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OPERATIONAL PLANNING IN THE MANAGEMENT OF PROGRAMMED MAINTENANCES A MILP APPROACH

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Abstract: Actual high competitive market's situation induces enterprises to consider the supply chain management as a key area to improve their business. Supply chains are systems with highly interconnected elements: suppliers, manufacturing, distribution network and customers. Each of them gives rise to a complex structure whose behaviour affects performances of the entire system. In literature, supply chain models completely deal with petroleum industry, whereas present research wants to analyze the tactical planning, through a large scale multisite modelling in the production and distribution of industrial gases, so to overcome programmed maintenance stops in an optimal way, keeping the satisfaction of market demand. *Copyright © 2007 IFAC*

Keywords: integer programming; optimization problems; maintenance engineering; large-scale systems; scheduling; planning.

1. INTRODUCTION

The supply chain management (SCM) mainly represents the ability to capture the synergy of intra and inter-company business processes. Historically, companies were focused on their resources, constraints and policies to make decisions and reduce costs; nevertheless, with intense competition and reduction in profit margins, this approach is no longer sufficient. They need of considering interactions between their suppliers and costumers and incorporating them into a well-defined decision-making process. So, the importance to develop all together the aspects of supply, the production, the storage and the distribution, induces a lot of companies to be interested in SCM. Generally, decisions are locally optimized only, at the production scale of the single process unit and they are not able to assure a global optimum for the entire enterprise. For the local decision-making, some decision support tools exist, such as planning, scheduling and management systems, but a mere electronic integration of these tools is not enough. Companies need of a unified approach for supply chain modelling and analysis, which explicitly captures interactions among singular production and distribution units of enterprises, Julka et al. (2002b) and Mauro et al. (2006). Shah (1998) had already reviewed some of the work developed so far, in terms of integrating planning and scheduling, and considers that the multisite problem will be the subject of significant research in the future. In the recent literature, supply chain models deal with petroleum industry such as oilfield infrastructures, crude oil supplies, refinery operations and products transportation, as discussed by Julka et al. (2002a) and Neiro and Pinto (2004, 2005) to name a few. Like that, the aim of present paper is to analyze, in section 2, a large scale problem concerning the production of oxygen, nitrogen and argon, characterized by two production sites, an oxygen pipeline, a branched structure for the distribution of liquid and gas phase products and a complex contract with the national supplier for the electric energy requirements. Sections 3 and 4 describe in detail the mathematical model of the single-site problem and the multisite structure, respectively; numerical results

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are discussed in section 5, whereas conclusions and future challenges are reported in section 6.

2. THE PROBLEM FORMULATION

2.1 The Network.

The overall network, figure 1, consists of two air separation units (ASUs) that are located in site A and site B, respectively. These plants are interconnected between themselves through a pipeline which has the aim to distribute the gas phase oxygen to main consumers and end users, such as steel mills. Instead, gases for minor users and liquid phase products (oxygen, nitrogen and argon) are delivered to costumers by cryogenic trucks.

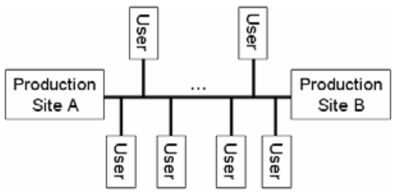

Fig. 1. Schematic architecture of the system: two ASUs interconnected by a gas phase oxygen pipeline which supplies main consumers.

2.2 The Structure of the Production Site.

Main elements of an air separation supply chain are the energy supply, the air refrigeration and separation section, end product storages and their distribution, figure 2. In the pre-refrigeration section the air is compressed till 5-6 atm. Then, it is purified by impurities, such as water, carbon dioxide and hydrocarbons. The refrigeration cycle liquefies the air flow, which is subsequently separated into its three main components: oxygen, nitrogen and argon. A part of liquid phase products is stored into tanks, whereas another part is re-gasified to recover energy in the refrigeration cycle. Downstream the separation zone, the gas phase oxygen is introduced into the pipeline, whereas the gas phase nitrogen is generally sent to vent for its overproduction. When demand portfolio requires it, one plant (site A) has the opportunity to liquefy gas products, even if it inevitably leads to the increase in energy consumptions.

