Raising the Decision-Making Level to Improve the Enterprise-Wide Production Flexibility

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When market demand significantly changes, as in the ongoing worldwide economic crisis, many production plants are forced to operate far from nominal conditions. In this case, the current plant-wide optimization of production sites is a myopic approach that could lead to plant inefficiencies and unconventional operation issues, thus, resulting in ineffective prevention of economic losses. A way to tackle low-demand conditions is to raise the decision-making process from the plant-wide (or business-wide) level to the enterprise-wide (or corporate) level by assigning a Boolean variable to each production site so as to manage their on/off status. By doing so, certain additional (social) constraints may become relevant. The case of operating industrial gases supply chains is considered. © 2012 American Institute of Chemical Engineers *AIChE J*, 59: 1588–1598, 2013
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Introduction

Operations research has been an important topic for a long time, and it is of great interest in past years since many production fields are undergoing a long period of reduced market demand due to the ongoing worldwide crisis. Actually, the current scenario is causing relevant economic losses as many processes lose efficiency when they are forced to operate far from their nominal conditions. It is worth saying that many production plants were engineered and constructed years ago, when the main objective was to maximize the production (production-driven scenario) despite the plant flexibility and operability, whereas these features should be particularly useful in the current market-driven scenario.

The industrial gases supply chains are particularly involved in this scenario,[1,2] and they have the need to handle a current persistent low-demand condition: contrary to many other production fields, facing a significant reduction in the market demand (hence, in profits),[3,4] industrial gas supply chains have not a corresponding decrease in costs since their raw material (air) is free. Moreover, the overall energy efficiency of the energy-intensive plants such as air separation units (ASUs) dramatically drops down when production is low (nonlinear chemical-physical relationships behind their behavior).

There are no process optimizations at the plant-wide level that can ensure a net operating margin to the ASUs when they are forced to operate below a certain competitive threshold. Notwithstanding, there is the possibility to exploit the typical decentralized-production structure of the industrial gas companies (i.e., Air Products, Linde, Air Liquide) not only to practically limit the losses, but even to obtain positive margins: the decision-making process of the industrial gases production must be raised from the plant-wide (or business-wide) level to the enterprise-wide (or corporate) level.

In fact, it is well-known that the production of nitrogen is larger than the demand, and in past years of low-demand conditions, oxygen demand is so reduced that ASUs must vent this product sometimes, therefore, the low-demand scenario must be tackled from a corporate point of view, accounting also for connections among production sites, logistics, and geographical distribution of the production and storage capacities.[5,6] From this perspective, the supply chain planning at the corporate level is an appealing approach to provide an economic solution if combined with Boolean logic, since it has the possibility to ponder the temporary shutdown of certain ASUs and, at the same time, to force some others to operate close to their nominal conditions, and, thus, with good plant efficiencies. As it is easy to understand, the corporate optimum imposed to the ASUs may be significantly far from the ones dictated by the optimization of the single ASU. From this perspective, this article is aimed at introducing the general concepts of supply chain management. Then, a section is dedicated to the description of the mathematical MILP/MINLP (mixed-integer linear/nonlinear programming) problem, which the methodology here proposed is based on. The mathematical model of the corporate is described and the numerical results and quantitative/qualitative comparison between the plantwide and enterprise-wide decisions are discussed.

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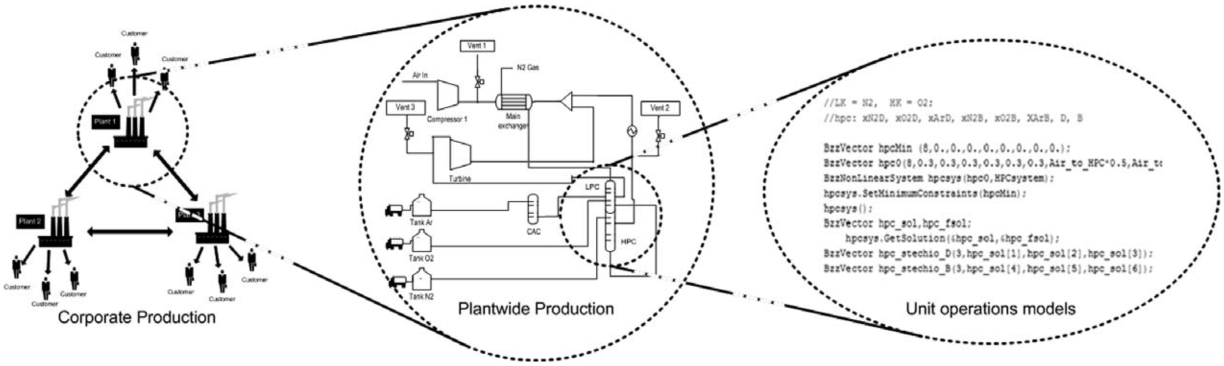

Figure 1. Qualitative representation of the multiscale optimization problem.

Supply Chain Management

Supply chain optimization is defined as the ability to capture the synergy among vertical administration levels and horizontal production hierarchy of a company, by considering interactions between their suppliers and customers and incorporating them into a well-defined decision-making process.[7–10] The modern supply chain involves the entire corporate network and every single area, from production to the market.[7] Logistics, because its intrinsically enterprise-wide nature played a determinant role in past years for every type of company, and also for strategic meanings heavily concurred with strategic goals, thus, increasing the entire corporate business profitability. However, production is still optimized plant- by -plant,[11] and usually incurring difficulty in plant operation. Nevertheless, the recent economic crisis and the increasing market competitiveness emphasize the need for an overall approach that involves the entire production network. Thus, survival for each plant in a decentralized production model cannot be treated as a single entity anymore, but rather must be achieved as single members of a larger group, where they all take part in the same objective, e.g., customer satisfaction. From this perspective, the supply chain management can read the specific needs of chemical processes and their chemical-physical nature, down to their molecular scale, and can optimize complex production networks with the aim to maximize not only the production but also the economic yield. This is possible nowadays using certain well-established detailed models for the chemical unit operations together with the characterization of commercial and economic phenomena through a kind of multiscale methodology for the optimization of complex production networks (Figure 1).

Strategic levels

Supply chain management can be seen as part of the highest levels of process control hierarchy, with the planning and scheduling of production; these levels are characterized by medium-long time scales and lead to MILP/MINLP mathematical problems since they include decisional (discrete) variables.

Shah[12] described the planning as a fixed infrastructure that optimizes the production, internal and external distribution, and storage resources of the supply chain, by considering both customer orders and demand forecasts. Shah discriminated also between recipe-based and property-based planning. The former is largely adopted in the literature[13–16] and concerns large gross-margins, where processes are operated at fixed conditions and recipes. The latter is typical of blend sites, refineries, oil and gas processing, and those plants are characterized by reduced margins.[3,4,17–19]

The literature provides different definitions and architectures even for strategic levels; their classification has been schematized by Van Landeghem and Vanmaele[20] in strategic planning (supply chain infrastructures planning policies), tactical planning[7] (demand chain planning with market parameters to fix planning set-points, supply chain planning with customer orders and demand forecast), and also execution planning (decentralized productions, distribution networks).

