TOWARDS OPTIMAL PRODUCTION OF INDUSTRIAL GASES WITH UNCERTAIN ENERGY PRICES

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Motivation

- How to optimize participation in electricity markets under uncertainty in the operation of power-intensive air separation processes.
  - ***Day-ahead markets*** (forecasts are available)
  - ***Spot/Imbalance markets*** (hard to predict)

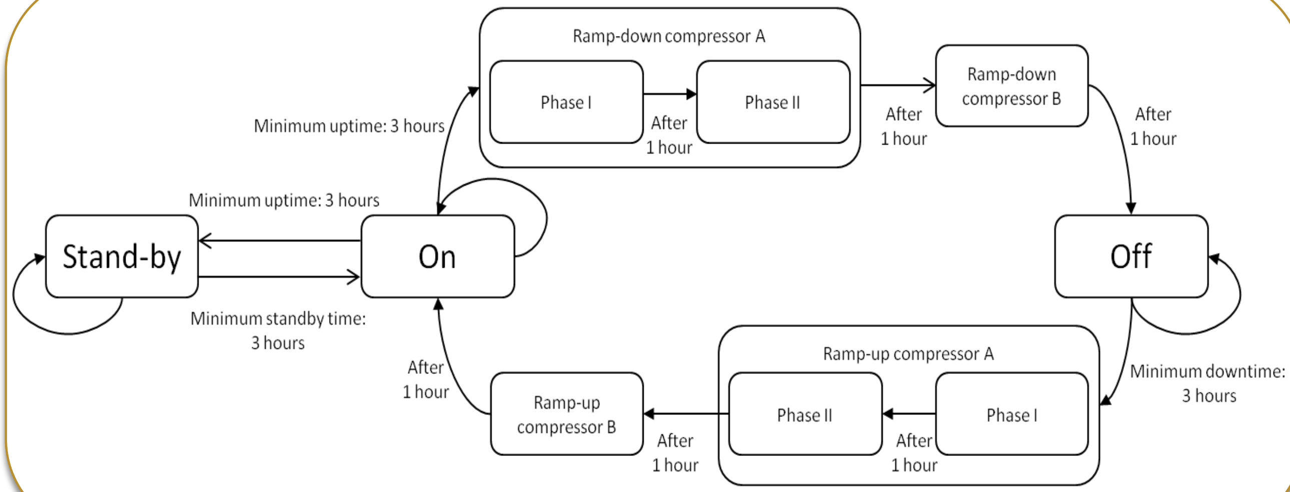
- Efficiently ***adjust production*** operation according ***to time-dependent electricity pricing***.
- Consider explicit modeling of **feasible plant operational transitions**. Propose a systematic way of representing **transition states**.
- Develop a systematic discrete-time, deterministic MILP model to optimal production planning of continuous power-intensive air-separation processes.
- Propose an efficient ***predictive and reactive solution strategy*** for real-world industrial scale problems.

Problem Definition

Major Problem Features

Min/max production rates based on the plant state

1. Power consumption for the different operating modes
2. Power consumption follows linear correlation: **PW = a + b*Production**
3. Min/max storage capacity in the plant
4. Minimum final tank levels at the end of the scheduling horizon
5. Expected daily demand and hourly electricity cost.

