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# Optimization-based assessment of design limitations to air separation plant agility in demand response scenarios

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ABSTRACT

The significant effect that the design of a plant can have on its dynamic performance has led to methodologies for systematic analysis of the interaction between design and control, and for inclusion of dynamic performance considerations in plant design. This article focuses on the assessment of design limitations to the agility of a nitrogen plant in response to demand and electricity price fluctuations. A two-tiered approach is proposed, where an economics-based optimization problem is first solved to determine the optimal steady-state operating point, after which a dynamic optimization problem is solved to minimize a measure of the transition time to the new operating point. Design limitations to the plant's responsiveness may be inferred by analysis of the active constraints. The approach is demonstrated on a comprehensive case study based on an existing industrial nitrogen plant. The design limitations of the existing plant configuration are identified, and the potential benefits of selected design modifications to demand response operation are assessed.



## 1. Introduction

The impact that the design of a plant has on its dynamic performance has led to a number of research studies on the topic, particularly over the past three decades. Plants with poor dynamic performance characteristics may result in failure to meet product demand specifications, violation of operational, safety and environmental constraints, and degradation in economic performance. Optimization provides a useful and flexible framework for addressing design limitations to dynamic performance, and has been the basis for several studies, including [1–3]. Typically, an economic objective function is optimized, subject to satisfying the dynamic model equation constraints, design constraints, and path constraints on the plant input and response variables. Comprehensive reviews on approaches toward addressing this problem are provided in [4–6].

In the air separation industry, plant dynamic performance was historically judged based on the ability to reject disturbances. The agility and switchability (i.e., ability to switch between operating points quickly and optimally) were of little importance [7,8], mainly because such plants used to experience infrequent changes in operating conditions. This is no longer the case due to electricity price deregulation in many regions, which has resulted in fluctuations in electricity price. Since electricity consumption is the major operational cost for an air separation plant, responding optimally to electricity price changes could yield significant economic benefits [9,10]. A related effect is that customers of air separation products may also adjust their consumption level in accordance to the electricity price, thereby providing valuable demand response (DR) service and assisting the mitigation of peak loads on the electric grid.[3] These economic factors ultimately translate into frequent plant load changes that must be performed within a given (and typically short) time window. The use of steady-state simulation tools to design plants that will be subject to highly dynamic demand and utility price patterns has limitations, motivating the adoption

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[3] Demand Response is defined by the Federal Energy Regulatory Commission (FERC) [11] as "Changes in electric usage by demand-side resources from their normal consumption patterns [in response to economic incentives and dynamic pricing structures] at times of high wholesale market prices or when system reliability is jeopardized."

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of approaches that take the dynamics of transitions directly into account.

We review here briefly a number of studies that address the design or operation of air separation units under uncertainty. Sirdeshpande et al. [12] formulate a mixed-integer nonlinear programming problem (MINLP) to determine the cost-optimal configuration of an air separation unit from a number of options, given a product slate. They analyze the flexibility of the optimal design to assess the range of liquid and gaseous oxygen production rates for which feasible operation can be maintained. Algebraic models regressed from Aspen HYSYS simulations are used in the analysis. Zhu et al. [13] apply a multi-scenario approach to the design of an air separation plant to account for uncertainty in argon demand and a thermodynamic parameter. The expected cost is minimized, subject to feasible steady-state operation over all scenarios. In [14], optimal operation under demand uncertainty is considered. Steady-state process models are employed, and the formulation is extended to multiple time periods to which a parallel implementation of an interior-point optimization method is applied. Mitra and Grossmann [15] present a mixed-integer linear programming (MILP) model to determine optimal production planning under specified time-dependent demands and electricity prices. Rather than a detailed plant model, a model based on production modes, transition logic and mass balances is used.

Several studies have used dynamic models in the design and performance analysis of air separation units. White et al. [7] formulate a dynamic optimization problem to minimize a measure of transition time between two steady-state operating points. Approximate compartmental models are used for the distillation systems. Schenk et al. [16] consider integrated design and control of a cryogenic air separation plant through a mixed-integer dynamic optimization (MIDO) formulation. An economic objective function is optimized, with design variables comprising distillation column diameters and numbers of trays, control structure, and proportional-integral (PI) controller tuning parameters. Disturbances in inlet air temperature and flow rate, and liquid nitrogen feed flow rate are considered, together with a ramping specification. Miller et al. [8] investigate the reduction in start-up time of an air separation unit through the reintroduction of liquid collected during shutdown. The analysis is conducted through dynamic simulation studies. Nonlinear predictive control has also been investigated for air separation units, motivated largely by the need for effective control during load changes [17–19]. Xu et al. [19] consider in addition an upper layer supervisory control structure.