Specifically, execution planning has been studied in this research activity for plant-wide and enterprise-wide management of industrial production sites. More information on the lower levels can be found elsewhere.[21–23]

Supply chain contextualization to industrial gases manufacturing

Industrial gases market and enterprises are subject to specific conditions that make their mixed-integer optimization different from other applications:

- Air is the raw material: the raw material supply is free and without any limitations, contrary to the majority of the industrial applications. Thus, the only external expenses are represented by electrical energy to be supplied to each ASU.
- The power supply is regulated by complex agreements and contracts with the National Electric Energy supplier.[24–26] These contracts ensure the electrical supply to the ASU, but they also define possible penalties and large discount opportunities in the monthly/yearly energy bill. The energy cost is also very difficult to predict because of its variability and high-market volatility. In this work, night runs from 8 PM to 8 AM, and day is from 8am to 8pm, with the energy price variability been taken into consideration according to the Italian energy market manager. The electric energy price is referred to the Italian situation: there are several rules for the energy deregulated market, but they are slightly different from other countries: the deregulation (like "take or pay" contracts, or cost-effective contracts) can be applied up to a certain threshold of power consumption (i.e., about 2 MW but it depends from the different zones). ASU's are over this threshold and have to pay the PUN's price (PUN; unique national price) stated by the energy supplier price (as seen in Figure 2). A plot for the prices used for the simulation can be seen in Figure 3.
- Some ASUs may be directly connected via pipelines to customers like steel mills or oil refineries. The connection is usually related only to one of the products of the ASU and all the other products derived by air liquefaction

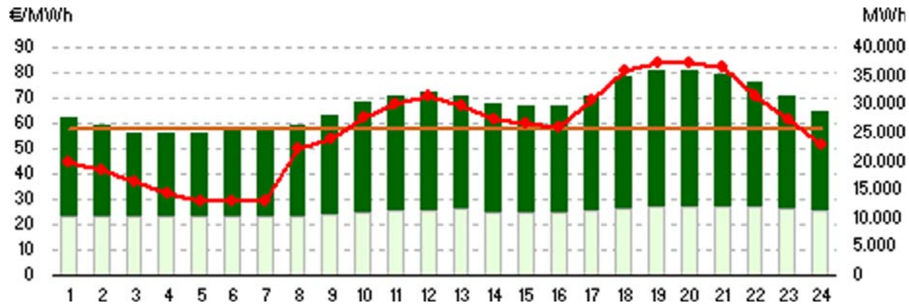

Figure 2. Energy price variability in 24 h in the Italian energy market.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

have a totally different demand, causing certain unbalanced situations.

- Cryogenic storages of industrial gases manufacturing are very expensive and, nowadays, the increasing market competitiveness is pressing companies to move toward the so-called just in time production policy, characterized by minimum stored volumes and real-time inventory scheduling.

Enterprise-wide mathematical models

The enterprise-wide production planning is a complex optimization problem since it involves nonlinearities of chemical/industrial processes, discrete variables to support the decision-making, large dimension of the resulting systems due to the mathematical models of production plants, and uncertainty due to market/demand fluctuations and volatilities. To be effective and preserve the connection with the production field, the enterprise-wide production planning should be based on detailed physical-chemical models that properly characterize the relevant phenomena behind the behavior of each ASU as well as the connections among ASUs (i.e., pipelines, storages, trucks, railways…). This unavoidably accounts for certain nonlinearities typical of these kinds of processes such as air fractionators,[27] polytrophic compression, cryogenic storages,[28] etc. The intrinsic nonlinearity of ASUs makes the enterprise-wide production planning problem particularly cumbersome[29–31]: we need to solve a usually large-scale, mixed-integer, constrained, nondeterministic, real-time, nonlinear optimization problem:

- It is large-scale since it involves several plants, with production trains each and many processes and unit operations. Thus, the number of state variables, decision variables, and degrees of freedom increases exponentially, leading to a large-scale problem.
- It is mixed-integer since it includes certain discrete (Boolean or integer) variables to model the decision-making process (i.e., for a plant, 0 means off, and 1 means on). The enterprise-wide production planning is a strategic optimization usually aimed at assigning the most profitable production load to each plant so as to maximize the net operating margin. The final purpose changes when demand is low, since corporate production planning is aimed at defining which plant should produce and which should not, thus, by assigning a Boolean variable to each plant. Thus, decision variables are of discrete/Boolean nature and they transform the process optimization into a mixed-integer nonlinear programming (MINLP) problem.[26,32–34]
- It is constrained since the optimization is subject to mathematical constraints such as the mass and energy balances governing the ASUs and liquid inventories or the take- or -pay contracts[25] regulating the sales and purchase tasks.
- It is nondeterministic since there is the need to predict the future behavior of the enterprise-wide and the prices/costs to obtain an effective production planning. This means that we need to work with production and market uncertainties, which increase with longer prediction horizons. To reduce the effect of uncertainty, the so-called rolling horizon methodology must be adopted.[21,35]
- It is real-time[24] since the problem must be solved promptly to have effective support to the decision-making.
- As mentioned, it is nonlinear for the nonlinear nature of industrial gases plants.[22,36,37]

Definition and solution of MINLP

The nonlinear nature of MINLP problems[26,32–34,38,39] may arise from:

- nonlinear relations in the integer domain exclusively;
- nonlinear relations in the continuous domain only;
- nonlinear relations in the joint integer-continuous domain.

