CHEMICAL ENGINEERING TRANSACTIONS
VOL. 29, 2012
Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1229065

Online Superstructure Optimization for Energy Saving of an Industrial Gas Distribution System

Matteo D'Isanto[a], Flavio Manenti[a,*], Maria G. Grottoli[a], Marcello Altavilla[b], Roberto Di Marco[c]

[a]Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", Leonardo Chemical Engineering LAB, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b]Linde Gas Italia, Terni Plant, Viale Benedetto Brin 214, 05100, Terni, Italy
[c]Linde Gas Italia, Headquarter, Via Guido Rossa 3, 20010 Arluno (MI), Italy
flavio.manenti@polimi.it

Mixed-integer optimization is a common approach to handle decision-making problems. Nevertheless, such an approach still presents certain operational limitations, especially for online superstructures. One of these limitations is given by Jacobian singularity, which arises for certain combinations of the set of Boolean variables and which easily leads to possible infeasible numerical solutions. This paper proposes a novel approach to overcome this problem, ensuring the use of mixed-integer optimization also to solve online issues. The case of nitrogen supply for the Thyssen-Krupp steel mill placed in Terni (Italy) is considered as validation case.

1. Introduction

The optimization of gas transport network is a very important industrial problem (Martin et al., 2006; Ehrhardt and Steinbach, 2005; Domschke et al., 2011). Many industrial gases production plants are directly connected to tonnage users such as steel mill plants and refinery plants requesting thousands of Nm^3 per hour of gases at different pressures and without a previously accorded planning. Therefore a strategy to react rapidly and flexibly to the requests will be of significant importance for the gas company to reduce energy consumption and to better exploit plant performances. This leads to a very complex problem to solve because of the Boolean nature of the variables involved, which is challenging either for a mathematical point of view or to better tackle with the business challenge (Ierapetritou et al., 2002; Floudas et al., 2005; Glankwamdee et al., 2008; D'Isanto et al., 2011). Here it is presented a new simulation and optimization tool for this problem. The situation is basically the minimization of distribution costs (for nitrogen only) from the gas production site (Linde Gas Italia, Terni) to a high capacity steelworks plant (Thyssen-Krupp); to supply Thyssen-Krupp, an existing network is used. It is rather complicated since it has two different sources, consisting of two separate air separation units, with one of them that produces gas products only and the other one that produces both liquid and gas products. Moreover, the distribution line of a disposed air separation unit is still operating and it can be used whenever the energy cost makes it appealing. The gaseous nitrogen distribution network here considered includes several compressors dedicated to the supply of a high-capacity steelworks plant that requests nitrogen at three different pressures with a demand that significantly changes many times within the day due to different steel treatments and castings. The energy consumption for the entire distribution network is high due to the large amount of power for the compression work, but also to the fast-response required to adapt the distribution network to the

Please cite this article as: D'Isanto M., Manenti F., Grottoli M. G., Altavilla M. and Di Marco R., (2012), Online superstructure optimization for energy saving of an industrial gas distribution system, Chemical Engineering Transactions, 29, 385-390

instantaneous and unpredictable changes in nitrogen demand. Energy costs for intensive users, like air separation units for industrial gases, have been largely investigated in the literature (Ierapetritou et al., 2002; Zhu et al., 2010), at least for their operational issues. Thus, several well-established solutions and a well-consolidated experience are used to optimize the operations and to dictate the best operating conditions when a certain demand is assigned (Manenti, 2009; Westerlund et al., 2011). The present work is aimed at exploiting the potentialities of the existing solution by introducing a strategic coordinator that manages online the overall superstructure of the distribution system. This work proposes a novel approach to manage the operations of distribution, which is based on the implementation of a mixed-integer optimizer that allows the user to promptly have the configuration that minimize the energy consumption with a noticeable increase in profit. Moreover, the optimizer allows matching the significant discontinuities of the industrial gas demand, without any energy dissipation. To make the solution very performing, the simultaneous re-organization of the Jacobian's structure of the resulting systems, which significantly changes for the Boolean nature of certain variables, specific numerical methods are implemented (Buzzi-Ferraris, 2011a; Buzzi-Ferraris and Manenti, 2010; Buzzi-Ferraris, 2011b).

