Production Scheduling of an Air Separation Plant

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Abstract: Cryogenic air separation plants consume a large amount of electricity to produce various gaseous and liquid products; they can reduce their operational cost by proper exploitation of energy contracts and intelligent utilization of liquid products. In this paper, we propose a State Task Network (STN) based model which replicates a representative air separation plant. This STN based representation owing to its significantly more granular modelling can reap higher benefits in terms of improved decision making than the approaches proposed in literature. Production Scheduling based on this model computes the optimal operating conditions for the plant under variable power pricing options and demand scenarios. The modelling framework is very rigorous and includes almost all the real world limitations and constraints in air separation plant operation. This unit wise scheduling approach provides more flexibility and also pave the way for integration of the scheduling layer with the lower layered (hierarchically) control system. The proposed framework has been evaluated on the representative air separation plant and the results demonstrate the benefits of optimal plant operation.

Keywords: State Task Network, Production Scheduling, Demand Side Management, Power Contracts.

1. INTRODUCTION

Today’s agile market conditions with rapidly changing market trends compel an industry to lower its operational cost as much as possible by ensuring maximum utilization of its resources, as well as making intelligent decisions regarding its operating procedures. Energy-intensive processes such as cryogenic air separation, where the main contributor of the operating cost is electricity price, need to adopt Energy Demand Management also known as, Demand Side Management (DSM) to keep them afloat. DSM basically encourages the electricity consumers to schedule their operation in such a way that they coordinate in an optimal way with the power pricing during the peak hours.

According to Mitra et al. (2012) concept of DSM can further be classified into two key components. 1) Energy Efficiency (EE) and 2) Demand Response (DR). The main goal of energy efficiency is to decrease the electricity consumption whereas, demand response programs align the operational procedure according to the power availability and time sensitive electricity markets.

In literatures implementation of DSM in air separation plants has been handled in two different approaches. The notable contributions in control based approach either used a highly complex nonlinear mechanistic model to calculate the optimum operating conditions of the process (Zhu et al. (2011)) or proposed an economic nonlinear model predictive control (Huang (2010)). Though this approach provides a detailed plant representation, solving these models is time expensive and also does not handle the discrete plant decisions well. Another approach is based on planning and scheduling. In recent years DSM based scheduling frameworks have been reported for Air separation plants (Ierapetritou et al. (2002), Karwan and Keblis (2007)).

Mitra et al. (2012) had developed a surrogate model of an air separation plant considering the entire plant as a single unit. They had also introduced different operational modes and formulated an efficient model to express the modes transitions. The minimum uptime and downtime concept to reduce stress on the equipment was also entertained. However, the treatment of the entire air separation plant as a single unit is rather simplistic since the process involves several unit operations and interactions between those can not be ignored. To make the model more rigorous and applicable one should consider every unit separately,

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675
and construction of a state task network for the plant is necessary. Mitra et al. (2012) also mainly focused on time of use power pricing; however, additional inclusion of various power contracts could substantially enhance the optimality.

In this paper we exploit the above ideas and introduce a state task network based approach in which all the units of a plant are considered separately. Entire formulation was made in such a way that it accounts for most of the real world constraints and limitations of an air separation plant. Each unit can be operated in different number of modes. Some units like air separation unit (ASU) or liquefaction units have transition modes, e.g. startup or shutdown. These transition periods are required to reach the required purity for the products. This proposed STN approach is more granular and as it considers every unit separately, we believe this framework can be used for integration of scheduling and control in future, which will definitely pave the way for more flexible and intelligent production decisions. In this work we have considered different power contracts which are encountered in real world scenarios. Proper exploitation of these contracts is necessary to achieve a proper DSM approach. Furthermore, efficient electricity utilization alone may not be necessarily effective, for instance when demands during high power price period is also high. Alternate degrees of freedom such as judicious utilization of liquid products can also be simultaneously exploited to provide better optimality. Uncertain market conditions also compel the consumers to decrease their inventory costs, which in turn increases need for short-term order fulfilments (Harjunkoski et al. 2009)). These liquid spot sales are also lucrative to the producers as these earns more revenue than the regular orders.