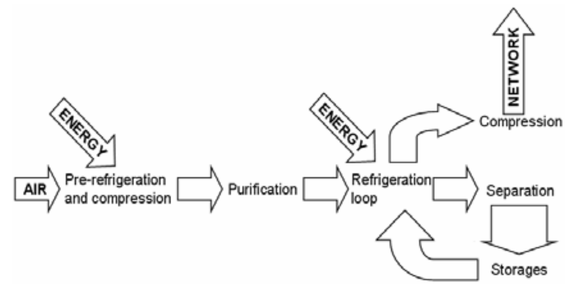

Fig. 2. Process flow chart of a typical air separation unit: pre-refrigeration, compression, purification, main refrigeration, separation and storage.

Production planning decisions that make the problem MILP concern the selection of particular discrete events, such as the start up and the shut down of rotating equipments, their full and partial operative condition or the employment of liquefiers, gasifiers and vent flows. The global optimum has to be evaluated taking into consideration the market demand, storage costs, distribution costs, the energy consumption and its cost variability during the day and the week.

2.3 Site A.

As starting point, the single-site problem is taken into consideration, dividing the plant in different elements such as air compression, air liquefaction, distillation and final storages, figure 3. These unit operations form nodes of the supply chain, interconnected by intermediate process streams.

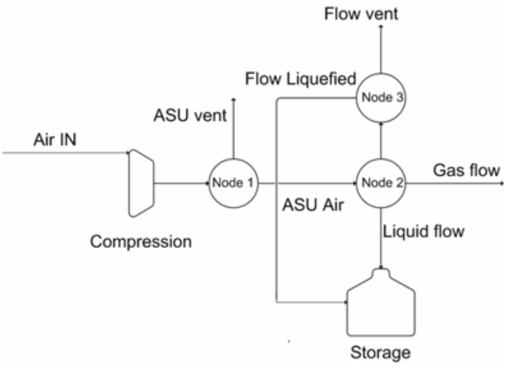

Fig. 3. Operation units considered in the modelling of the site A. Node 1 represents the refrigeration section, node 2 is the separation zone and in node 3 there are the liquefiers.

The model is mainly characterized by mass balances on the different nodes of the plant and by constraints on every unit, supposing a linear behaviour around the design conditions. After the air compression, there is a first node with a vent. The air is sent to liquefaction section where it is liquefied and separated. The output of the 2nd node is characterized by three streams for each product: liquid phase flow, gas phase flow to pipeline (only for the gas oxygen), gas phase flow to vent. On this node, constraints to liquid production are imposed. The gas flow vent reaches the 3rd node where, if necessary, it can be partially liquefied and sent to tanks. Tanks are units of the production chain, where the single operation allowed is the storage of different feed streams. Every tank has fixed constraints on the maximum and the minimum volume that can be stored. Stocked end products are subject to variable costs which depend on stock volumes and medium production costs. Moreover, the model takes into consideration two important aspects, the start up for the plant and for the base equipment and the energy supply. For each process unit of the plant, the start up duration, the corresponding loss of production and the energy consumption are assigned. For plant start up, losses in production of any singular component are distinguished too. As an example, during the start up, an ASU usually needs 12 hours to reach the specified purity in the oxygen and nitrogen production, while it needs of 24 hours to produce pure argon. These aspects are well described in the model. The model also considers different electric energy supply conditions for every ASUs. In fact, the selected sampling time in the MILP resolution is 12 hours, in order to differentiate electric energy costs between day and night.