2. Plant description

The network presented in this paper is an existing gas nitrogen (GAN) distribution network linking a gas nitrogen production site and a liquid nitrogen production site (two different air separation units) to the high capacity Thyssen-Krupp's steel mill placed in Terni, Italy. As it is possible to see in Figure 1, the network consists of several compressors and lines and it is able to supply GAN to the steel mill at three different pressure values:

- a low pressure GAN (LPGAN) at 6 bar
- a medium pressure GAN (MPGAN) at 17 bar
- and a high pressure GAN (HPGAN) at 30 bar

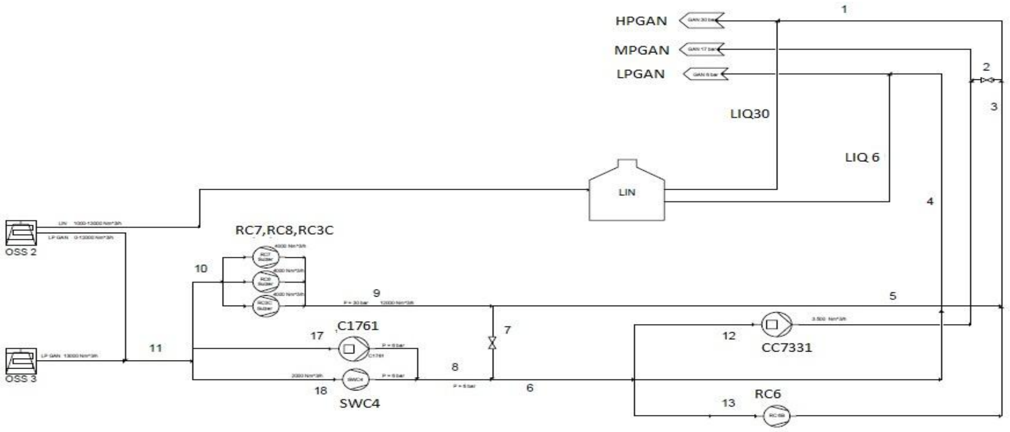

Figure 1: Simplified PFD of the GAN distribution network at the Terni plant

The GAN is introduced into the network from two different sources: the so-called OSS2 ASU, producing both liquid and gas nitrogen, and the OSS3 ASU, entirely dedicated to the production of GAN. The two gas lines coming from the plants are collected in a mixer. The network is composed of 20 different lines and 7 compressors. 5 compressors (RC7, RC8, RC3C, SWC4, RC6) are reciprocating multistage type, whereas the remaining 2 compressors are centrifugal type (C1761, CC7331). Every compressor has its own operative curve except for RC7 and RC3C that have the same curve and a particular control system that allows operating the compressor energy saving also at low flow rates (HYDROCOMM®); every curve have been linearized. Compressors RC7, RC8, RC3C, and RC6B produce HPGAN; compressors C1761 and SWC4 produce LPGAN; and the compressor CC7331 is the only one that produces MPGAN. Furthermore, there is the possibility to gasify the liquid nitrogen produced by the OSS2 ASU in LPGAN and HPGAN and there are also two lines (no. 2 and 7 of Figure 1) where a lamination valve allows producing LPGAN and MPGAN, respectively, from the HPGAN lines.

3. Model description and mathematical programming

The study and optimization of the GAN distribution network involves both continuous and discrete variables. The former variables are, for instance, the flow rates of the nitrogen supplied to the steel mill or the pressure within each stream, whereas the discrete variables are mainly the on/off conditions of the compressors of the GAN distribution network, which are the result of the optimization and thus the support to the decision making process for energy saving purposes. Also, the large dimension of the resulting system is due to the mixed-Boolean nature of the problem and the uncertainty affect the mathematical programming since the steel mill requirements cannot be predicted (steel mill casting). To model the GAN distribution network of the Section 2, the compressor curves are linearized. The resulting matrix $\mathbf{M} \in R^{12\times 20}$ characterizing the GAN distribution system is a largely-sparse, unstructured, and under-dimensioned matrix.
The resulting problem is a mixed-integer linear programming problem (MILP) (Bonami et al., 2008; Biegler and Grossmann, 2004; Grossmann and Furman, 2008).The objective function to minimize is the total energy consumption for distribution:

$$\begin{aligned} &\min_{\mathbf{x},\mathbf{b}} \Phi = \sum_{i=1}^{i=NC} pow\_comp_i\left(\mathbf{x},\mathbf{b}\right)\cdot energy\_cost + \sum_{j=1}^{j=LL} liquid\_flow_j\left(\mathbf{x},\mathbf{b}\right)\cdot liquid\_cost \\ &s.t.: \\ &f\left(\mathbf{x},\mathbf{b}\right)=0 \\ &g\left(\mathbf{x},\mathbf{b}\right)\geq 0 \end{aligned} \tag{2}$$