In this work, the proposed STN based granular model additionally considers the following conditions that reflect decision making in a more realistic way: 1) Addition of Non Argon mode, 2) Liquid purchase from competitors and spot sale, 3) Efficient utilization of free diox liquid, 4) Economic Shutdown etc. Inclusion of these aspects makes the resulting model represent the real world constraints more closely and the resultant schedule based on this model can be implemented on a real air separation plant.

The remainder of the paper is organized as follows, in section 2 an air separation plant will be described and an overview of constraints and limitations will be discussed. The main aspects of the model will be discussed in detail in section 3. Scheduling result based on different scenarios will be discussed in section 4. In section 5 we will conclude by summing up key aspects.

2. PROBLEM STATEMENT

Cryogenic air separation technique is the most popular and cost effective method to produce gaseous and liquid products from air (Smith and Klosek (2001)). Air separation plant separates atmospheric air into almost pure air components. The products from air separation unit are either gaseous air component streams (GO2, GN2 & GA) produced from LAr) or liquid air component (LO2, LN2 and LAr) products. The gaseous products are supplied by pipeline to onsite customer while liquid products are transported to merchant liquid customers. As the raw material (air) is free (zero cost), the major cost of production is cost of power (electricity) used for air separation. The functioning or manufacturing activity in air separation plant is governed by gaseous as well as liquid product demand. However it is constrained by plant capacity and operation modes in which an air separation plant can operate. Furthermore, availability or cost (which can vary by location and by time of day) of power also impacts the production of gaseous and liquid products.

Hence, the aim of the production scheduling activity is to meet gaseous as well as liquid product demand with minimum production cost taking into consideration production and storage limitations such as production capacity represented by production modes, liquid product inventory and storage capacity.

A discrete time framework was designed is which the time horizon was divided in hourly basis. The scheduling will be done for a week long horizon. The duration of the time bucket can be changed. We have decided on hour wise discretization as the forecasted electricity prices and onsite demands are given in an hourly basis.

So, the expected outcomes from the production scheduling are:

1. Operation schedule for each process.
2. Gaseous and liquid demand fulfilment.
3. Proper choice of power sources based on hourly prices and contracts.
4. Load shifting based on time of use power pricing.
5. Effective utilization of liquid products meeting all the inventory limitations and demand constraints.

3. MODEL FORMULATION

There are mainly two ways of modelling a process. The traditional way is Mechanistic approach, in which a model is made based on detailed heat and mass balance of the process. The resultant model is very intricate and computationally challenging. The other way is to replicate the system in a reduced space such as, product space (Mitra et al. 2012)). If the detailed model is available for the plant, the feasible region can be computed by solving the mechanistic model offline. If the detailed model is not present then the feasible region can be calculated based on the historical data.

A feasible region is like an envelope in which the surrogate model is able to replicate the actual plant. Each unit of the plant has certain number of operation modes, such as, ‘on’, ‘off’, ‘startup’, ‘shutdown’ etc. Each mode is a collection of operation points or slates. Each slate provides a combination between power consumption and production/consumption. A minimum number of slates are pre-calculated offline in such a way that any point in the feasible region can be approximated by a linear combination of these slates.
3.1 Allocation Constraints

An air separation plant is composed of several units, such as, 1) Air separation unit, 2) Liquefaction unit to convert GN2 to LN2, 3) Compressor of different types like low to medium pressure, medium to high pressure, low to high pressure, 4) Driox Units to convert the liquid products into gaseous one, 5) Venting units. Each of these units has different modes. The state task network for an air separation plant with operation modes is illustrated in figure 1.