The coupling of the integer domain with the continuous domain along with their associated nonlinearities makes the class of MINLP problems very challenging from the theoretical, algorithmic, and computational point of view. The general MINLP formulation can be stated as

$$\begin{aligned} \min \quad & f(x,y) \\ s.t.: \quad & h(x,y)=0 \\ & g(x,y)\le 0 \\ & x\in X\subseteq R^n \\ & y\in Y\subseteq N^m \end{aligned} \qquad (1)$$

presents two major challenges/difficulties, which are associated with the nature of the problem, namely, the

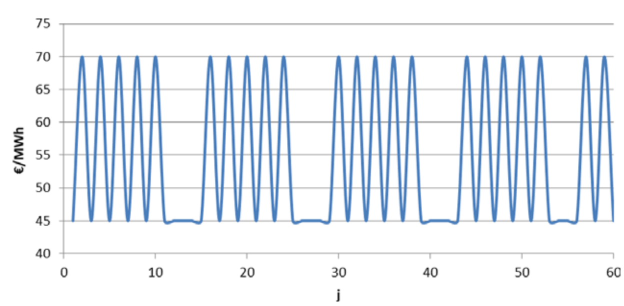

Figure 3. Energy price variability used for the simulation horizon.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

combinatorial domain (**y**-domain), and the continuous domain (**x**-domain):

- as the number of binary variables y increases, one faces a large combinatorial problem.
- due to nonlinearities the MINLP problems are in general nonconvex, which implies the potential existence of multiple local solutions.[33,34]

The resulting mathematical problem can be solved using several tools. The most common one is the GAMS environment.[40,41] We selected the MS Visual C++ programming language and the numerical methods belonging to the BzzMath library.[42–44]

Case study

The selected case is an enterprise for industrial gases production. One of the most efficient technologies for large production capacities is the air separation via cryogenic process. A typical ASU is an energy-intensive plant, which separates the air components into gaseous and liquid oxygen (GOX and LOX), gaseous and liquid nitrogen (GAN and LIN), and liquid argon (LAR). The gaseous argon is not required by any customer in the selected industrial case-study. The first part of this paragraph deals with the modeling of a single ASU, taking into consideration the key-unit operations and investigating the main issues at the plant-wide level. The second part of the paragraph deals with the additional enterprise-wide constraints.

Plant-wide modeling

The main parameters for characterizing an ASU are the compression capacity, the refrigeration capacity and the separation efficiency. The separation efficiency is the main parameter to design an ASU since it defines the total amount of products, their production ratios and their purity; the refrigeration capacity defines production capacity of liquid products; the compression capacity determines the general ASU capability and the possibility to send gaseous products to any online users. In the definition of a supply chain problem for an ASU,[45,46] given the energy supply contracts and the market demand for every single product, there is the need to determine the best solution to satisfy market requests in order to minimize the energy consumption, possibly considering all the physical and chemical phenomena that govern the following operations:

1. Air compression,
2. air refrigeration,
3. air rectification,
4. liquid products inventories,
5. product distribution.

The air is compressed and refrigerated. It is purified from impurities such as water, carbon dioxide and hydrocarbons using special units. The refrigeration loop liquefies the process stream and separates its main components (oxygen, argon and nitrogen) through air fractionators.[47] The liquid products are stored into cryogenic tanks, except for a portion that is regasified to recover energy for the refrigeration loop. When the liquid market demand requires it, certain special process layouts of ASUs allow liquefying the gaseous products by means of liquefiers, even though this inevitably brings to larger energy consumptions.

Plant-wide model details

A reasonably detailed scheme for the generic ASU is illustrated in Figure 3, where the main process units can be easily identified. Specifically, Figure 3 shows the qualitative scheme to obtain industrial gas products. The air is purified and compressed in C-1. A vent is placed immediately after the compressor to regulate the production according to market demand. Actually, keeping the compression zone at an assigned set of conditions, it is possible to regulate the production by means of the vent Fvent1. The compressed air is refrigerated (booster) and separated by means of the air fractionators. The liquid products are sent to the cryogenic storages (or vented for some reasons in Fvent2). Cryogenic trucks usually deliver the liquid products. Figure 3 shows an ASU layout, which is reasonably detailed for the enterprise-wide optimization. It is possible to distinguish the process streams and the main units such as heat exchangers and the air fractionators (crude argon column (CAC), low-pressure column (LPC), high-pressure column (HPC)), which have been modeled in detailed starting from recent literature models.[46]

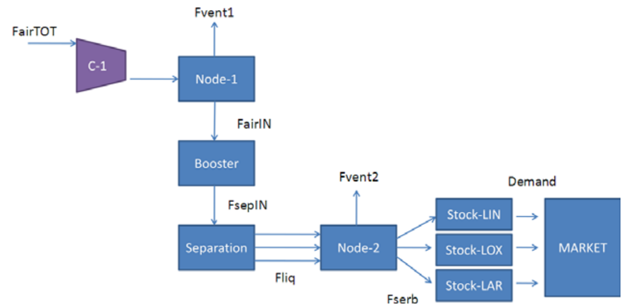

Figure 4. Qualitative scheme of ASU.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Mixed-integer corporate model

An existing corporate for industrial gases production has been studied. The following hypotheses are currently assumed: (I) three production sites (ASUs) are considered; (2) the production sites have the same production capacity and the same process flow diagram; (3) the sites can share their gas and liquid products free of logistic costs: it has been supposed that a distributed demand of the three liquid products where the plants were connected via pipeline; however, pipeline equations or logistic costs have not been considered for the time being, and the three plants can share the three liquid products free of charge; (4) a daily discretization and a monthly time horizon are assumed; (5) when a plant is in operation, its efficiency decreases by 0.5% for each sampling time; (6) when a plant is maintenaned, its efficiency increases by 0.5% for each sampling time; (7) the degrees of freedom of the optimization problem are the vent lines (three vents for all plants, see Figure 4); (8) the daily energy cost varies between night and day, but it is the same for all three plants; (9) storage capacity and initial conditions are the same for all plants except for the initial production efficiency equal to $\alpha_1 = 0.973$, $\alpha_2 = 0.881$, and $\alpha_3 = 0.748$, respectively, for the three plants; (10) to avoid too short (and physically infeasible) shutdown periods, at least 14 sampling times of shutdown period is assigned when the enterprise-wide production planning forces a plant to stop, and (11) at the same time, 14 sampling times are the maximum period for the stop to avoid any kind of social problems. Although ASU plants can be remotely controlled, a certain number of people work on them for

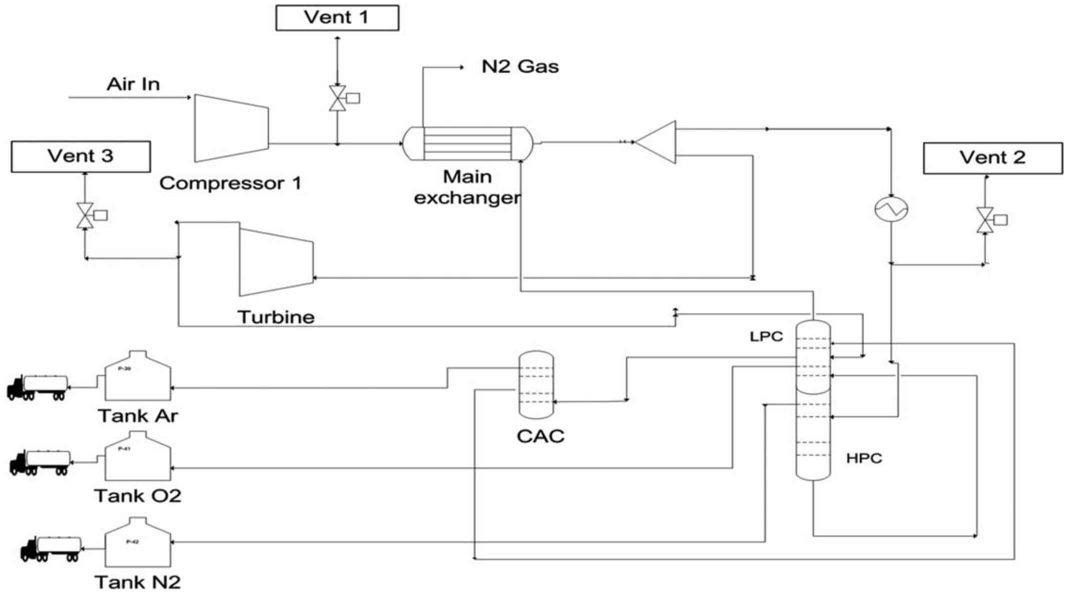

Figure 5. Reasonably detailed process scheme for ASU.