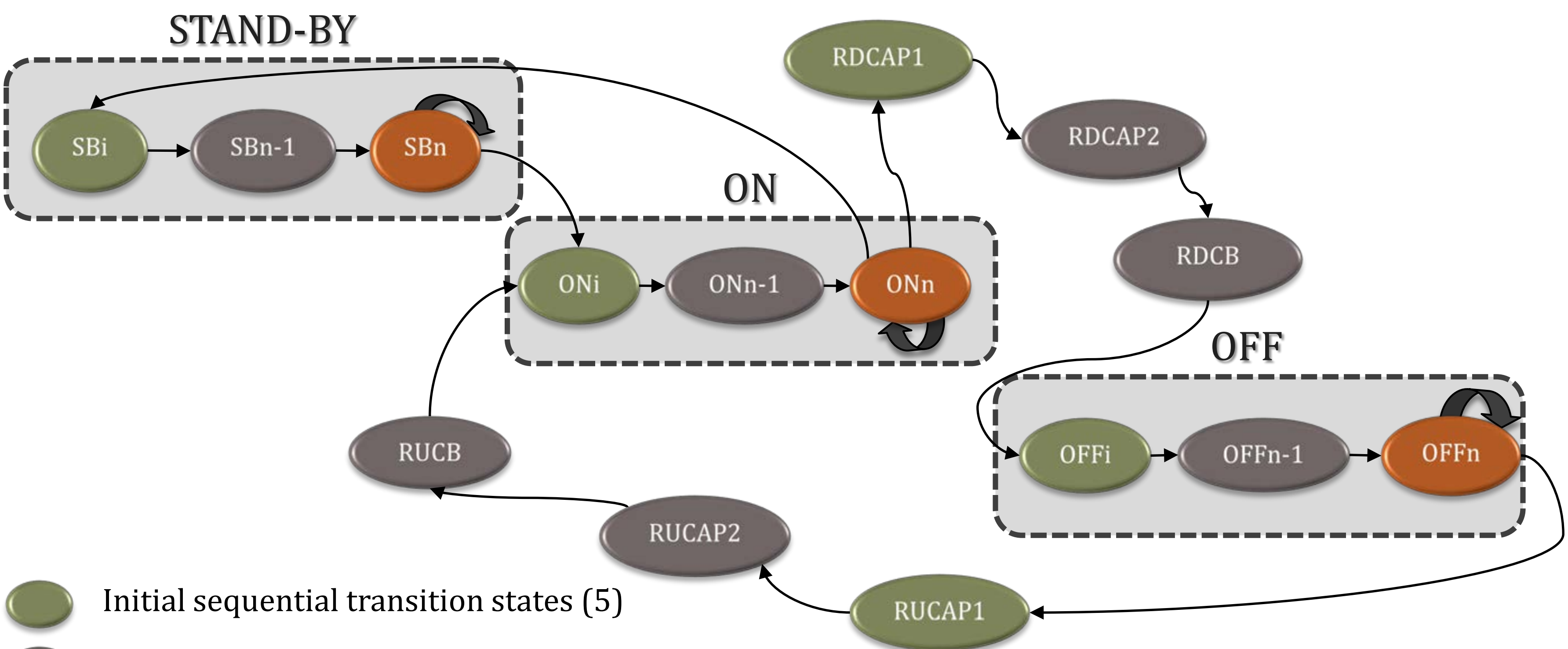


State Graph of an Industrial Plant

PSTN - *Process State Transition Network*

Plant states with minimum duration: ***3 hours***

Decomposition in 3 sub-states: ***1 hour each***



- Initial sequential transition states (5)
- Intermediate transition states (7)
- Critical transition states (3)

Proposed MILP Model

Indexes

t	Time periods (168)
s	States (15)
d	Days (7)

Parameters

$MinP_s$	Min production per hour in each state
$MaxP_s$	Max production per hour in each state
$MDTL_d$	Minimum final tank levels at the end of the day
ED_t	Hourly expected Demand
FPC_s	Fixed Power Consumption
VPC_s	Variable Power Consumption
EP_t	Hourly energy prices for the week
$Qmin$	Min Tank Level
$Qmax$	Max Tank Level
min_res	Minimum residence time
max_res	Maximum residence time
inc	Percentage increase production
dec	Percentage decrease production

Continuous Variables

$P_{s,t}$	Production at time t for state s
PW_t	Power consumption at time t
I_t	Inventory available at the end of time period t
$Cost$	Objective function (total energy cost)

Sets

T, S, D	
$S^{initial}$	Initial sequential states
S^{inter}	Intermediate transition states
$S^{critical}$	Critical transition states
NTS	Next to transition states
LIC	Last intermediate and critical state

Binary Variables

$W_{s,t}$	Indicates whether plant operates in state s during time period t

Proposed MILP Model

- Plant State

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

- Sequential Transition States

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

- Critical Transition States

$$W_{s,t} + W_{s',t} = \sum_{s'' \in NTS} W_{s'',t+1}$$

$$\forall t \in T, s \in S^{critial}, s' \in LIC$$

$$W_{s,t} = W_{s',t+1} \qquad s \in LIC, s' \in S^{critial}$$

$$W_{ON1,t+1} = W_{SBn,t} + W_{RUCB,t}$$

- Min/Max Production

$$W_{s,t} * MinP_s \leq P_{s,t} \leq W_{s,t} * MaxP_s$$

$$\forall t \in T, s \in S$$

- Min/Max Storage Capacity

$$Qmin \leq I_t \leq Qmax \qquad \forall t \in T$$

- Tank Level Constraints

$$I_t = 2000 + \sum_{s} P_{s,t} - ED_t \qquad \forall t \in T: t = 1$$

$$I_t = I_{t-1} + \sum_{s} P_{s,t} - ED_t \qquad \forall t > 1$$

$$I_t \geq MDTL_d \qquad \forall t = 168, d \in D$$

- Power Consumption

$$PW_t = \sum_{s} (W_{s,t} * FPC_s + VPC_s * P_{s,t})$$

$$\forall t \in T$$

- Objective Function

$$Cost = \sum_{t} (PW_t * EP_t)$$

Proposed MILP Model

- Residence time Constraints:

Minimum Residence Time

$$mn * W_{s,t} = \sum^{t+mn} W_{s',t'} \qquad \forall t \in T, t < (169 - mn), s \in S^{inter}, s' \in S^{critical}$$

$$(168 - mn) * W_{s,t} = \sum_{t'=t+1}^{168} W_{s',t'} \qquad \forall t \in T, (169 - mn) < t < 169, s \in S^{inter}, s' \in S^{critical}$$

$$mn = min_{res} - 2$$

Maximum Residence Time

$$\sum_{t'=t}^{t+mx} W_{s,t'} \leq mx \qquad \forall t \in T, t < (169 - max_{res}), s \in S^{critical}$$

$$mx = max_{res} - 2$$

Proposed MILP Model

- Min/Max Production

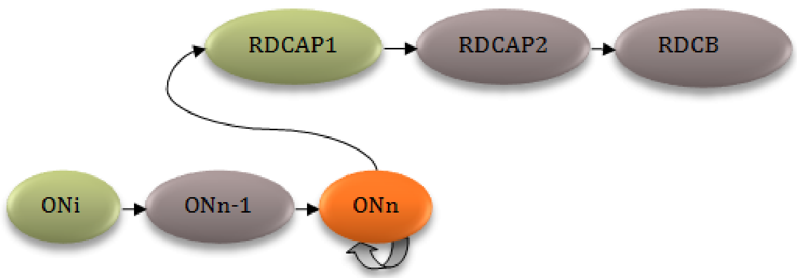
$$W_{s,t} * MinP_s \leq P_{s,t} \leq W_{s,t} * MaxP_s \qquad \forall t \in T, s \in S$$

Ramp-up Production

$$P_{ONi,t} = W_{ONi,t} * MinP_{ONi} \qquad \forall t \in T, t < 169$$

$$inc * P_{ONi,t} \geq P_{ONn-1,t+1} \qquad \forall t \in T, t < 169$$

$$inc * (P_{ONn-1,t} + P_{ONn,t}) \geq P_{ONn,t+1}$$



Ramp-down Production

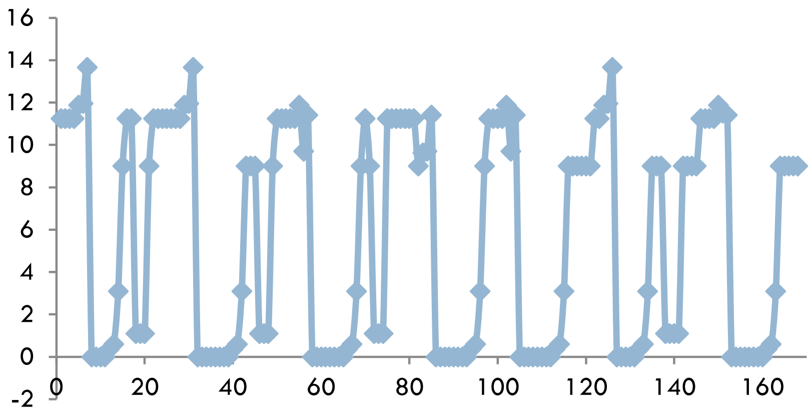
$$dec * (P_{ONn-1,t} + P_{ONn,t}) \leq P_{ONn,t+1} + P_{RDCAP1,t+1} \qquad \forall t \in T, t < 169$$

