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Optimal scheduling for power-intensive processes under time-sensitive electricity prices

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Abstract

The competitiveness of power-intensive industries is highly tied to their ability to adjust production according to time-sensitive electricity prices. A classic example are Air Separation Units (ASUs), where large, electric-power air compressors are used to reach cryogenic temperatures. Due to the volatility nature of the energy markets, there is significant opportunity to reduce production costs by scheduling production during the cheapest hours of the day. In this work, a mixed-integer linear model (MILP) model is presented based on a discrete-time scheduling formulation that allows modeling and optimizing operating decisions for any process under time-sensitive energy prices. The main goal is to find an optimal production schedule over a given time horizon that guarantees product demand satisfaction and that minimizes total energy cost. The novel formulation used to model transitions between operating modes results in a very efficient and robust model. The model is applied to a simplified industrial case The results show optimal solutions for the proposed methodology with modest computational effort.

Keywords: Scheduling, MILP model, Continuous power-intensive processes, Energy consumption cost, Air separation plant.

1. Introduction

In this paper, we consider industrial production processes that are power-intensive and are exposed to time-sensitive energy markets. We introduce a specific case study related to the operation of an air separation plant. Due to the significant energy consumption of key factor that influences the operating decisions is energy price volatility (Mitra et al., 2013; Karwan et al., 2007). The challenge is to obtain a production schedule for the plant to take advantages of the spikes and valleys in electricity prices (Mitra et al., 2012; Hadera et al., 2014; Castro et al., 2010).

Given electricity price and demand forecasts at a time discretization $h \in H$, the objective is to find the production schedule that minimizes the total energy cost while satisfying demand. The plant is model using a novel representation of the typical state transition network. The scheduling problem involves minimum and maximum production rates based on the plant state, storage capacity of the plant and minimum final tank level constraint, considering that minimum final tank levels must be fulfilled each day of the week and the last time period of the scheduling horizon. Figure 1 shows a schematic representation of the feasible operating modes and allowed transitions consider in the illustrative example addressed below.

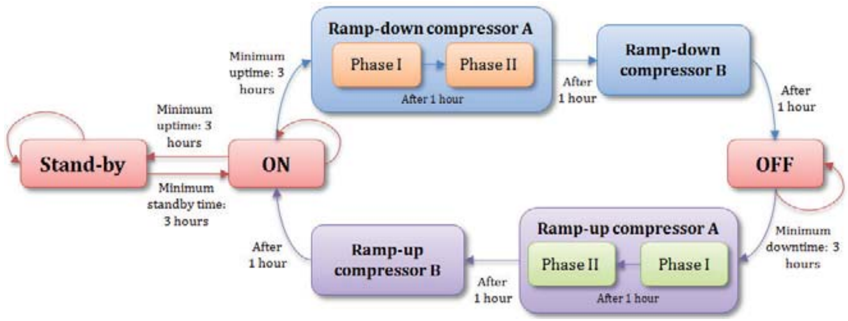

Figure 1. A state graph of the plant

An important aspect in this problem is to consider that there is an operational constraint on the minimum amount of time the plant should be running in the same operation mode. In the example, the plant has states, while others states (on, standby and off) have a minimum duration of 3 time periods. A deterministic MILP model is proposed based on novel way of representing the state graph network for the optimal production planning of continuous power-intensive air-separation processes to efficiently adjust production according to time-dependent electricity pricing.

2. Process State Transition Network

We propose an explicit and systematic way of representing plant operating states (see Figure 2): demoted as the Process State Transition Network (PSTN). States with minimum duration of 3 time periods are decomposed in 3 sub-states of 1 time period each and are called initial sequential transition states, intermediate transition states, and critical transition states, respectively. Note that this decomposition occurs in stand-by, on and off operating states in which the plant can remain between 3 and an undetermined number of time periods.