instance for maintenance purposes or truck filling, and long stop periods could lead to social issues.

Economic objective function

The objective function (Eq. (2)) consists of the evaluation of revenues and costs for each plant I = 1,…,NP = 3, and sampling time j = 1,…,NT = 60 (half a day each) of the selected time horizon (30 days)

$$\min_{\mathbf{x},\mathbf{b}} \Phi = -\sum_{j=1}^{NT=60} \left[REV_j(\mathbf{x},\mathbf{b}) - \sum_{i=1}^{NP=3} Cost_{i,j}(\mathbf{x},\mathbf{b})\right] \quad s.t.: \quad \begin{cases} f(\mathbf{x},\mathbf{b}) = 0 \\ g(\mathbf{x},\mathbf{b}) \geq 0 \end{cases} \tag{2}$$

Given the demand for every single product, the initial efficiency, products and energy costs (Figure 3), the optimizer determines the best corporate configuration in order to satisfy all the constraints.

Both $REV_{i,j}$ and $Cost_{i,j}$ involve different terms; the first one includes all the profits resulting from the sales (Eq. (3))

$$REV_j = \sum_{s=1}^{n^o products} Demand_{s,j} \cdot product\_price_s \tag{3}$$

The term $Cost_{i,j}$ includes all the costs deriving from the power consumption of the energy-intensive units of the three plants and the costs deriving from the three vent lines (degrees of freedom)

$$Cost_{i,j} = \sum_{g=1}^{pieces\_of\_equipment} Sw_{j,i,g} \cdot EE\_\mathrm{cost}_j \tag{4}$$

These costs are evaluated calculating the specific work of the units (see Figure 5):

- Compressor 1

$$Sw_1 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_c_i \cdot b_{i,j} \cdot AirIn_i \tag{5}$$

- Vent 1

$$Sw_2 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_c_i \cdot b_{i,j} \cdot Vent1 \tag{6}$$

- Main heat exchanger

$$Sw_3 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_ex_i \cdot b_{i,j} \cdot (AirIN_i - Vent1_i) \tag{7}$$

- Vent 2

$$Sw_4 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} (Sw\_c_i + Sw\_ex_i) \cdot b_{i,j} \cdot Vent2_i \tag{8}$$

- Turbine

$$Sw_5 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_t_i \cdot b_{i,j} \cdot (AirIN_i - Vent1_i) \cdot Split1_i \tag{9}$$

- Vent 3

$$Sw_6 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} (Sw\_c_i + Sw\_ex_i - Sw\_t_i) \cdot b_{i,j} \cdot Vent3_i \tag{10}$$

- LPC

$$Sw_7 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_LPC_i \cdot b_{i,j} \cdot \sum feed\_LPC \tag{11}$$

- HPC

$$Sw_8 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_HPC_i \cdot b_{i,j} \cdot \sum feed\_HPC \tag{12}$$

- CAC

$$Sw_7 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_CAC_i \cdot b_{i,j} \cdot \sum feed\_CAC \tag{13}$$

- Tanks (liquid argon, oxygen and nitrogen)

$$Sw_9 = \sum_{j=1}^{NT=60} \sum_{i=1}^{3} Sw\_tkN_{2i} \cdot N_2\_stock_{i,j} + Sw\_tkO_2 \cdot O_2\_stock_{i,j} + Sw\_tkAr_i \cdot Ar\_stock_{i,j} \quad (14)$$

- Inventory balances for the three products

$$\begin{aligned} Vol_{N_2}^{stock}{}_{i,j} &= Vol_{N_2}^{stock}{}_{i,j-1} - Demand_{N_2,j} + N_2\_stock_{i,j} \\ Vol_{O_2}^{stock}{}_{i,j} &= Vol_{O_2}^{stock}{}_{i,j-1} - Demand_{O_2,j} + O_2\_stock_{i,j} \\ Vol_{Ar}^{stock}{}_{i,j} &= Vol_{Ar}^{stock}{}_{i,j-1} - Demand_{Ar,j} + Ar\_stock_{i,j} \end{aligned} \quad (15)$$

Model constraints

As mentioned previously, the production capacity of an ASU plant is not only directly connected to logistics and customers' demands, but it is also limited by the capacity to produce the necessary cryogenic capacity to ensure the air liquefaction. A part of the liquid products (usually nitrogen) is used to liquefy the inlet air before going to the vent lines. These energy constraints are translated into liquid production constraints. In the plants considered here, we have inserted two different types of constraints:

1. The inequality constraints imposed to the liquid levels in the cryogenic tanks

$$\begin{aligned} Vol_{N_2,i}^{stock}(j) &\geq Vol_{N_2,i}^{stock_{MIN}} \\ Vol_{O_2,i}^{stock}(j) &\geq Vol_{O_2,i}^{stock_{MIN}} \\ Vol_{Ar,i}^{stock}(j) &\geq Vol_{Ar,i}^{stock_{MIN}} \end{aligned} \quad (16)$$

$$\begin{aligned} Vol_{N_2,i}^{stock}(j) &\leq Vol_{N_2,i}^{stock_{MAX}} \\ Vol_{O_2,i}^{stock}(j) &\leq Vol_{O_2,i}^{stock_{MAX}} \\ Vol_{Ar,i}^{stock}(j) &\leq Vol_{Ar,i}^{stock_{MAX}} \end{aligned} \quad (17)$$

2. the linear constraints on the maximum length of plant shutdown period (social constraint)

$$\sum_{j=1}^{time\ horizon} (SamplingTime_{off}) \leq 7 \quad (18)$$

Solution Strategy and Numerical Results

Considering three plants and 60 sampling times (12 h each), the whole optimization problem involves 12,060 equations and 630 decision variables (90 Boolean variables and 540 continuous variables), where optimization variables (or degrees of freedom for the optimizer) are the three "vent lines" for each plant and their value is stated by the optimizer so as to satisfy the global economic objective function. The Boolean variables indicate whether the plant is "on" or "off" during a day (30 Boolean variables for three plants). Other variables, calculated for example by a nonlinear system or function root-finding (i.e., condenser temperature or outlet compressor stage temperature), are computed for simulation purposes by limiting the optimization variables within appropriate bounds.

