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Multiperiod model for the optimal production planning in the industrial gases sector

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HIGHLIGHTS

- A multiperiod model for the optimal scheduling of an industrial plant is proposed.
- The model relies on maximizing profit by minimizing energy consumption.
- Real variability in electricity prices from spot and future markets is considered.
- Model capabilities are demonstrated on existing cryogenic air separation process.
- This approach provides non-intuitive alternatives allowing energy savings.

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ABSTRACT

Cryogenic air separation to produce nitrogen, oxygen and argon with high quality requirements is an energy-intensive industrial process that requires large quantities of electricity. The complexity in operating these networks stems from the volatile conditions, namely electricity prices and products demands, which vary every hour, creating a clear need for computer-aided tools to attain economic and energy savings. In this article, we present a multiperiod mixed-integer linear programming (MILP) model to determine the optimal production schedule of an industrial cryogenic air separation process so as to maximize the net profit by minimizing energy consumption (which is the main contributor to the operating costs). The capabilities of the model are demonstrated by means of its application to an existing industrial process, where significant improvements are attained through the implementation of the MILP.

1. Introduction

At present, cryogenic air distillation is the most efficient technology [1] to obtain technical gases (i.e., nitrogen, oxygen and argon) in large quantities with high standard requirements. Compression and liquefaction in the cryogenic separation require large amounts of electricity which leads to large operating costs. Therefore, it is not surprising that energy saving opportunities in the air separation technology have been object of study since long ago [2]. Xenos et al. [3] attempted to reduce power consumption and therefore operational costs in a network of compressors by introducing models to estimate the best distribution of the load. Similarly, Kopanos et al. [4] developed a mathematical framework for compressors operations in the context of air separation plants to simultaneously optimize maintenance and operational tasks. Üster and Dilaveroglu [5] extended the scope of the analysis beyond compression stages to address the optimization of a natural gas network while satisfying customers' demand.

We note that in the present contribution we address a more complex problem, as we consider the volatility of the electricity market price. Electricity is purchased in an organized wholesale market, also called "spot market", which works similarly in all European Union regions. OMIE [6] is the electricity market operator who manages the "spot market" in the Iberian Peninsula, similarly as Nord Pool Spot [7] does in the Nordic countries, EPEX Spot [8] in France, Germany and other Central European countries, or GME [9] in Italy. The electricity market allows the purchase and sale of electricity between agents (producers, consumers, traders, etc.) at a price subject to market fluctuations [10]. Furthermore, the steeping up of renewable energy

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Nomenclature

CBU	conversion unit
CU	compression unit
DCU	distillation column unit
ECU	external compression unit
EDCU	external distillation unit
FP	final products
GANIP	gas nitrogen intermediate product
GANP	gas nitrogen product
GOXIP	gas oxygen intermediate product
GOXP	gas oxygen product
ILOXP	industrial liquid oxygen product
LOXIP	liquid oxygen intermediate product
LARIP	liquid argon intermediate product
LARP	liquid argon product
LINP	liquid nitrogen product
LQU	liquefaction unit
MILP	mixed-integer linear programming
MLOXP	medical liquid oxygen product
MX	mixers
OGAN	purchased gas nitrogen
OGOX	purchased gas oxygen
PU	pump unit
PTU	pretreatment unit
P1-P6	electrical tariff period
SP	splitters
T	storage tank
U	utility
VU	vaporizer unit

Sets/indices

I	set of process units indexed by i
P	set of properties indexed by p
S	set of streams indexed by s
T	set of time intervals indexed by t
U	set of utilities indexed by u

Subsets

EC	set of units whose electricity consumption is constant
EE	set of units with electrical consumption
EO	set of outside units whose electricity consumption is accounted for
EV	set of units whose electricity consumption is variable
FCL	set of streams with maximum switch flow limitations in a time period
FP	set of streams s which are final products
GP	set of units whose gasoil consumption is proportional to inlet flow
MINCAP	set of units with a minimum flow requirement
MO_i	main output stream of unit i
MS_i	main input stream of unit i
SI_i	set of input streams of unit i
SO_i	set of output streams of unit i
$SPTI_i$	set of units which are splitters in which one output stream can only be used if the inventory level of tank i is over $VSINV_i$
SPW	set of units which are SP which cannot use simultaneously both output streams
ST	set of units which are tanks
TVS	set of tanks which can send tankers to associated storage plant
UPR2	set of units which belong to supply process
UPR1	set of units which belong to main process
VS	set of streams which are tankers to storage plant

Continuous variables

$AV_{s,t}$	absolute value for flow changes in stream s in period t, N m^3/h
$\partial_{i,t}^{+}$	positive slack for inventory in unit i period t, N m^3/h
$\partial_{i,t}^{-}$	positive slack for inventory in unit i period t, N m^3/h
ECONS	total electricity consumption, kWh
$F_{s,t}$	volumetric flow rate of stream s in time period t, N m^3/h
FEP	Fine when $MAXPR2_t + MAXPR1_t$ is exceeded, €
$FD_{s,t}$	disaggregated variable for death time (volumetric flow rate of stream s in time period t), N m^3/h
GOCONS	total gasoil consumption, L
$INV_{i,t}$	inventory of unit i in time period t, N m^3
$INVD_{i,t}$	disaggregated variable for inventory at level at which it can be depleted by means of tankers (inventory of unit i in time period t), N m^3
PROFIT	profit, €
SALES	sales, €
$UTCONS_{i,u,t}$	consumption of utility u in unit i in time period t, kWh
$Z_{i,d,t}$	auxiliary variable for F_s in interval d of piecewise equation for electricity consumption of unit i in time period t

Binary variables

$y_{i,d,t}$	binary variable (1 if interval d in piecewise equation for electricity consumption of unit i is active in time period t, 0 otherwise)
$yfc_{s,t}$	binary variable (1 if the flow of stream s is switched in time period t, 0 otherwise)
$yi_{i,t}$	binary variable (1 if unit i is working in time period t, 0 otherwise)
$yinv_{i,t}$	binary variable (1 if inventory of tank i in time period t surpasses the minimum required for it to be depleted by means of tankers, 0 otherwise)
$yon_{i,t}$	binary variable (1 if unit i is switched on in time period t, 0 otherwise)
$yw_{i,t}$	binary variable that equals 1 or 0 depending on which output stream s is used in i in time period t

Parameters

η	vaporizer efficiency
$a_{i,d}$	slope of straight line in interval d of piecewise equation for electricity consumption of unit i
$b_{i,d}$	independent term of straight line in interval d of piecewise equation for electricity consumption of unit i
$CAPVOL_i$	maximum capacity allowed for input stream of unit i, N m^3/h
CF	corrective factor between input and output streams in unit CBU
CF2	corrective factor between OGOX and OGAN in EDCU
$DEM_{s,t}$	demand for product in stream s in time period t, N m^3/h
DISC	supplier discount on outsourcing cost, €
DT	death time in liquefiers, h
$ECONCOST_t$	cost of electricity bought in advance for time period t, €/kWh
$ECOST_t$	electricity cost in time period t, €/kWh
GOCOST	gasoil cost, €/L
GSCAP	maximum capacity for a given stream, N m^3/h
HVAPN2	heat of vaporization of N_2, kJ/N m^3
$INVCAP_i$	capacity of unit i, N m^3
$INVini_i$	initial inventory of tank i, N m^3
$INVfin_i$	final inventory of tank i, N m^3

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