2.4 Site B.

The site B formulation presents some fundamental difference. It has a similar scheme to site A, even if liquefiers don't exist: then, there's not the opportunity to liquefy gas products if the liquid market demand is high. Moreover, the site B has to guarantee the gas phase oxygen supply to an on-line user (oil refinery) and the remaining only can be introduced into the network. Sometimes, if the oxygen demand of the on-line consumer is too high, the site B can become a network user, receiving oxygen by the pipeline, rather than providing it. Last but least, the starting air compressor is not fed by electrical energy, because the on-line user supplies medium or high pressure steam.

3. MATHEMATICAL MODELLING OF SITE A

3.1 Economic Objective Function.

Every optimization problem is characterized by an objective function. Equations (1-5) show the economic objective function adopted in the site A formulation, whereas the site B will not be considered for space reasons:

$$\begin{aligned} PROFIT = \sum_{t=1}^{NP} (REV\_A_t - COST\_A_t) + \\ + REV\_BreakingOff\_A \end{aligned} \quad (1)$$

REV_A (2) may include gas and liquid phase products sold; *COST_A* (3) represents the costs summation of the electric energy, the storage volumes, the re-gasification energy consumption, products to vent and so on. The equation (4) refers to storage costs and (5) is a particular clause involved in the complex energy contract of the site A.

$$\begin{aligned} & REV\_A_t = \\ & = \sum_{y=1}^{NPD} \left[GasPrice_y \cdot \left(Fgas_{y,t} + Fgasifier_{y,t} \right) \right] \end{aligned} \quad (2)$$

$$\begin{aligned} & COST\_A_t = ee\_tot\_A_t \cdot Costfor_t + \\ & + \sum_{y=1}^{NPD} Fflashnatural\_A_{y,t} \cdot LiqPrice_y + \\ & + \sum_{y=1}^{NPD} Vstock\_A_{y,t} \cdot CostStock_y + \\ & + \sum_{y=1}^{NPD} Fgasifier\_A_{y,t} \cdot (liqPrice_y - GasPrice_y) + \\ & + \sum_{y=1}^{NPD} \left(Fvent\_A_{y,t} \cdot LiqPrice_y + \right. \\ & \left. - Fvent\_A_{Az,t} \cdot LiqPrice_{Az} \right) \end{aligned} \quad (3)$$

$$CostStock_i = Vstock_i \sum_{k=1}^{N^{equip}} \frac{E_k}{F_i \cdot S_i} \cdot \bar{C}^{elect} \quad (4)$$

$$REV\_Int\_A = INT \cdot BreakingOff \quad (5)$$

3.2 Energy Consumption Equations.

About main units, the electric energy consumption is calculated considering the air fed (*F_Equipment*) and using parameters obtained by the regression of industrial data (*m_Equipment*; *q_Equipment*) using BzzMath library, Buzzi (2006). *X_Equipment* is a Boolean variable which is null if the unit is off.

$$\begin{aligned} & EnergyConsumption_t = \\ & \quad + F\_Equipment_t * m\_Equipment + \\ & \quad + q\_Equipment * X\_Equipment_t \end{aligned} \quad (6)$$

Following set of equations (7) report the energy consumption of the two air compressors included in the pre-refrigeration section, named *C1* and *C2*, the energy requirements of the booster in the refrigeration cycle, of liquefiers and other utilities. The overall needs of the electric energy is evaluated in (8).

$$\begin{aligned} & ee\_C1\_A_t = Fair\_C1\_A_t \cdot mC1\_A + \\ & \quad + qC1\_A \cdot Xair1\_A_t \\ & ee\_C2\_A_t = Fair\_C2\_A_t \cdot mC2\_A + \\ & \quad + qC2\_A \cdot Xair2\_A_t \\ & ee\_booster\_A_t = (Fair\_C1\_A_t + \\ & \quad + Fair\_C2\_A_t) \cdot mbooster\_A + \\ & \quad + qbooster\_A \cdot Xair1\_A_t \\ & ee\_liq\_A_t = \sum_{y=1}^{NPD} PLiquefier\_A_y \cdot Xliq\_A_{y,t} \\ & ee\_utilities\_A_t = ee\_utilities\_C1\_A \cdot \\ & \quad \cdot Xair1\_A_t + ee\_utilities\_C2\_A \cdot \\ & \quad \cdot Xair2\_A_t \end{aligned} \quad (7)$$