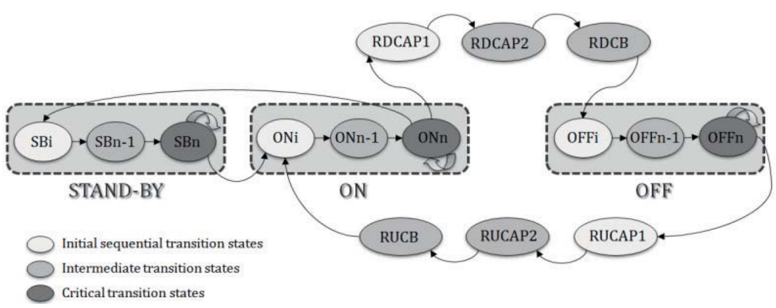

Figure 2. Process State Transition Network

3. Model formulation

Although continuous time models have been effectively used for this type of production scheduling (Hadera et al., 2014; Nolde and Morari, 2010), given the operational restrictions and time characteristics required in this problem, a discrete time representation is used. The scheduling horizon is divided into fixed intervals of equal length, In this section we propose a mathematical formulation that leads a mixed integer linear programming problem (MILP). The nomenclature of the formulation is given in Table 1 and operational constraints are described below.

Table 1: Nomenclature

Sets	***Parameters***
$T(index\ t)$,Time periods	$MinP_s$, Min. production per hour in each state
$S(index\ s)$,States	$MaxP_s$, Max. production per hour in each state
$D(index\ d)$,Days of a week	$MDTL_d$, Min. final tank levels at the end of the day
$S^{initial}$, Initial sequential states of On, Off and Stand-by modes	ED_t, Hourly expected demand
S^{inter}, Intermediate transition states of On, Off and Stand-by modes	FPC_s, Fixed power consumption
$S^{critical}$, Critical transition states of On, Off and Stand-by modes	VPC_s, Variable power consumption
$S^{down-initial}$, Initial state to ramp-down	$EP_{(t,d)}$, Energy prices forecast for a week
$S^{up-initial}$,Initial state to start-up	$Qmin$, Minimum Tank Level
$S^{down-inter}$, Intermediate states to ramp-down	$Qmax$, Maximum Tank Level
$S^{up-inter}$, Intermediate states to start-up	I_0, Initial tank level
LIC, Last intermediate states before critical states	$T\_D_{(t,d)}$, End time of each day
NTS, Next to transition states	$d1_d$, Starting day of scheduling
Continuous Variables	nd,Amount of intermediate states in the shutdown process
$P_{s,t}$, Production at time *t* for state *s*	ns, Amount of intermediate states in the startup process
PW_t, Power consumption at time *t*	min_res, Minimum residence time
I_t, Inventory available at the end of time period *t*	max_res, Maximum residence time
$Cost$, Objective function (total energy cost)	***Binary Variables***
	$W_{s,t}$, Indicates whether plant operates in state *s* during time period *t*

Since the plant has to operate in a single state each hour, so Eq. (1) forces the plant to be in a single production mode at each time period.

$$\sum_s W_{s,t} = 1 \qquad \forall t \in T \tag{1}$$

Eq. (2) and (3) represent the operating sequence at the occurred in on, off or stand-by state. If the operating point of the plant in the time period t is the initial state of on, off or stand-by mode, then at time $t+1$ and $t+2$ the plant has to operate in the corresponding states, intermediate and critical, respectively.

$$W_{s,t} = \sum_{s' \in S^{inter}} W_{s',t+1} \qquad \forall t \in T, s \in S^{initial} \tag{2}$$

$$W_{s,t} \leq W_{s',t+1} \qquad \forall t \in T, s \in LIC, s' \in S^{critial} \tag{3}$$

The start-up and shut-down processes may not be interrupted. Eq. (4) and (5) apply to the sequence $off \rightarrow startup \rightarrow on$ and $on \rightarrow shutdown \rightarrow off$, respectively.