Following the numerical complexity of the enterprise-wide production planning described in the second paragraph, specific numerical solvers are needed. A set of very robust and efficient optimizers belonging to BzzMath scientific library is adopted to solve the resulting NLP problems (for more details, refer to Manenti[21]). These algorithms exploit the openMP directives for parallel computing on shared memory architectures (multiprocessor machines) to automatically improve the computational speed according to the available processors (conscious approach of object-oriented programming already discussed elsewhere).[21,42–44] The same set of optimizers is behind the nonlinear system solver of BzzMath adopted to solve the nonlinear constraints of the mathematical models of ASUs, which the enterprise-wide optimization problem is subject to. The mixed-integer nature of the problem is solved using a "brute force" method, since the reduced branched structure of the discrete portion of our problem is solved by investigating, in practice, all the integer possibilities; thus, it was preferred to decompose the mixed-integer mathematical problem into a set of continuous optimization problems rather than implementing a branch and bound algorithm. In Figure 5, the flow chart of the solution algorithm is reported. The algorithm is developed exploiting the object-oriented philosophy, and the model of the system is completely managed by the optimizer. The object-oriented structure confers the algorithm with a very high flexibility (possibility to switch from one model to another one without any change in structure). Raising the decision-making process to the corporate level, which means assigning a Boolean variable for all plants, it is not necessary anymore to maintain the relatively short time scale adopted for operations. Actually, a reasonable interval of time to handle corporate level optimization could be in the order of plant maintenance time, which is several days or, better still, several weeks. We selected 1 week for this basic case-study. From this viewpoint, it is worth saying that the linear constraints on the maximum length of the plant shutdown period, so called "social constraint", drastically reduces the possible Boolean combinations to deal with using a brute force method: there are $30-7+1 = 24$ "7-days" periods but it has to be considered that if a plant is shut off, the aforementioned constraint (see Eq. (18)) force the optimizer to set the Boolean variable on the specific plant at value "0" for all of the following week. The robust optimizer (see Figure 5) needs from 500 to 800 iterations to reach the minimum depending on the first attempt values. The computational effort for the monthly planning is about 4 h on an Intel i7 processor with 8 Gb Ram.

The rolling horizon methodology to handle uncertainties is not yet implemented in this preliminary activity, but the development of dedicated branch and bound method and rolling horizon are planned as a future development, as testified by recent tests on the moving horizon methodology and on novel linear programming methods.[44,47] Specifically, the class BzzNonLinearSystem is used to solve the resulting nonlinear systems; the class BzzFunctionRootRobust is used to evaluate the top temperature of air fractionators; the class BzzMinimizationRobust is used to solve the multidimensional nonlinear optimization problem.

Market and Enterprise-Wide Selected Scenarios

Two different scenarios are taken into consideration to study the applicability and the advantages of the new concept of supply chain management described in this article, and to compare the differences in decisions between the conventional plant-wide optimization and the global (enterprise-wide) optimization. The first scenario is characterized by relevant, initial, liquid product storages; this is the typical condition of the operating plants. The second scenario is characterized by null liquid storages; this is the typical condition of cold plant start-ups (startup after a relatively long shutdown period). Both the scenarios accounts for a monthly production planning problem under low-demand conditions.

Scenario 1

The initial storage of liquid products (LIN, LOX and LAR) in their respective cryogenic tanks is:

1. Plant 1:
   a. LIN = 40%
   b. LOX = 50%
   c. LAR = 60%
2. Plant 2:
   a. LIN = 3%
   b. LOX = 30%
   c. LAR = 40%
3. Plant 3:
   a. LIN = 2%
   b. LOX = 3%
   c. LAR = 4%

The optimal monthly production planning for the three products and for the three plants is illustrated in Figure 6.

Please note that the enterprise-wide production capacity is significantly larger than the current market demand due to the low-demand conditions for worldwide economic crisis. In this context, rather than operating the three plants for low production, for example, at the 60% of their normal capacity, that leads to very low and completely unprofitable production efficiencies, it could be preferable to operate two plants at their maximum design capacity and keep one of them off for additional maintenance to improve the efficiency. It is worth remarking that even though it is not so evident as per cracking, coking or heavy oil operations, also air separation plants have pieces of equipment that have a decreasing performance with time with effects on the whole efficiency. For instance, the pleated filters that purify atmosphere air before the main compressor, the molecular sieves, and the units for CO_2 and water removal are key operations with performance decay; in addition, alternative compressors that are frequently used in this type of plant may have a decrease in performance due to vibrations.

As reported in Figure 6, Plant 1 is forced to undergo a programmed maintenance during the fourth week; Plant 2, the second week, and Plant 3 the remaining weeks of the month. This is because the three plants have a different production efficiency, which is translated in different energy consumptions and production costs: the most efficient Plants (1 and 2) are generally operating, while Plant 3 is used in spare to the others for its low-production efficiency. Consequently, Plant 3 is characterized by strong oscillations in the liquid storages, whereas the other plants start immediately producing a certain amount of commodities at the beginning of the month.

Figure 6 shows the liquid levels of LIN, LOX and LAR during the monthly enterprise-wide planning. Please note that Pants 1 and 2 fill the storage tanks by liquid products during the first week, and then they empty the storages day-by-day to keep an optimal steady-state set of operating conditions as well as to reduce the expensive costs related to cryogenic storages.

Since it is very difficult to produce (there is a small amount in the air (<1%), and we need a complex splitter to separate it), the LAR demand significantly influences the ASU vents.