$$\begin{aligned} & ee\_tot\_A_t = ee\_C1\_A_t + ee\_C2\_A_t + \\ & \quad + ee\_booster\_A_t + \\ & \quad + ee\_utilities\_A_t + ee\_liq\_A_t \end{aligned} \quad (8)$$

3.3 Energy Contract.

Production sites need the electrical energy especially to compress and liquefy the air flow, even if each ASU singularly acquires the energy with different costs and conditions, influencing the production, the distribution and the planning. The *ee_BreakingOff* is a Boolean variable employed for calculating a possible discount in the overall energy cost. The energy consumption on the whole prediction horizon is evaluated (9); then, as defined by contract terms, the electrical consumption is purified by periods of programmed and failure maintenances (10), so to obtain the effective breaking off (*BreakingOff_eff*) utilization. The national energy supplier applies the discount only if the ratio between the effective breaking off and the estimated consumption already defined by contract (*P_BreakingOff*) is greater than one (11-12).

$$ee\_BreakingOff = \sum_{t=1}^{NP}\left(ee\_C1\_A_t + ee\_C2\_A_t + ee\_booster\_A_t + ee\_liq\_A_t\right) \quad (9)$$

$$\begin{aligned} &BreakingOff\_eff = \\ &= \left(\frac{ee\_BreakingOff}{(NP - h\_maint / h\_period)}\right) \Big/ h\_period \end{aligned} \quad (10)$$

$$Ratio\_BreakingOff = \frac{BreakingOff\_eff}{0.8 \cdot P\_BreakingOff} \quad (11)$$

$$BreakingOff \le Ratio\_BreakingOff \quad (12)$$

Generally speaking, the breaking off is a particular service that the society in study gives the electrical network supplier the opportunity to interrupt the energy supply, with or without notice. It represents one clause only of the complex energy contract.

3.4 Start-up Procedure of Unit Operations.

For each unit operation, an ad hoc start up procedure is modelled. As an example, following conditions refer to the start up of *C1* (13) and *C2* (14). The *startup_Equipment_A*, a Boolean variable, is equal to zero not only if the unit is off, but also if the unit works at the steady state conditions, whereas another decisional variable, *init_cond_Equipment_A*, defines the on/off condition of a unit.

$$\begin{aligned} &Xair1\_A_t - Xair1\_A_{t-1} \le startup\_C1\_A_t \\ &\left(Xair1\_A_t - Xair1\_A_{t-1} + 1\right) \cdot 0.5 \ge startup\_C1\_A_t \\ &startup\_C1\_A_t \ge Xair1\_A_1 - init\_cond\_C1\_A \\ &startup\_C1\_A_t \le \\ &\qquad \le \left(Xair1\_A_1 - init\_cond\_C1\_A + 1\right) \cdot 0.5 \end{aligned} \quad (13)$$

$$\begin{aligned} &Xair2\_A_t - Xair2\_A_{t-1} \le startup\_C2\_A_t \\ &\left(Xair2\_A_t - Xair2\_A_{t-1} + 1\right) \cdot 0.5 \ge startup\_C2\_A_t \\ &startup\_C2\_A_t \ge Xair2\_A_1 - init\_cond\_C2\_A \\ &startup\_C2\_A_t \le \\ &\qquad \le \left(Xair2\_A_1 - init\_cond\_C2\_A + 1\right) \cdot 0.5 \end{aligned} \quad (14)$$

A possible interaction between *C1* and *C2* in the start up phase is considered too (15). In fact, if both air compressors are simultaneously switched on, the binary variable *startup_C1_C2_A* has a positive value.

$$\begin{aligned} &startup\_C1\_C2\_A_t \le \\ &\qquad \le (startup\_C1\_A_t + Xair2\_A_t)/2 \\ &startup\_C1\_C2\_A_t \ge \\ &\qquad \ge (startup\_C1\_A_t + Xair2\_A_t - 1)/2 \end{aligned} \quad (15)$$

4. MULTISITE MODEL

The multisite model is based on the two single-site models discussed in the previous section. Therefore, the global approach which considers the pipeline and logistic interconnections between the two production sites is shown in the following picture.