where $\mathbf{x}$ and $\mathbf{b}$ are the continuous and discrete variables, respectively; *NC* is the number of compressors; *LL* is the number of streams of the gasified liquids from the OSS2 ASU; *f* and *g* represent the linear equality and inequality constraints, respectively, for the model of the GAN distribution network.
The optimizer can exclude one or more compressor from the optimization, setting it in maintenance mode $\left(b_i=0\right)$ in accordance with the different sets of energy costs, gasification costs, nitrogen requirements. Nevertheless, there are several problems to be faced. First of all the matrix is rectangular and it may lose its singularity for certain combinations of Boolean variables; this aspect must be considered in a tool for online optimization. Moreover, the solution must be particularly performing since, as mentioned above, the steel mill requests are unpredictable and whenever a change happens, the optimal distribution must be detected and the energy saving policy must be promptly implemented. There is the possibility to transform the current system into a more appealing system from the numerical point of view. Using the real-integer matrix decomposition, it is possible to separate the discrete nature from the continuous one. Decomposing the matrix $\mathbf{M}$, we can distinguish two matrices:

$$\mathbf{A}=\mathrm{Re}\left(\mathbf{M}\right)=\left[a_{i,j}\right]\in R^{(i=1,\dots,n)\times(j=1,\dots,m)} \tag{3}$$

which is the real part of $\mathbf{M}$ (no Boolean variables), and:

$$\mathbf{B}=\mathrm{Bo}\left(\mathbf{M}\right)=\left[b_{i,j}\right]\in\left\{0;1\right\}^{(i=1,\dots,n)\times(j=1,\dots,m)} \tag{4}$$

which is the Boolean part of $\mathbf{M}$ (mixed variables). The continuous portion $\mathbf{A}$ can be made symmetric by multiplying it with its transpose matrix. Unfortunately, such an operation increases the filling degree of the resulting matrix and leads to certain losses in the number of significant digits, but allows exploiting the so-called Cuthill-McKee algorithm (Cuthill and McKee, 1969), which is useful for symmetric matrices only, to diagonalize the resulting system and, thus, to remove automatically the possible matrix singularities and to significantly speed the calculations up as well. Let us proceed by steps.

The system $\mathbf{ABx} = \mathbf{c}$ to be solved must have the coefficient matrix symmetric to apply the Cuthill-McKee algorithm. Therefore, the following system can be considered:

$$\mathbf{A}^{\mathrm{T}}\mathbf{ABx} = \mathbf{A}^{\mathrm{T}}\mathbf{c} \tag{5}$$

Although the transpose operation of a matrix reduces the number of significant digits, it is possible to perform such an operation by preserving a relevant piece of information (Buzzi-Ferraris and Manenti, 2010). Denoting by $\mathbf{S} \in R^{m \times m} = \mathbf{A}^{\mathrm{T}}\mathbf{A}$, it results in:

$$\mathbf{SBx} = \mathbf{A}^{\mathrm{T}}\mathbf{c} \tag{6}$$

$$\left(\mathbf{SB}\right)^{\mathrm{T}}\mathbf{SBx} = \left(\mathbf{ASB}\right)^{\mathrm{T}}\mathbf{c} \tag{7}$$

and with $\mathbf{R} = \left(\mathbf{SB}\right)^{\mathrm{T}}\left(\mathbf{SB}\right)$, we obtain:

$$\mathbf{Rx} = \left(\mathbf{ASB}\right)^{\mathrm{T}}\mathbf{c} \tag{8}$$

It means that we can perform in advance a single factorization of the overall system and, exploiting it, we are able to solve instantaneously all the possible requests of the steel mill (variations in the vector $\mathbf{c}$ only) without any additional matrix computation and preserving the non-singularity of the coefficient matrix $\mathbf{R}$. It results in a strong robustness of the solver as well as in very high performances, which ensure the proper optimal operational structure of the GAN distribution network in real time, whenever the unpredictable requests of the steel mills change.

The very high efficiency of the proposed solution method allows solving quickly also the resulting MILP problem discussed in this paper simply solving all the possible Boolean combination (2^{NC}) and comparing the value obtained for the objective function; in this way a very robust resolution is ensured.

