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Optimal scheduling of multiple sets of air separation units with frequent load-change operation

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ABSTRACT

Cryogenic air separation is a highly energy-intensive process used to produce gaseous and liquid products. When the demand of gaseous products is frequently varying as in an iron and steel plant, air separation units (ASUs) are required to immediately respond to meet the changing demand. For a plant with multiple sets of ASUs and frequent load-change demands, the optimal scheduling of each unit becomes essential. In this study, an air separation process with different types of ASUs, together with vaporizers and liquefiers, is analyzed. Both gaseous and liquid products are involved in the process. A separate-mode strategy is proposed for modeling the ASUs with load-change capability. The production of units is represented with a set of operating modes determined by operating feature, and each mode is described with a convex hull according to historical industrial data. Transition behaviors are modeled, especially during load change. Considering the different load features of the units, a scheduling strategy is proposed to optimize the total profit margin within a certain time horizon. A mixed-integer linear programming (MILP) is developed for the process scheduling. With the data obtained from real industrial operations, the good performance of the proposed system is demonstrated. Effects of the demand uncertainty are also analyzed.

1. Introduction

Cryogenic air separation is an important industrial process that produces large quantities of purified oxygen, nitrogen, and argon as gaseous and liquid products [1]. This process is generally a highly energy-intensive procedure with electricity as its major operating cost. In 1998, the US industrial gas industry consumed approximately 31,460 million kilowatt hours (over $ 700 million/year), which was approximately 3.5% of the total electricity purchased by the manufacturing industry [2,3]. As such, flowsheet should be optimized efficiently to save energy and operation of an industrial gas company should be optimized to increase its profit. Considerable research has investigated the process synthesis and optimization of air separation. Fu and Gundersen [4] conducted exergy analysis to reduce the power consumption in air separation units (ASUs) for oxy-combustion processes. Pattison and Baldea [5] introduced a novel pseudo-transient equation-oriented framework for process modeling and together with a time relaxation-based optimization algorithm to optimize the design of the plant subject to a time-of-day price scenario. Cao et al. [6] investigated the modeling approaches for the primary section of a super-staged argon plant. Zhu et al. [7] proposed a homotopy-based backtracking method for the simulation and optimization of cryogenic ASUs. Cao et al. [8] assessed the design limitations to air separation plant agility in demand response scenarios. Sirdeshpande et al. [9] introduced a MILP formulation to select the optimal equipment set for a given product slate for cryogenic air separation. Dowling et al. [10,11] presented a framework for efficient large-scale flowsheet optimization. Fu et al. [12] applied the equation-oriented framework to an air separation process to address several issues, including parameter estimation, process analysis, and process optimization with varying load demands.

For a cryogenic air separation plant that produces both liquid and gaseous products, all liquid products are stored on-site in cryogenic tanks and then delivered to customers, whereas the gaseous products are usually connected to pipelines that serve customers nearby according to the previously negotiated contracts on an hourly demand [13]. Contradiction between the hourly varying demand of its products and the continuous nature of air separation process requires the optimal scheduling of ASUs in order to meet the demand while maintaining steady production. Basically, there are two lines of research concerned with optimal scheduling. Some publications follow the idea of modeling the process with first

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Nomenclature

Indices
- g products
- u units
- j vertices
- m, m', m'' operating modes
- r operating regions
- t time periods

Sets
- G products
- $\overline{G}$ liquid products
- $\widehat{G}$ gaseous products
- U units
- ASU ASUs
- NC ASUs without load-change capability
- AC ASUs with load-change capability
- VAP vaporizers
- LIQ liquefiers
- T whole time periods
- $\overline{T}$ time periods in the scheduling horizon
- M_u operating modes of unit u
- R_m operating regions in mode m
- AL allowed transitions from mode m to mode m' of unit u
- DAL disallowed transitions from mode m to mode m' of unit u
- $Trans$ predefined sequences of mode transitions
- MS transitions for unit u from mode m into another mode m' with a minimum stay relationship

