Buzzi-Ferraris and Manenti, 2012) in order to meet the needed efficiency requirements for online application. It is tested in a case study, based on a portion of the real supply-chain/production network of Linde Gas Italia S.r.l. (subsidiary of the Linde Group). This case study is employed to demonstrate the effectiveness of the proposed strategy and to compare it to the solution obtained using traditional supply-chain/production optimization methodologies.

The rest of the paper is divided into the following sections:

- The description of the supply-chain network modelling along with the description of the strategy employed for the treatment of the storage facilities;
- An outline of the approach applied for the modelling of the production sites and the production network;
- An explanation of the choices made to define a proper performance function for a whole IGP and the structure of the resulting supply-chain and production optimization problem;
- The presentation of the results of the case study;
- Some concluding remarks.

2. Supply-chain network and storage system modelling strategy

This section addresses both the description of the features of a generic IGP supply-chain plus the modelling approach adopted for it and the description of a typical IGP storage system. The specific features of such a supply-chain are reported in Section 2.1, the adopted modelling approach and the resulting mathematical model are described in Section 2.2 and the storage system model is studied and reported in Section 2.3. All the equations, described in Sections 2.1–2.3, constitute the set of supply-chain and storage constraints in the IGP global optimization problem, i.e. the optimization problem whose solution consists in the optimal IGP operating condition.

2.1. Special features of IGPs supply-chain

The production and sale of industrial gases is a unique business from several viewpoints and thus the relating production sites (ASUs) and supply-chain networks have characteristic features that need to be reviewed. These specific features are listed below:

- The raw material, from which industrial gases are produced, is air that is free and always available in any required amount. Thus no raw materials restock and/or cost issues have to be taken into account;
- Industrial gases are stored in liquid phase at very low temperatures thus long haul transportation is unsuitable; as a consequence, products are typically either trucked in liquid phase or carried via pipeline in gas phase (at a short distance) from the production plants to the customers;
- Each IGP owns its own fleet of tankers that are used to deliver the products;
- IGPs and competitor companies draw-up commercial agreements that establish the option, for the IGPs, of buying products from competitor sites at low price. These volumes of purchased products are then typically employed to satisfy some of the demands of the IGPs customers (this restock method is named “shipment upon payment”);
- IGPs also draw up so-called SWAP contracts with their competitor companies. By means of these contracts an IGP can effectively treat its competitors’ production sites as its own production sites (competitors can do the same). As a result, an IGP can load product from a competitor site with its own tankers and carry it to its own customers (competitors can do the same). On a yearly basis the amount of each product that an IGP can load from a competitor