4. Results

Table 1 shows the optimization results of 10 scenarios that may occur:

- Scenarios 1, 2, 3: the optimizer is free to choose the combination that best fit the requests with all compressors working. In case 1, we have a usual request of all the three products from the steel mill and the right choice is using only one of the three alternative compressors at the minimum power possible. When the requests of HPGAN and MPGAN increase also a second alternative compressor is in "on-mode" (RC7) and the RC6 is switched off. In Scenario 3 the HPGAN's request is zero and the optimizer decides to use RC3C to produce HPGAN to be laminated to MPGAN (see L2).
- Scenario 4: alternative compressors for producing HPGAN (RC7, RC8, RC3C) are under maintenance and so the optimizer imposes to gasify liquids to produce HPGAN.
- Scenario 5 present a situation where compressors CC7331 for 17 bars and RC6 are not working and the tool suggests to pump up the production of 30 bars and then use the lamination valve 2 to produce MPGAN.
- Scenario 6: compressors CC7331, RC3C and RC8 cannot work.
- Scenario 7: the only compressors working are RC7 and RC3C and so the optimizer imposes both to gasify liquids to produce the right amount of LPGAN and to use lamination valve 2.
- Scenario 8: the main compressor, C1761 (always used before), is unable to work pushing usage of RC7 and RC3C and RC6 to the max and imposing to open both valves 2 and 7 to produce MPGAN and LPGAN.
- Scenario 9: alternative compressors RC7 and RC3C are not working and so the optimizer has to use RC8 to produce HPGAN which is the one that consume the biggest amount of energy in relationship to the flow.
- Scenario 10 presents a situation where OSS2 is not able to produce gaseous products and OSS3 has a limited production. It is possible to observe that the amount of liquid to be gasified is really high.

Table 1: Comparison between 10 different scenarios: HPGAN, MPGAN, LPGAN are the requests [Nm^3] from the steel mill; RC7,RC8, RC3C, C1761, SWC4, RC6, CC7331 are the powers of compressors in kW, LIQ30, LIQ6 are the liquid gasified producing 30 or 6 bar GAN, Line 2 (L2) and Line7 (L7) are the volumetric flow rates passing through the lamination valves [Nm^3].

#	LPGAN	MPGAN	HPGAN	RC7	RC8	RC3C	C1761	SWC4	RC6	CC7331	LIQ30	LIQ6	L2	L7
1	500	3500	3500	0	0	650	785	0	220	201	0	0	0	0
2	500	6000	6000	900		816	734	0	0	227	0	0	1500	0
3	800	8000	0	0	0	650	828	0	220	227	0	0	3500	0
4	500	3500	4500	0	0	0	785	0	220	201	2000	0	0	0
5	500	3500	4500	900	0	900	582	0	0	0	0	0	3500	0
6	500	3500	4500	900	0	0	666	0	220	0	1500	0	3500	0
7	500	3500	4500	900	0	900	0	0	0	0	0	500	3500	0
8	500	3500	6000	900	0	900	0	750	0	188	0	0	500	1500
9	500	3500	6000	0	900	0	785	0	220	201	0	0	0	0
10	500	3500	6000	0	0	0	768	0	220	201	4000	0	0	0

The optimizer is able to handle every possible situation, providing the combination that minimizes the energy consumption of the whole network and allows prompt response also under the worst situation, as in scenario 10, and under uncommon requests from the tonnage user. The solution for Scenario 1 is reported in Figure 2.

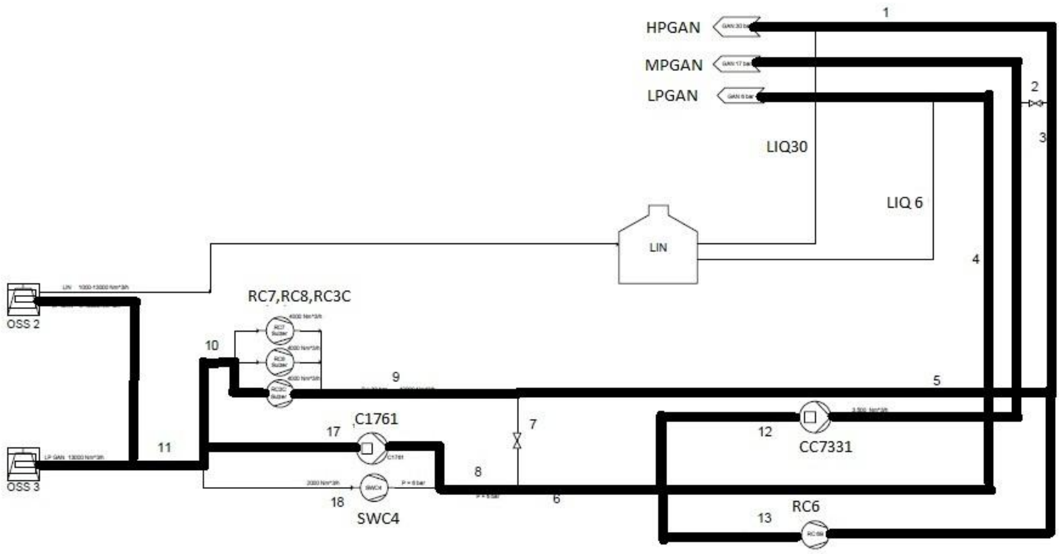

Figure 2: Plant configuration for scenario 1, the highlighted black lines are in use.