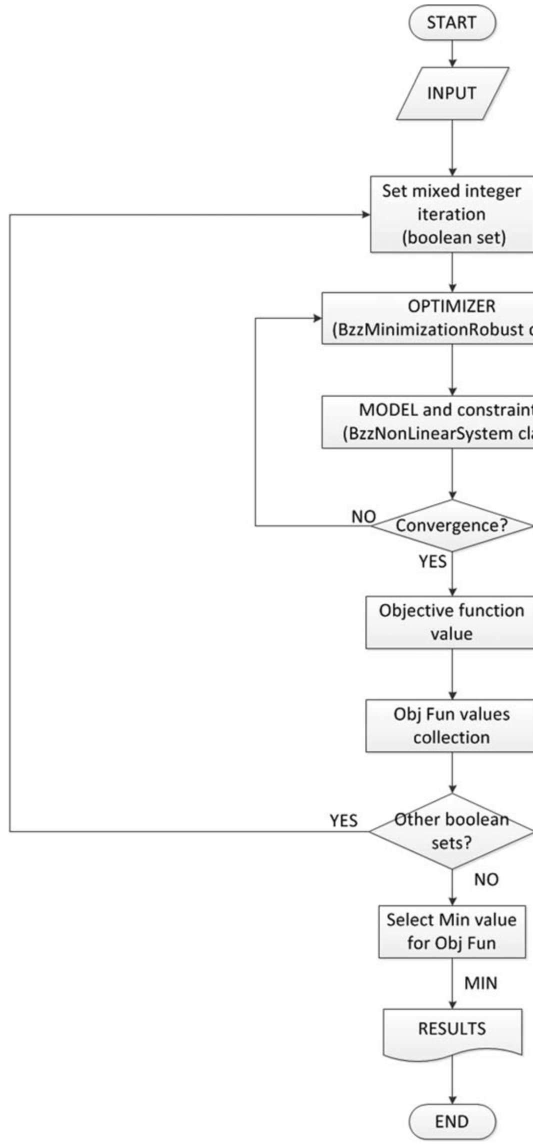

Figure 6. Flow chart for the solution algorithm.

It is important to see that the LAR level in the Plant 1 decreases until it becomes null the day before the shutdown. To fulfill the LAR demand during Plant 1 shutdown Plant 3 significantly increases production so as to cover its own market demand, but also to bridge the temporary lack of LAR production of Plant 1. on the other hand, Plant 2 enters the maintenance shutdown while the LAR level is positive (ca. 20%); by doing so, Plant 2 is able to fulfill the LAR demand with its own storage on the overall shutdown period, while Plant 3 production allows Plant 1 to preserve the LAR level during the second week and, at the same time, to satisfy the overall LAR demand of the enterprise-wide. Thus, the possibility to keep the LAR level at the second week allows Plant 1 to stay operating up to the last week.

The LOX is usually stored in the largest tanks essentially for two reasons: its storage cost is significantly lower than the LIN cost; it is only one fourth of the nitrogen in the air and this unavoidably makes it the bottleneck of liquid products of the ASU. Thus, when LOX is produced, it is generally stored to match possible demand peaks and market dynamics. On the other hand, the LIN is the most expensive item of ASU storages and, preferably, it is not stored in advance; actually,

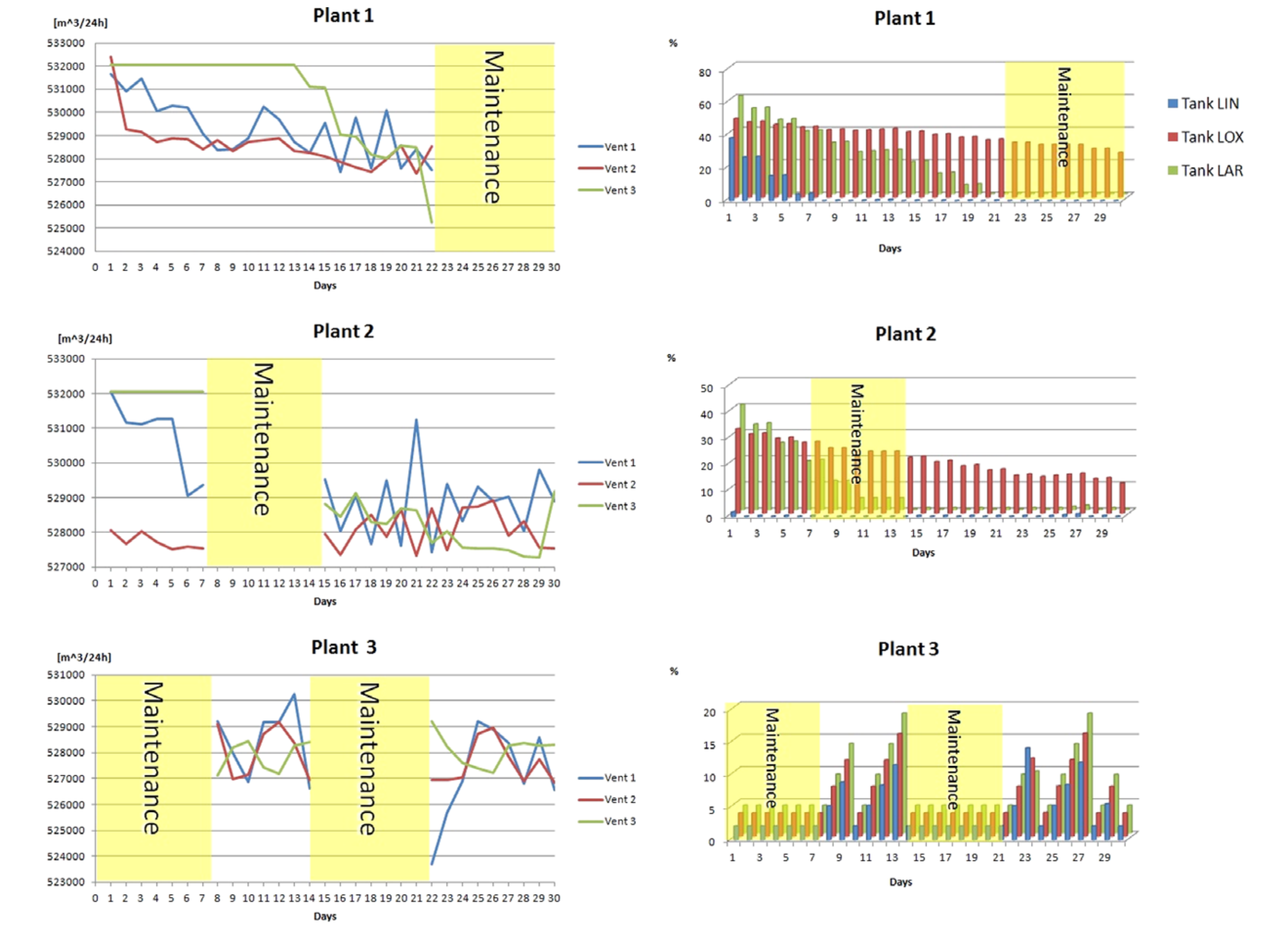

Figure 7. Vent lines flows (lefthand side) and liquid levels of LIN, LOX, LAR (righthand side).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

its predominant composition within the air induces a kind of just in time production even when market demand presents strong oscillations. Under the low-demand scenario supposed in this study, the stored amount of LIN is practically zero.

The monthly enterprise-wide planning practically assigns full load (with corresponding high-production efficiency) to two of the three available production sites by keeping the third site under maintenance for relatively short periods; this production scenario is very different from the single-site plant-wide optimization, which should force all the plants to operate around the 50–60% of their nominal capacity (very far from their nominal capacity, and, therefore, with low production efficiency).