At any time period(t) one unit(u) performing a task(j) can only run in one operation mode(o) (1). The slates(l) selected in any time period in an unit should belong to the operation mode selected at that time period (2). When the air separation unit is started it takes around 1-2 hrs. to reach the desired quality for LO2 and LN2 but it takes around 18hrs. to reach the specified purity for liquid argon. To replicate this phenomena a new mode ‘NoArOn’ is introduced. When the ASU will run in this mode there will be no production for argon, but LO2 and LN2 will get produced. All the other processes except driox and vent are dependent on ASU. So, when the ASU is off all the other units should also be off (3). The plant maintenance and predeceded fixed modes are also considered in this formulation (4,5).

\[
\sum_{j=1}^{J} \sum_{o=1}^{O} \text{vbUJOT}_{u,j,o,t} = \begin{cases} 
1 & \forall u, \forall t; (t = 1..NT) 
\end{cases}
\]

\[
\sum_{l=1}^{L} \text{vcUJOLT} \text{SlateCoeff}_{u,j,o,l,t} = \text{vbUJOT}_{u,j,o,t} \\
\forall u, \forall j; (J_{u,j} = 1), \forall o; (O_{u,j,o} = 1), \forall t; (t = 1..NT)
\]

If the production of gaseous products are inadequate to meet onsite demands, some portion of liquid inventory is drioxed (converted to gas). But driox is costly as it decreases the liquid product sale. So, the drioxed gases should not get vented. Equation (6) ensures that when the driox units are on, associated vent units should be off.

\[
\sum_{j=1}^{J} \sum_{o=1}^{O} \text{vbUJOT}_{u,j,o,t} + \sum_{j=1}^{J} \sum_{o=1}^{O} \text{vbUJOT}_{w,v,j,o,t} \leq 1 \\
\forall u; (U\text{Driox}_u = 1), \forall j; (J_{u,j} = 1), \forall o; (O_{u,j,o} = 1 and o \neq U\text{JOFF}_{u,j}) \\
\forall v; (U\text{AssociateDrioxUnit}_v = u), \forall j; (J_{w,v,j} = 1), \forall o; (O_{w,v,j,o} = 1 and o \neq U\text{JOFF}_{w,v,j}) \forall t; (t = 1..NT)
\]

3.2 Transition Constraints

When a unit is switching from one mode to other, a mode transition happens. The transition constraints not only take care of the mode sequences but also enforce the unit to continue on that mode for some specified time after a changeover occurs. This time is known as minimum uptime. For instance, if a unit is switched on and the minimum uptime for ‘on’ mode for that unit is 6 hrs., then the unit needs to be kept on for at least 6 hrs. before turning it off. The transition constraints are an integral part of this formulation and have been enforced in the calculation for finding the optimum schedule for the plant. However, due to brevity, and since, similar constraints can be found in Mitra et al. (2013) and Zhang et al. (2015), these constraints are not mentioned in this paper but will be a subject matter of a future publication (Misra et al. (2016)).

3.3 Mass Balance Constraints

The main products of an air separation plant are Gaseous Oxygen (GO2), Gaseous Nitrogen (GN2), Gaseous Argon (GAr), Liquid Oxygen (LO2), Liquid Nitrogen (LN2) and Liquid Argon (LAr). Where GO2, LO2, LN2 and LAr are...
directly sold to the customers, GN2 is compressed and sold as two products, 1) MPGN2 (medium pressure gaseous Nitrogen) and HPGN2 (High pressure gaseous Nitrogen). Gaseous argon is not directly produced in ASU. The liquid argon is converted to gas and sold to customers. Gaseous productions are driven by onsite customer contracts, upcoming maintenance activity etc. The target constraints are generally soft constraints and hence violation of them are allowed with penalty. It is important to note that inventory constraints (mass balance, capacity and target limitation) are defined only for liquid products.

The proper utilization of liquid is one of the key aspects of this formulation. Liquid products can be purchased from other plants to fulfill demand or meeting inventory targets. The merchant liquid demand is fulfilled from inventory at plant location and from other sources. Merchant liquid demand can be classified in two types, 1) Regular demand, 2) Spot demand. Regular Demand needs to be fulfilled, where, spot demands are optional. But spot demands earn more revenue, so, maximum fulfillment of spot demands are encouraged.