Parameters
- δt time discretization
- $x_{u,m,r,j,g}$ extreme points j of the convex hull of region r in mode m of unit u for products g
- $\tilde{x}_{u,m,g}$ extreme point of mode m of unit u for products g
- $\delta^l_{m_2,g}$ minimum load increase rate
- $\delta^h_{m_2,g}$ maximum load increase rate
- $\delta^l_{m_3,g}$ minimum load decrease rate
- $\delta^h_{m_3,g}$ maximum load decrease rate
- $K^{min}_{u,m,m'}$ minimum number of hours unit u has to stay in mode m' after a transition from mode m
- $K^{max}_{u,m,m'}$ maximum number of hours unit u has to stay in mode m' after a transition from mode m
- $K_{u,m,m'}$ number of hours unit u has to stay in mode m' after a transition from mode m
- Rel^u_g maximum release level for product g
- $Inv^l_{u,g}$ minimum inventory level for product g at unit u
- $Inv^u_{u,g}$ maximum inventory level for product g at unit u
- $Inv\_ini_{u,g}$ initial inventory level for product g at unit u
- D^l_g minimum pipeline storage level for product g
- D^u_g maximum pipeline storage level for product g
- D_ini_g initial pipeline storage level for product g
- $y\_ini_{u,m}$ whether unit u operates in mode m at time 0
- $z\_ini^{t_i}_{u,m,m'}$ whether unit u switches from mode m into mode m' from time period $t_i - 1$ to t_i
- t_f final time period
- c_g sales price of product g
- β electricity price

Continuous variables
- $Pr^t_{u,g}$ production level for product g at unit u at time t
- $\widetilde{Pr}^t_{u,m,g}$ production level for product g in mode m at unit u at time t
- $\lambda^t_{u,m,r,j}$ coefficient for vertex j of region r in mode m at time t
- $Inv^t_{u,g}$ inventory level for product g at unit u at time t
- D^t_g pipeline storage level for product g at time t
- Rel^t_g release level for product g at time t
- $S^t_{u,g}$ sales level for product g at time t

Binary variables
- $y^t_{u,m}$ whether unit u operates in mode m at time t
- $\bar{y}^t_{u,m,r}$ whether unit u operates in region r of mode m at time t
- $z^t_{u,m,m'}$ whether unit u switches from mode m into mode m' from time period-1 to t

principle. Miller et al. [14] conducted an ideal thermodynamic work to analyze the operating strategies under variable power costs. Zhu et al. [15] developed a rigorous nonlinear model to determine the optimal daily multi-period operating strategy, which considers varying electricity pricing and uncertain product demands. Other literatures use data-driven method. Daryanian et al. [16] presented a conceptual framework for the response of storage-type customers to electricity spot prices without considering the discrete operating decisions. Ierapetritou et al. [17], and Karwan and Keblis [3] extended the methodology to incorporate the discrete operating decisions in the planning problem. Mitra et al. [18] introduced an MILP model, which focuses on modeling transition, to deal with optimal production planning under time-sensitive electricity prices. These researchers [19] extended their model by integrating operational and strategic decision making for continuous power-intensive processes under time-sensitive electricity prices. Pattison et al. [20] proposed a novel scheduling approach based on scheduling-oriented low-order dynamic models identified from historical process operating data and applied to an air separation unit operating under time-sensitive electricity prices.

The line of research mentioned in the preceding paragraph mainly focused on the process scheduling level of a single ASU. The process control dynamics of various types of ASUs can exhibit different features. In many manufacturing processes, such as metal production, the demand for gaseous products is not fixed that requires ASU to automatically respond to changing demands. Otherwise, emergency vents must be opened to release the surplus gaseous products, resulting in significant energy loss; or the demand cannot be met, leading to a deficiency in metal production. To deal with the frequently changing demands, automatic load change (ALC) [21] was developed. This technique enables an ASU to operate at varying loads given by a set of scheduled instructions. However, the scheduling system can hardly allocate production among different units because a cryogenic air separation plant may include units with and without load-change capability. This study considers how the process scheduling is integrated with the ASU feature, especially during the frequent load-change operations. In particular, the integrated scheduling of multiple types of ASUs in response to changing demands is addressed. Both types of ASUs with and without load-change capability, together with liquefiers and vaporizers, are involved in the study. The production of a unit is represented with a set of operating modes, and each mode is described with a convex hull according to historical data. Operating modes are determined by the operating feature of different units, for example, load-change modes are tailored for ASUs