Scenario 2

In this case, the monthly production planning starts with empty storage tanks for all the liquid products. Figure 7 presents a comparison between the liquid levels trends of the scenarios 1 and 2.

In scenario 2, the optimal plan is to fill the tanks up in the first operative week so as to bring back the levels of liquid products LOX, LIN, and LAR to the levels of scenario 1; actually, from the second week, the levels are the optimal ones to satisfy customers demand with minimum costs. Although the initial conditions are significantly different, it is worth noting that the maintenance schedule is preserved by emphasizing that the possibility to manage the on/off condition of the plants confers the enterprise-wide with high-production flexibility and higher margins. Specifically, Plants 1 and 2 are forced to operate very close to their nominal conditions. The trends for Plant 3 are the same as the previous scenario, since this plant plays the same role of spare production plant, being it the least efficient one in terms of production/energy costs.

Plant-Wide and Enterprise-Wide Optimization: Flexibility Comparison

A comparison between the plant-wide and the enterprise-wide optimization of the production is given for Plant 1 (Figure 8). Please note that the liquid levels of the LIN, LOX, and LAR are the same for both the plants. It means that this is the optimal condition to face the current market demand. Unfortunately, the production planning in the two cases is significantly different as it can be noted in the trend of the vent lines. It denotes a certain difficulty of the plant-wide approach to ensure the optimal liquid storages. In fact, its operational conditions are particularly unstable, with the vents that continuously oscillate along the overall month (bang-bang condition) and, obviously, the plant results physically impossible to operate under these strong oscillations:

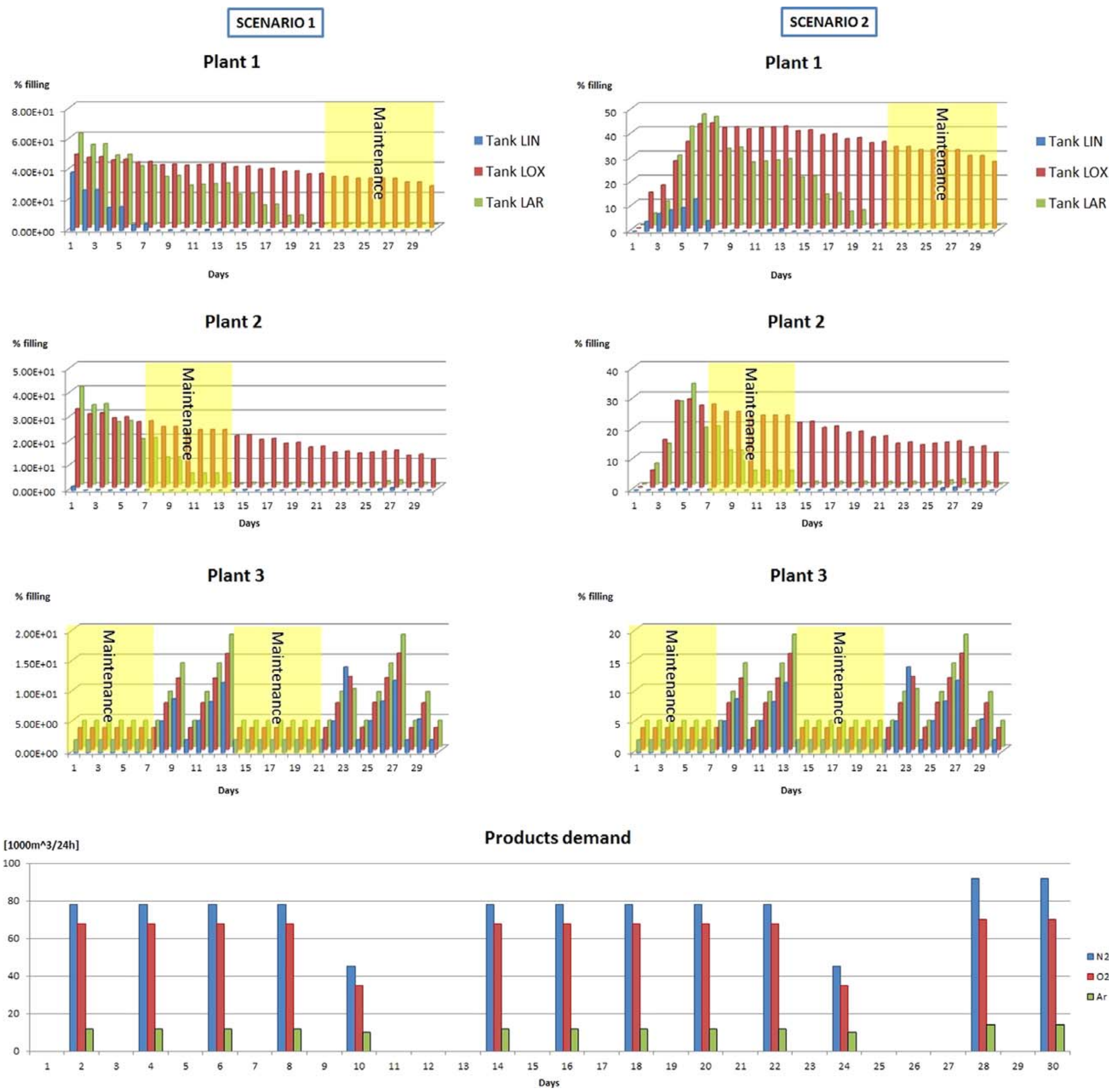

Figure 8. Comparison between the two different scenarios and typical request for products.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

- First, the management of the plant under these conditions is particularly dangerous for safety and environmental viewpoints. These are directly referred to energy consumption and production. ASUs do not produce pollutants themselves but they are so energy intensive that reduced consumptions equal to improved energy exploitation and sustainability as well as to reduced emissions for energy production.
- Second, large-scale production plants should avoid wide and persistent oscillations in their operating conditions to save the unit life cycle, to make easier the work of the field and control-room operators.
- Third, the strong inertia due to the mass and energy holdups of cryogenic plants makes physically infeasible in practice these fast changes of operating conditions.

In other words, the plant-wide production planning is characterized by less degrees of freedom than the enterprise-wide production planning, and its stiffness is highlighted by the instability in the monthly operations. Conversely, the enterprise-wide optimization has vent lines particularly stable. Nevertheless, the enterprise-wide optimization has the need to manage the on/off status of the production plants and certain additional social constraints must be taken into account. In any case, the possibility to alternate the shutdown of the production plants allows to increase the overall margin of the enterprise-wide, and, hence, to largely cover the social and economic expectations due to the plant turnover.