3.4 Power Balance Constraints

Power required in a unit at any time period is a combination of the power requirement of various slates which are selected at that time period. Total power consumption in a unit for a time period is expressed in equ (10). The total power required to run all the units should be less than the total power available(11).

\[
\sum_{j=1}^{J} \sum_{o=1}^{O} \sum_{l=1}^{L} \left[ vcUJOLTSlateCoeff_{u,j,o,l,t} \times UJOLPSlateChangeRate_{u,j,o,l,p} \times (TTime_{t,2} - TTime_{t,1}) \right] = vcUPTPowerRequired_{u,t} \forall u, \forall t (t = 1..NT)
\]

\[
\sum_{j=1}^{J} \sum_{o=1}^{O} \sum_{l=1}^{L} \left[ \frac{vcUJOLTSlateCoeff_{u,j,o,l,t} \times UJOLPdPurchaseInventory_{u,j,o,l,t} \times (TTime_{t,2} - TTime_{t,1})}{vcUJOLPSlateChangeRate_{u,j,o,l,p}} \right] = \frac{vcUJOLPdPurchaseInventory_{u,j,o,l,t}}{vcUJOLPSlateChangeRate_{u,j,o,l,p}} \forall u, \forall t (t = 1..NT)
\]

Now power is available from many sources(s). The power purchased from a suitable power source should be within minimum and maximum availability limits. The limits can be specified for a particular hour or a period. It is important to note that not purchasing power is an option, however if purchased it should be greater than minimum availability for supply network stability (if the minimum availability limit is mentioned). There are 9 types of power sources (different in price, availability and contract obligations) present in India. Irrespective of power source, we can assume time of the day power pricing. If power price is not varying with time of day, same price is applicable in all time slots. The power cost calculation is shown in equ (12).

\[
vcECost_s = \sum_{t=1}^{NT} \left[ \frac{vcETPurchase_{e,t} \times ETPower_{e,t}}{vcETPurchase_{e,t} \times ETPower_{e,t}} \right] \forall e
\]

When MTOP (minimum take or pay) limit is defined for a particular power source, production scheduling activity should aim to purchase power equal to or more than MTOP limit to minimize the power bill. However, it is important to note that power purchase equal to or more than MTOP limit is not compulsory if other options provide less power bill even after inclusion of MTOP penalty. To
account this effect we have introduced a penalty variable in minimization objective function; which will take positive value only when MTOP Limit is violated. If MTOP limit is defined for longer duration compared with production scheduling horizon, value corresponding to horizon can be arrived to direct production scheduling to consider MTOP limit. 
In case of discount purchase, discount is applicable on entire purchase quantum if purchase quantum is greater than discount limit. If purchase quantum is less than discount limit, no discount is applicable. To handle it we defined two binary variables which will dictate if purchase quantum from that particular source is greater than discount limit or not. These binary variables are defined in such a way that both variables can not assume positive value at a time period. These two binary variables will segregate the entire power purchase from that source in two slabs. (e.g. discount slab and non-discount slab). The power mix scenario is also entertained in this formulation which means if availability limitations are restricting a power source to fulfill the entire power requirement at any time period we can buy the rest amount from other sources.

3.5 Driox Constraints

If the gaseous production is inadequate to meet onsite customer demand, a portion of liquid inventory is converted to gas and supplied to the onsite customers to meet the gaseous demand. This process is called as Drioxing in an air separation industry (Zhang et al. (2015)). But drioxing liquid inventory is costly as it reduces the liquid product sale. Now lets assume a scenario where, the liquid production is much more than the cumulative amount of liquid demand and positive inventory buildup (i.e. Target inventory − initial inventory where, Target inventory > Initial inventory). Then this excess liquid will be termed as, Free Driox Liquid. This Free Driox liquid calculation is done over the entire horizon. To identify which part of the liquid inventory can be treated as, free driox liquid, understanding the following conditions are necessary.