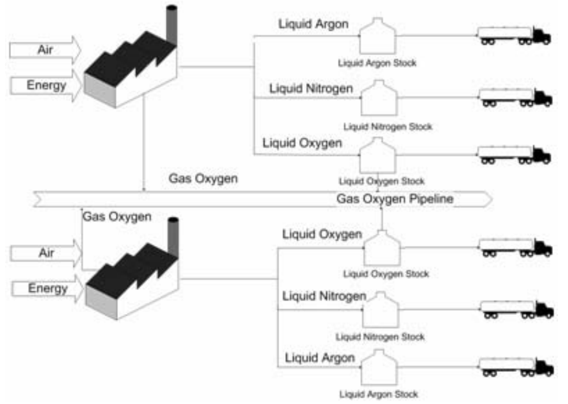

Fig. 3. Multisite model scheme: supply, production, pipeline, storages and distribution.

Of course, each single-site model presents its own peculiarities, such as electric energy furniture, purchase agreement, production capacity, stock constraints, base equipment start up and so on, besides different process design and configuration. On the other hand, the multisite model allows to describe with accuracy the distribution of the end product between ASUs and the synergic production coming from the possibility to move the workload production from a site to the other one. The model has two main characteristics: first of all, it allows to consider the programmed stop of plants and to manage the production when a plant is turned down. The multisite mathematical model permits to transfer the liquid product from site A to site B too and vice versa, in order to make up liquid phase market demand. In this sense, end product costs are higher because a logistic term is added (16).

$$C^{tot} = C^{prod} + C^{stock} + C^{log} \quad (16)$$

5. NUMERICAL RESULTS

Some applicative example of the supply chain is described and especially two cases are taken into consideration:

- The single-site optimization with an unusual market demand peak.
- The multisite optimization with a four days programmed maintenance stop on the site B, leaving completely operative the site A.

5.1 MILP Solver.

The global and multi-period model is based on a mixed integer linear programming (MILP) problem, characterized by a large number of continuous and integer variables:

- Site A consists of about 5500 equations (more than 500 decisional variables)
- Site B consists of about 5000 equations (around 400 decisional variables)

The solution can be performed using GAMS (General Algebraic Modeling System) and Coin-CbC as MILP solver, Brooke et al. (1998, 2004).

5.2 *Unusual Peak in the Market Demand.*

The first case regards the sole site A plant optimization. The comparison concerns two different market scenarios: the first one is characterized by an ordinary demand, whereas the second one is a market situation with an atypical demand peak during the fourth week. Note that during the night the demand is null and it induces a characteristic serrated trend, reported in figure 4, where stocks for liquid oxygen are reported too. Stock levels are kept at their lowest value from Monday to Friday, when energy costs are the highest and then the production is the minimum enough for satisfying customer demand. During weekends, stock levels rise because production costs (especially energy costs) are the lowest and the gas flow sent to vent can be partially liquefied too. However, stored liquids are usually associated to storage costs, so a minimum stored volume is expected at the end of the simulation time. Instead, analyzing the typical market situation in figure 4, the planning of site A increases the stored volume during last days, through the production of more liquid oxygen: it could appear in disagreement with economic objectives, instead, the contrary is true: in fact, this overproduction allows site A reaching the breaking off production limit, with a considerable increasing in benefits and profits. On the other hand, in a market characterized by a demand peak (during days 21st-26th, the product demand is doubled for liquid end products and the plant capacity is not able to satisfy the oxygen request), it is possible to appreciate two main effects. The first one is the preventive accumulation in liquids during days before the critical week. The second effect concerns last two days: if site A was in an ordinary demand situation, the planning should present an overproduction; in this case, it is not necessary because the breaking off limit has been already obtained and the final storage volume appears considerably lower. About final liquid storages, the same consideration may be done in the nitrogen production case, reported in figure 5.