$$nd * W_{s,t} = \sum_{s' \in S^{down-inter}} \sum_{t'=t+1}^{t'=t+nd} W_{s',t'} \; \forall t \in T, s \in S^{down-initial} \tag{4}$$

$$ns * W_{s,t} = \sum_{s' \in S^{up-inter}} \sum_{t'=t+1}^{t'=t+ns} W_{s',t'} \; \forall t \in T, s \in S^{up-initial} \tag{5}$$

However, additional constraints (Eq. (6) and (7)) are necessary to complete the switching between the on and off states. Additionally we can use Eq. (8) to represent these two feasible paths to the ONi state (see Figure 2).

$$W_{RDCB,t} = W_{OFF1,t+1} \qquad \forall t \in T \tag{6}$$

$$W_{RUCB,t} \leq W_{ON1,t+1} \qquad \forall t \in T \tag{7}$$

$$W_{SBn,t} + W_{RUCB,t} \geq W_{ON1,t+1} \forall t \in T \tag{8}$$

Once the plant operates in a critical state in the period *t*, it can remain in the same state or switch to other at the next period (*t+1*). This is ensured formulating the Eq. (9) to describe possible transitions that can occur from the critical states.

$$W_{s,t} + W_{s',t} = \sum_{s'' \in NTS} W_{s'',t+1} \; \forall t \in T, s \in S^{critial}, s' \in LIC \tag{9}$$

To ensure the minimum and maximum processing times we formulate the constraints below (see Eq. (10-11)) which are applied to those modes with more than one hour of minimum residence in: "on", "off", and "stand-by" states.

$$(min - 2) * W_{s,t} = \sum_{s' \in S^{critical}} \sum_{t'=t+1}^{t+mn} W_{s',t'} \quad \forall t \in T, t \leq 168, s \in S^{inter} \tag{10}$$

$$\sum_{t'=t}^{t+mx} W_{s,t'} \leq (max_{res} - 2) \quad \forall t \in (168 - max_{res}), s \in S^{critical} \tag{11}$$

There are minimum ($MinP_s$) and maximum ($MaxP_s$) production limits at each operating point, see Eq. (12). Furthermore, Eq. (13)-(15) represent the constraints of ramping down and ramping up production.

$$W_{s,t} * MinP_s \leq P_{s,t} \leq W_{s,t} * MaxP_s \qquad \forall t \in T, s \in S \tag{12}$$

$$P_{s'} * dec \leq P_{s,t} \leq P_{s'} * inc \qquad \forall t \in T, s' \in S^{initial}, s \in S^{inter} \tag{13}$$

$$(P_{s''} + P_{s'}) * dec \leq P_{s,t} \leq (P_{s''} + P_{s'}) * inc$$
$$\forall t \in T, s' \in S^{inter}, s \in S^{critial}, s'' \in S^{initial} \tag{14}$$

$$P_{s,t} = W_{s,t} * MinP_s \forall t \in T, s \in S\ t \leq 168 \tag{15}$$

A mass balance is formulated in Eq. (16)-(17) to expresses the relationship between the amounts of product stored, produced, and demanded by the customers. The constraint establishes that the inventory level at the end of time period t will be equal to the product inventory at the end of the previous period ($t-1$), plus the current production level (period t) and less the demand at time t.

$$I_t = I_0 + \sum_s P_{s,t} - ED_t \qquad \forall t \in T: t = 1 \tag{16}$$

$$I_t = I_{t-1} + \sum_s P_{s,t} - ED_t \qquad \forall t \in T, 1 < t \tag{17}$$

Finally, the plant has to meet a minimum level of inventory at the end of the planning horizon.

$$I_t \geq MDTL_d \qquad \forall t \in T, d \in D, (t,d) \in T\_D_{(t,d)}, d \in d1_d \tag{18}$$

To calculate the amount of power consumed, we define the variable PW_t and formulate Eq. (19).

$$PW_t = \sum_s (W_{s,t} * FPC_s + VPC_s * P_{s,t}) \qquad \forall t \in T \tag{19}$$

Eq. (20) minimizes the total cost that consists of power consumption.

$$Cost = \sum_t (PW_t * EP_t) \tag{20}$$

4. Results

The proposed model was tested for an air separation plant with real-world electricity prices and demand input data for one week (168 hours). Due to confidentiality reasons, daily average demand and energy prices forecasts, and information on production levels and power consumption for the different operating modes are not disclosed.