5. Conclusions

The paper shows the tangible benefits for the network management and provides to the user a responsive solution to promptly have the configuration that minimize the energy consumption with a noticeable increase in profit. Moreover, the optimizer allows tackling with the significant discontinuities of the industrial gas demand, limiting any energy dissipation.

The results show that the tool here presented may play an important and fundamental role not only for the scope already mentioned but also in a design phase where all the possible operating optimal conditions should be studied to address an optimal investment.

References

Bonami P., Biegler L.T., Conna A.R., Cornuejols G., Grossmann I.E., Laird C.D., Lee J., Lodi A., Margot F., Sawaya N., Wachter A., 2008, An algorithmic framework for convex mixed integer nonlinear programs, Discrete Optimization, 5(2), 186-204.

Buzzi-Ferraris G., 2012. BzzMath: Numerical libraries in C++, Politecnico di Milano, <www.chem.polimi.it/homes/gbuzzi>, Accessed 20/03/2012.

Buzzi-Ferraris G., 2011a, Linear Programming with the Attic Method, Industrial & Engineering Chemistry Research, 50(9), 4858-4878.

Buzzi-Ferraris G., 2011b, New trends in building numerical programs, Computers & Chemical Engineering, 35(7), 1215-1225.

Buzzi-Ferraris G., Manenti F., 2010, A Combination of Parallel Computing and Object-Oriented Programming to Improve Optimizer Robustness and Efficiency, in Pierucci S., Buzzi-Ferraris G. ed. 20th European Symposium on Computer Aided Process Engineering, 337-342.

E. Cuthill, J. McKee, 1969, Reducing the bandwidth of sparse symmetric matrices, Naval Ship Research and development Center, Washington D.C.

D'Isanto M., Manenti F., Lima N.M.N., Linan L.Z., 2011, Corporate Production Planning for Industrial Gas Supply Chains under Low-Demand Conditions, Computer Aided Chemical Engineering, 29, 965-969.

Domschke P., Geissler B., Kolb O., Lang J., Martin A., Morsi A., 2011, Combination of Nonlinear and Linear Optimization of Transient Gas Networks, Informs Journal on Computing, 23(4), 605-617.

Ehrhardt K., Steinbach M.C., 2005, Nonlinear optimization in gas networks, Modelling, Simulation and Optimization of Complex Processes, New York: Springer, USA.

Floudas C.A., Akrotirianakis I.G., Caratzoulas S., Meyer C.A., Kallrath, J., 2005, Global optimization in the 21st century: Advances and challenges, Computers & Chemical Engineering, 29(6), 1185-1202.

Glankwamdee W., Linderoth J., Shen J., Connard P., Hutton J., 2008, Combining optimization and simulation for strategic and operational industrial gas production and distribution, Computers & Chemical Engineering, 32(11), 2536-2546.

Ierapetritou M.G., Wu D., Vin J., Sweeney P., Chigirinskiy M., 2002, Cost minimization in an energy-intensive plant using mathematical programming approaches, Industrial & Engineering Chemistry Research, 41(21), 5262-5277.

Manenti F., 2009, Modelling Long-Term Decisions to Limit Effects of Market Uncertainties, in S. Pierucci ed., Icheap-9: 9th International Conference on Chemical and Process Engineering, Chemical engineering Transactions, Volume 17, 1323-1328.

Martin A., Moller M., Moritz S., 2006, Mixed integer models for the stationary case of gas network optimization, Mathematical Programming, 105(2-3), 563-582.

Westerlund T., Lundell A., Westerlund J., 2011, On Convex Relaxations in Nonconvex Optimization, in S. Pierucci ed., Icheap-10: 10th International Conference on Chemical and Process Engineering, Chemical engineering Transactions, Volume 24, 331-336.

Zhu Y., Legg S., Laird C.D., 2010, Optimal design of cryogenic air separation columns under uncertainty, Computers & Chemical Engineering, 34(9), 1377-1384.