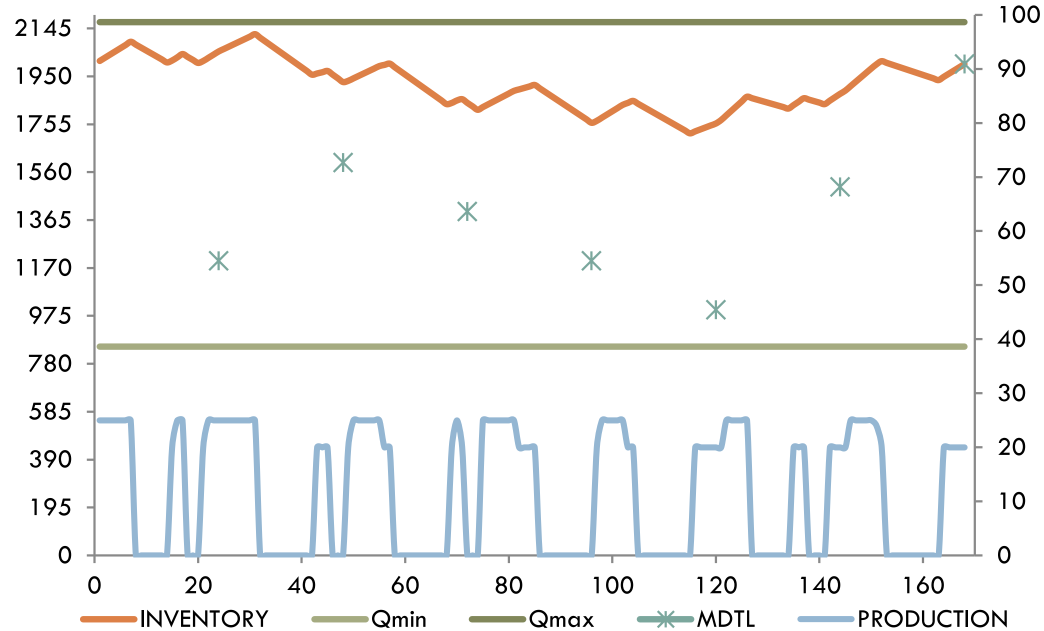
$$dec * P_{RDCAP1,t} \leq P_{RDCAP2,t+1} \leq inc * P_{RDCAP1,t} \qquad \forall t \in T, t < 169$$

$$dec * P_{RDCAP1,t} \leq P_{RDCB,t+1} \leq inc * P_{RDCAP2,t} \qquad \forall t \in T, t < 169$$