In Figure 3, solutions based on a minimum residence time of 3 hours and a maximum residence time of 8 hours can be visualized.

The results in Table 2, show optimal quality solutions for the proposed methodology with a modest computational effort considering a one-hour time grid and one-week time horizon. Solutions generated by using CPLEX in a PC Intel Xeon X5650 2,6 GHz.

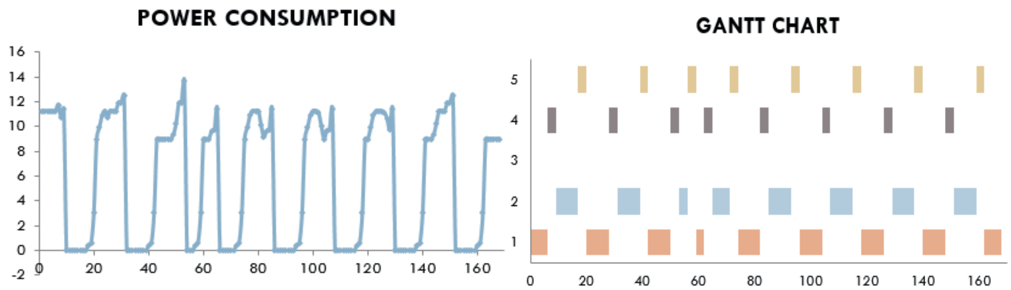

Figure 3. Solution based on time of day prices

Table 2. Results of the main scenarios

Scenario	*Minimum Residence time*	*Maximum Residence time*	*Ramping Constraints*	*Energy total cost*	*CPU time (sec.)*
1	3	168	No	36348.17	0.5
2	8	168	No	37018.97	1.092
3	12	168	No	38374.67	22.45
4	12	168	Yes	38430.00	1.93
5	8	16	No	37159.69	2.28
6	8	16	Yes	37296.25	2.53
7	3	8	No	38693.03	22.68
8	3	8	Yes	39683.76	31.95

5. Conclusions

The proposed model allows the evaluation of daily and hourly reactive decisions based on energy price changes. Based on the preliminary results, it can be concluded that the MILP-based scheduling model is very efficient and robust. Besides, The PSTN model can be easily adapted to other plant configurations. Therefore, the proposed scheduling framework is a promising approach for the application to real-world air separation industrial plants.

References

Mitra S., Sun L., Grossmann I.E., 2013, Optimal scheduling of industrial combined heat and power plant under time-sensitive electricity prices, Energy 54, 194–211.

Karwan M. H., Keblis M. F.,2007, Operations planning with real time pricing of a primary input, Comput. & Operations Research 34, 848-867.

Mitra S., Grossmann I.E., Pinto J.M., Arora N., 2012, Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes, Comput. Aided Chem. Eng. 38, 171–84.

Hadera H., Harjunkoski I., Grossmann I.E., Sand G, Engell S., 2014, Steel production scheduling under time-sensitive electricity cost, Comput. Aided Chem. Eng. 33, 373–8.

Castro, P. M., Harjunkoski, I., Grossman, I. E., 2010, Rolling-Horizon Algorithm for Scheduling under Time-Dependent Utility Pricing and Availability, Comput. Aided Chem. Eng. 28, 1171−1176.

Nolde K., Morari M., 2010, Electrical load tracking scheduling of a steel plant, Comput. Aided Chem. Eng. 34(11), 1899–903.