In this paper, we investigate design limitations to transitions in response to product demand and electricity price variation in an industrial nitrogen plant. We address this through a two-tiered optimization formulation, where an economically optimal steady-state operating point is first computed, followed by the solution of a dynamic optimization problem to determine an optimal trajectory to the new operating point based on minimizing a measure of transition speed. Section 2 gives a brief discription of cryogenic nitrogen plant. The plant model and proposed optimization formulation are described in Sections 3 and 4. A comprehensive multi-part case study is presented in Section 5, in which a number of demand and electricity price scenarios are considered and limiting constraints identified. The impact of selected design modifications on achievable transition speed is also explored. Conclusions and future research directions are presented in Section 6.

## 2. Process description

Products of air separation processes play key roles in a variety of market sectors, such as petrochemical, metal, food processing and health care. The separation of air into oxygen, nitrogen and argon can be achieved by either cryogenic or noncryogenic processes [12]. The cryogenic approach for air separation is based on low-temperature distillation and is capable of producing large quantities of high purity liquid and gas phase products. On the other hand, noncryogenic processes rely on adsorption and membrane separation, and are usually economically interesting at smaller production rates. The focus of our study is on cryogenic nitrogen plants.

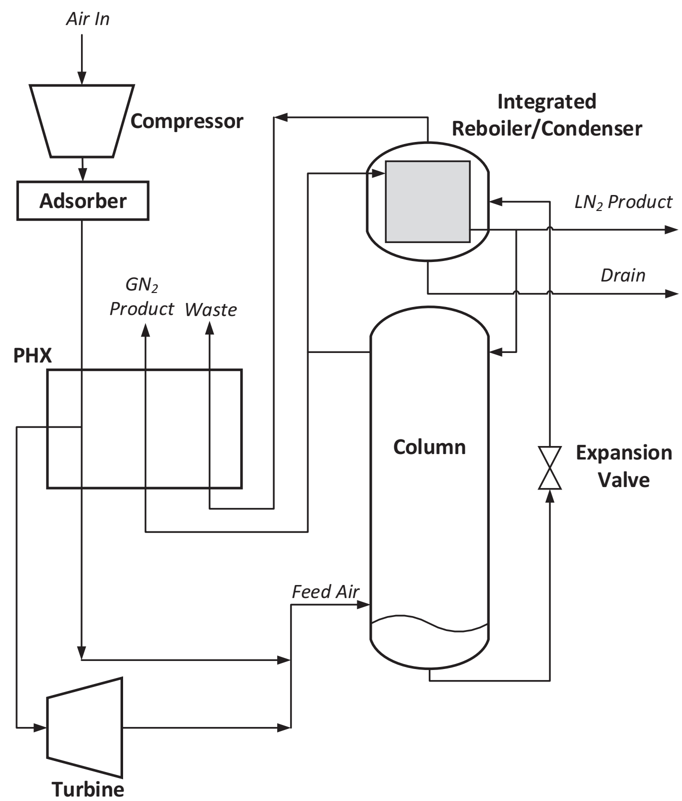


**Fig. 1.** Nitrogen plant process diagram, as depicted in [20]. $LN_2$ = liquid nitrogen; $GN_2$ = gas nitrogen; PHX = primary heat exchanger.

Fig. 1 shows a simplified schematic of major process equipment in a typical nitrogen plant. Zhu et al. [20] and Espie and Papageorgaki [21] provide a detailed process description. The intake air from the atmosphere is first compressed through a multi-stage compressor and then introduced to an adsorber or other purification units to remove impurities such as carbon dioxide and water. The treated air feed is cooled against the cryogenic gas product stream and waste stream from the distillation column in a multi-stream heat exchanger, typically of the plate-fin variety. A portion of the air feed is withdrawn at an intermediate point of the heat exchanger and goes through a turbine for additional cooling prior to being introduced to the column. The air feed, entering at the bottom of the column, is distilled into a high purity gaseous nitrogen stream, which leaves at the top, and an oxygen-enriched liquid which accumulates at the bottom. A portion of the overhead stream is withdrawn as the gas product while the rest is sent to the integrated reboiler/condenser to exchange heat with the oxygen-enriched stream drawn from the bottom to produce the reflux stream and the liquid nitrogen product [20,21].

## 3. Air separation unit model

In order to develop a rigorous model for the nitrogen plant, which captures the plant constraints and adequately represents its nonlinear nature, individual models were developed first and