Last, it is worth underlining that the approach proposed in this article is very appealing to investigate and then prevent whether the decision-making process induces plant instabilities in the operations of the single sites. Actually, the use of models with reasonable detail in the characterization of the physical-chemical phenomena behind the ASU behavior and their implementation in the overall enterprise-wide optimization structure as linear/nonlinear constraints, allows a reliable prevision of the plant behaviors also when the same plants operate far from their nominal operating conditions (Figure 9).

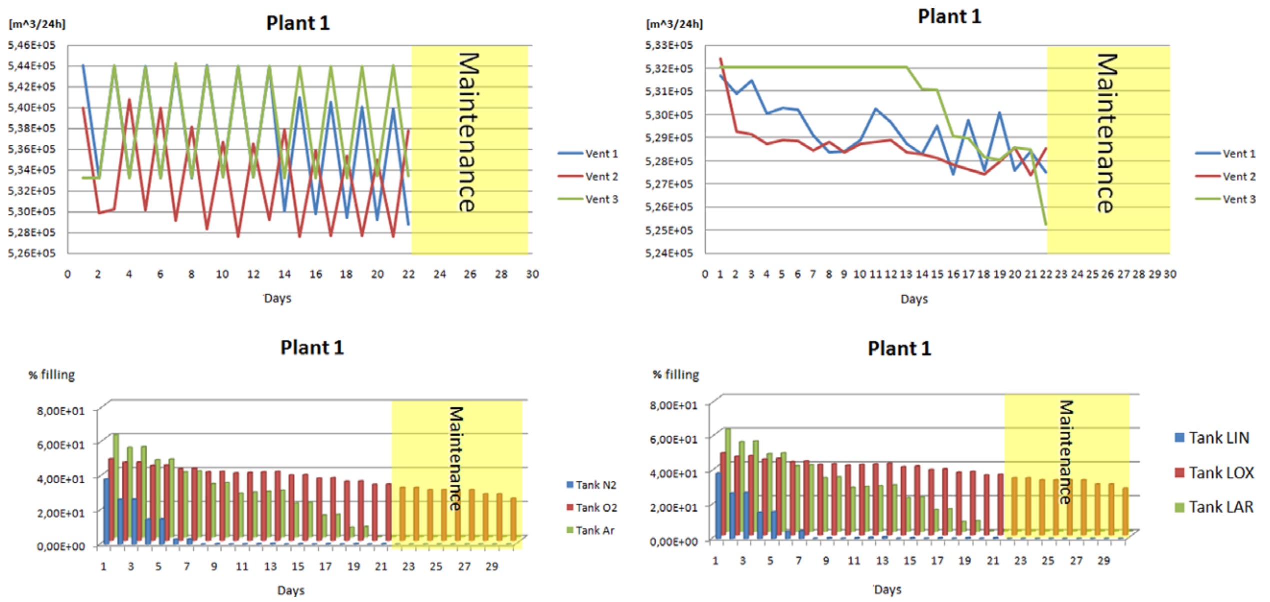

Figure 9. Comparison between plant-wide and enterprise-wide optimization.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Conclusions and Future Developments

This article shows certain tangible benefits of corporate production planning to tackle low-demand conditions. The proposed approach is fully developed in Microsoft Visual C++ and based on the scientific BzzMath library (freely downloadable numerical tool for scientific computing, Politecnico di Milano). The novelty of the proposed methodology is related to two key-points:

- The possibility to insert certain reasonably detailed physical-chemical models for the production plants into the optimization procedure of the enterprise-wide production planning.
- The possibility to introduce a Boolean variable for the production plant (0 = off; 1 = on) so as to higher the decision-making from the plant-wide level to the enterprise-wide level.

The results have demonstrated that the methodology is particularly appealing to reduce the losses under worldwide economic crisis and to plan the production of complex networks. Nevertheless, by doing so, certain additional social aspects deriving from enterprise-wide decisions (due to plant turnover) must be taken into consideration. Moreover, the instability conditions of the plant-wide optimization with respect to the proposed approach have been demonstrated. The proposed methodology allows enterprises in general to deal with massive economic losses deriving from the impossibility to merge plant and operational aspects to economic and logistics ones helping the manager to make right choices from both points of view avoiding high-products losses for excessive production.

Notation

Variables

$b_{i,j}$ = Boolean variable about on/off mode of plants
Sw_g = specific work for any piece of equipment, W/m^3
$Sw\_c_{i,j}$ = specific compression work
$Sw\_ex_{i,j}$ = main exchanger specific work
$Sw\_t_{i,j}$ = turbine specific work
$Sw\_LPC_{i,j}$ = LPC column specific work
$Sw\_HPC_{i,j}$ = HPC column specific work
$Sw\_CAC_{i,j}$ = CAC column specific work
$Sw\_tkN2_{i,j}$ = LIN storages specific work
$Sw\_tkO2_{i,j}$ = LOX storages specific work
$Sw\_tkAr_{i,j}$ = LAR storages specific work
$AirIN_{i,j}$ = air flow entering the plant, m^3/h
$Vent1_{i,j}$ = vent 1 flow
$Vent2_{i,j}$ = vent 2 flow
$Vent3_{i,j}$ = vent 3 flow
$Split1_{i,j}$ = splitting ratio at the first splitter
$\sum feed\_LPC_{i,j}$ = summation of flows entering the LPC column
$\sum feed\_HPC_{i,j}$ = summation of flows entering the HPC column
$\sum feed\_CAC_{i,j}$ = summation of flows entering the CAC column
$N_2\_stock_{i,j}$ = LIN flow entering the tank
$O_2\_stock_{i,j}$ = LOX flow entering the tank
$Ar\_stock_{i,j}$ = LAR flow entering the tank
${Vol_{N2}}^{stock}{}_{i,j}$ = LIN stored volume
${Vol_{O2}}^{stock}{}_{i,j}$ = LOX stored volume
${Vol_{Ar}}^{stock}{}_{i,j}$ = LAR stored volume
$REV_{i,j}$ = total revenues
$Cost_{i,j}$ = cost per day for all plants
$Samplingtime_{off}$ = days where the plant is in off-mode
Obj_fun_i = objective function value

Parameters

I = plant index
J = time period index
G = equipment index
S = product index
α_i = pant efficiency
α_i^0 = plant efficiency at initial time
${Vol_{N2}}^{stock\_MIN}$ = LIN minimum possible stored volume
${Vol_{O2}}^{stock\_MIN}$ = LOX minimum possible stored volume
${Vol_{Ar}}^{stock\_MIN}$ = LAR minimum possible stored volume
${Vol_{N2}}^{stockMAX}$ = LIN maximum possible stored volume
${Vol_{O2}}^{stock\_MAX}$ = LOX maximum possible stored volume
${Vol_{AR}}^{stock\_MAX}$ = LAR maximum possible stored volume
$product\_price_s$ = Single product price
EE_cost_j = energy cost for each period of time j
$Demand_{s,j}$ = products demands

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