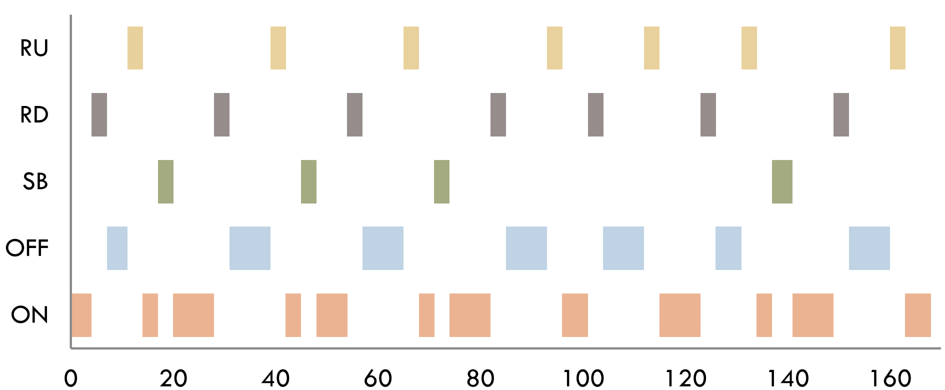
Computational Results

POWER CONSUMPTION





GANTT CHART SCHEDULE



***TOTAL COST* = 38693.03**

***Minimum Residence time*: 3 hours**

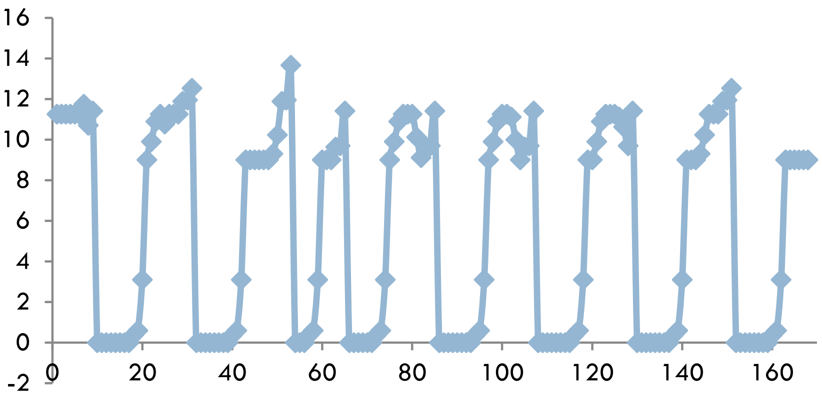
***Maximum Residence time*: 8 hours**

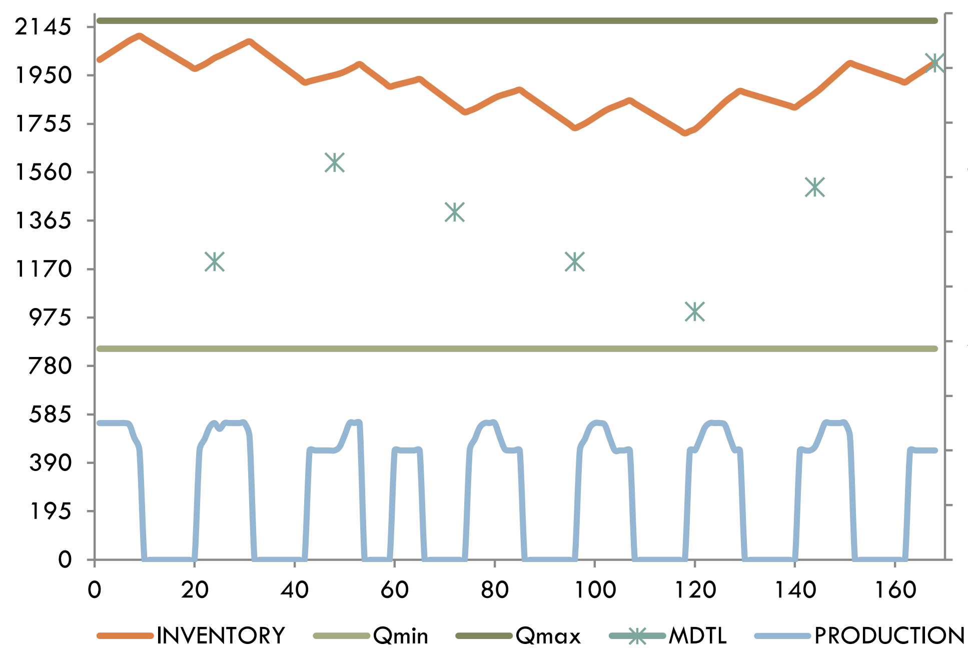
Final status of solution: OPTIMAL

CPU time: 22.68 sec.

Computational Results

POWER CONSUMPTION





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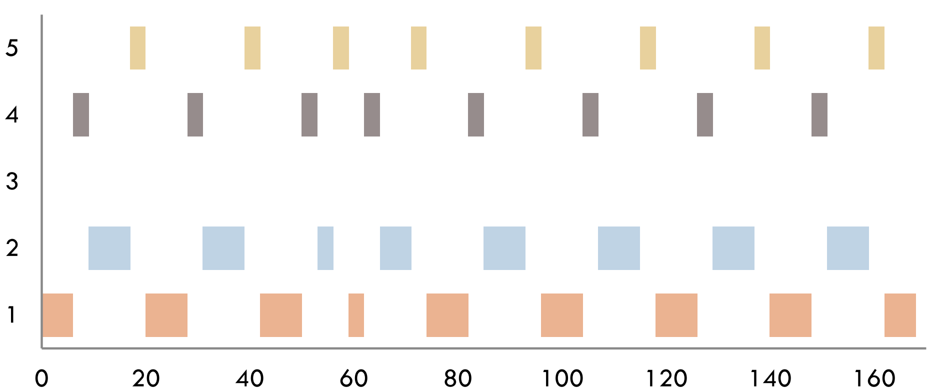

***TOTAL COST* = 39683.76**

***Minimum Residence time*: 3 hours**

***Maximum Residence time*: 8 hours**

Ramping Constraints

Final status of solution: OPTIMAL

CPU time: 31.95 sec.

Computational Results

Scenario	*Minimum Residence time*	*Maximum Residence time*	Ramping Constraints	Energy total cost	CPU time
1	3	168	-	**36348.17**	0.5 sec.
2	8	168	-	**37018.97**	1.092 sec.
3	12	168	-	**38374.67**	22.45 sec.
4	12	168	✓	**38430**	1.93 sec.
5	8	16	-	**37159.69**	2.28 sec.
6	8	16	✓	**37296.25**	2.53 sec.
7	3	8	-	**38693.03**	22.68 sec.
8	3	8	✓	**39683.76**	31.95 sec.

Remarks

- ✓ Very efficient and robust predictive MILP-based scheduling approach
- ✓ Modest computational effort considering a one-hour time grid and one-week time horizon
- ✓ Model able to consider all problem features and easy to adapt to reactive scheduling (a rolling horizon approach)
- ✓ Promising solution scheduling for real-world Air Liquide industrial plants

Future Work

- ❖ Evaluate daily and hourly reactive decisions based on energy price changes (day ahead and imbalance market).
- ❖ Test model with other Air Liquide plant configurations.
  Identify additional features to be included in the model.
- ❖ Evaluate model with uncertain demands.