- The above mentioned scenario, i.e. Free Driox Liquid = Production − Demand − positive inventory buildup
- Now, if the inventory buildup is negative, i.e. Initial inventory is higher than the target inventory, we will try to fulfill the demand from it. If demand is more than the difference between initial inventory and target inventory, the rest of the demand will be fulfilled from production. After meeting the entire demand if some of the produced liquid is left we will consider that as free driox liquid.
- If the negative inventory buildup is adequate to quench the entire liquid demand then total produced liquid will be considered as free driox liquid. No excess liquid from inventory (more than the target inventory after fulfilling all liquid demand) will be treated as free driox liquid in this case.

Another important aspect that was introduced in this formulation is Economical Shut Down. In this case if there is excess liquid left in inventory after meeting all the demands and target inventory limitations, the entire excess liquid can be drioxed to meet onsite customer demand keeping all the units which consumes electricity in OFF mode. The choice to opt for economical shutdown or not was given to the user. If the user set on the economical shutdown option then this decision of shutting down ASU will be taken by the optimizer considering the power price at that time period and drioxing cost.

3.6 Objective Function

The objective function is to minimize the overall production cost, which can be illustrated as follows,

\[
\text{Total Production cost} = \text{Total Power Cost} - \text{Discount earned} + \text{Penalty for Violating MTOP Limit} + \text{Penalty for violating eligible limit} + \text{Penalty for dumping liquid product} + \text{Penalty for venting gaseous product} + \text{Liquid purchase Cost from Other Sources} + \text{Penalty cost for violating inventory target} + \text{Driox Cost} - \text{Revenue earned from Spot Sale} + \text{Penalty for not meeting the regular liquid demand}.
\]

The revenue earned from spot sale are added as a negative term in a minimization program which in turn will maximize the quantity. The mathematical expression of the objective function is excluded from this paper for the sake of brevity.

4. RESULT AND DISCUSSION

Based on the mathematical formulation described above we have generated a MILP model. This above mentioned model is applied on some real-world industrial scenarios provided by Praxair. We solved the model in Fico©Xpress Optimization suite using mpxprs module version 2.8.0 on a Intel® Core™i5 (2.4 GHz) machine with 4GB RAM. The MILP model has 24943 constraints, 37566 variables, and 7854 binary variables. The termination criteria were set to 0.05% optimality gap. Several scenarios based on different demand and inventory scenarios are tested and only one of those are reported here due to brevity. The MILP problem was solved in all instances within few minutes.

Three types of power contracts are considered.

1. Power Grid : Time of use Power price.
2. Auction : Power Prices are based on auction. (Forecast for day ahead prices was given on an hourly basis).
3. MTOP : Power price is constant throughout the day. Penalty will be charged for under consumption.

Due to confidentiality issues the exact production or power consumption are not mentioned. The values in the graphs are normalized, again for confidentiality reasons. Figure (2) shows the liquid inventory profile of oxygen for a case where the initial inventory was high. The liquid demands are given for a day and that demand can be fulfilled any time on that day. The onsite demands at start are higher than the production capacity, so a portion of liquid inventory was drioxed to meet the demand. As, the initial
### 5. CONCLUSION

In this work, a novel state task network based formulation for an air separation plant was discussed. Solution of the resulting MILP problem provides schedule for each and every unit of the plant meeting all the demands and inventory limitations. The model also addresses many real world limitations and constraints such as, needing more time to reach required purity for a certain product, various electricity contracts etc. The result shows that effective utilizations of liquid product and exploitation of power contracts, are both necessary to minimize the overall production cost. The approach used here for modelling the process is very rigorous and can be extended to multiple plant production scheduling with minimal changes. The effect of liquid utilization on operation cost can be fully discerned when this approach will be used for multiple plant scheduling.

Though the proposed scheduling model was developed based on an air separation plant, the approach was much generalized and can be extended to any power intensive processes.

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