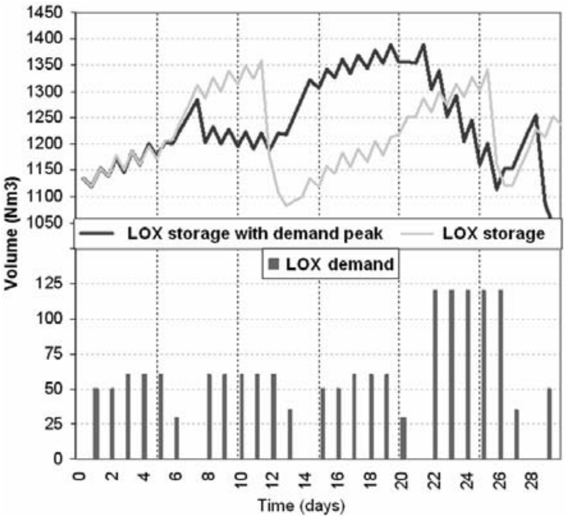

Fig. 4. Liquid oxygen stocks: comparison between a standard market situation (light line) and an atypical one (dark line) characterized by a demand peak during the 4th week.

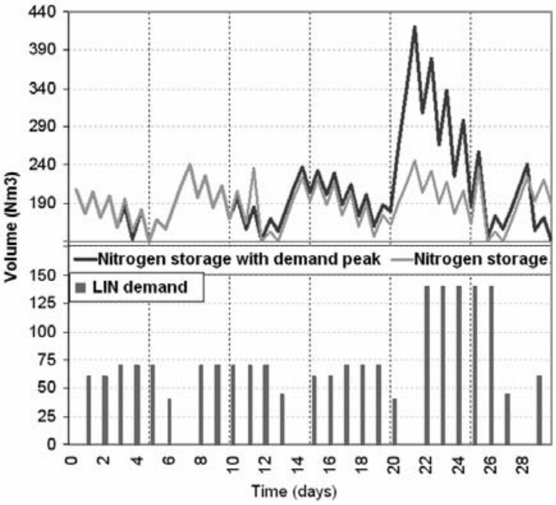

Fig. 5. Liquid nitrogen stocks: comparison between a standard market situation (light line) and an atypical market demand (dark line). The liquid nitrogen reacts to the market peak with a just in time production.

Nevertheless, the main difference with the oxygen case is that the site A is able to satisfy the market demand of that liquid product, without starting with a preventive accumulation during the third week: this kind of planning is the peculiarity of the just in time production, unrealizable in the oxygen production as analytically shown by Kimura and Terada (1981).

5.3 *Four-days of Programmed Maintenance Stop in the Site B.*

In the multisite optimization, site A and site B are interconnected between themselves by a gas oxygen pipeline. The simplest objective function may be the sum of economic objectives of both site A and site B, with the addiction of another economic term, which represents logistic costs (17):

$$
\begin{aligned}
PROFIT = & \sum_{t=1}^{NP} (REV\_A_t - COST\_A_t) + \\
& + REV\_BreakinOff\_A + \\
& + \sum_{t=1}^{NP} (REV\_B_t - COST\_B_t) + \\
& + \sum_{t=1}^{NP} (COST\_LOG_t)
\end{aligned} \tag{17}
$$

