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

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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...
Nomenclature

CU conversion 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
LARIP liquid argon intermediate product
LARP liquid argon product
LINDP 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 processes 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
MOi main output stream of unit i
MSi main input stream of unit i
SIi set of input streams of unit i
SOi set of output streams of unit i
SPTIi set of units which are splitters in which one output stream can only be used if the inventory level of tank t is over V$i,t$
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 main process

Continuous variables

$\text{AV}_{s,t}$ absolute value for flow changes in stream s in period t, N m$^3$/h
$\bar{\delta}_{i,t}^+$ positive slack for inventory in unit i period t, N m$^3$/h
$\bar{\delta}_{i,t}^-$ positive slack for inventory in unit i period t, N m$^3$/h
ECONS total electricity consumption, kWh
$\text{F}_{i,t}$ volumetric flow rate of stream s in time period t, N m$^3$/h
$\text{FEF}$ Fine when $\text{MAXPR2} + \text{MAXPR1}$, exceeded, €
$\text{FD}_{i,t}$ disaggregated variable for death time (volumetric flow rate of stream s in time period t), N m$^3$/h
GOCONS total gasoil consumption, N m$^3$/h
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$u_{i,d,t}$ consumption of utility u in unit i in time period t, kWh
$Z_{i,d,t}$ auxiliary variable for $\text{F}_i$ 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)
$y_{fc, s, t}$ binary variable (1 if the flow of stream s is switched in time period t, 0 otherwise)
$y_{i,l, t}$ binary variable (1 if unit i is working in time period t, 0 otherwise)
$\text{yinv}_{i,t}$ binary variable (1 if inventory of tank t in time period t surpasses the minimum required for it to be depleted by means of tankers, 0 otherwise)
$\text{yon}_{i,t}$ binary variable (1 if unit i is switched on in time period t, 0 otherwise)
$\text{yw}_{i,t}$ binary variable that equals 1 or 0 depending on which output stream s is used in i in time period t

Parameters

$\eta$ 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 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$i,t$ demand for product in stream s in time period t, N m$^3$/h
DISC supplier discount on outsourcing cost, €
$\text{DT}$ death time in liquefiers, h
$\text{ECONCOST}_t$ cost of electricity bought in advance for time period t, €/kWh
$\text{ECOST}_t$ electricity cost in time period t, €/kWh
$\text{GOCOST}$ gasoil cost, €/L
$\text{GSCAP}$ maximum capacity for a given stream, N m$^3$/h
$\text{HVAPN2}$ heat of vaporization of N$_2$, kJ/N m$^3$
INVCAP capacity of unit i, N m$^3$
$\text{INVini}$ initial inventory of tank i, N m$^3$
$\text{INVfini}$ final inventory of tank i, N m$^3$
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