A programmed maintenance stop (days 16th-19th) in the site B is considered. In this sense, it’s possible to note how the nitrogen and the oxygen storage levels grow, in order to ensure customers demand during the break of the production due to the programmed maintenance, empting stocks in the immediately successive period, when the site B production is prevented. Because the site B has to guarantee, by contract, the gas oxygen supply to the on-line user, at first it tries a preventive accumulation, reported in figure 6. Nevertheless, even if the operational planning imposes to increase the gas oxygen stock, this is not enough because the storage volumes are too much limited in the site B; so, the site A increases its gas production too and sends, via pipeline, the gas phase oxygen to the site B during the whole programmed maintenance period. Then, in the analysis of the site A production planning, the market conditions are the same of a gas oxygen demand characterized by an unusual peak in correspondence of the site B maintenance stop. On the contrary, about the nitrogen planning, the site B overcomes the programmed maintenance period through the sole preventive production, without modifying the site A production planning. These results well represent the air separation supply chain, in fact, the market demand portfolio influences production planning, where costs are optimized considering all the more important aspects of electric energy supply in a global approach. The two production sites are an integrated part of the entire system and their monthly production is optimized considering the global benefit of the problem.

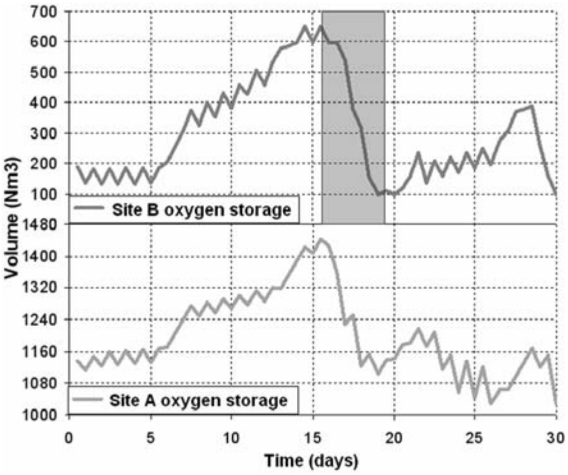

Fig. 6. Programmed maintenance stop in site B (banded period): liquid oxygen storage for both production sites.

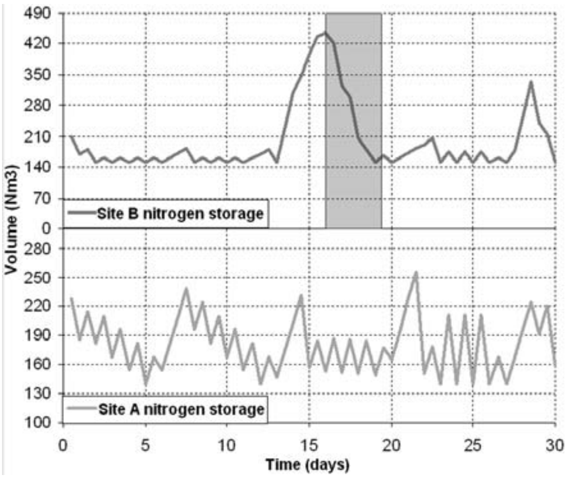

Fig. 7. Programmed maintenance stop in site B (banded period): liquid nitrogen storage for both production sites.

6. CONCLUSIONS

Today, the SCM has become the strategic area that has direct impact over the success of any enterprise in the actual highly competitive business environment. In this paper, a system that emulates an air separation supply chain has been developed and a concrete implementation has been described. Some preliminary result for the strategic and the operational supply chain are discussed, applied on the single-site and the multisite air separation enterprise, mainly describing economical advantages, such as reduction in energy consumption and better utilization of raw materials. Future work will include a more detailed pipeline description and it will be possible to introduce in the multisite model the demand uncertainty in order to comprehend the behaviour of the entire supply chain in front of unexpected market floating. Moreover, a mixed integer nonlinear approach will be adopted for modelling some process unit, which has a strongly nonlinear behaviour, and for improving the start up and the shutdown procedure efficiencies. Finally, a probabilistic approach, for modelling failure maintenances, will be possible.

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