Computers and Chemical Engineering 104 (2017) 25–37

Contents lists available at ScienceDirect

Computers and Chemical Engineering

journal homepage: www.elsevier.com/locate/compchemeng

Integrated real-time production scheduling of a multiple cryogenic air separation unit and compressor plant

Richard Adamson[a,*], Martin Hobbs[b], Andy Silcock[b], Mark J. Willis[a,*]

[a] *School of Chemical Engineering and Advanced Materials, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom*
[b] *BOC Gases Ltd., Bawtry Road, Brinsworth, Rotherham S60 5NT, United Kingdom*

ARTICLE INFO

Article history:
Received 3 January 2017
Received in revised form 31 March 2017
Accepted 1 April 2017
Available online 6 April 2017

Keywords:
Production scheduling
Site-wide optimisation
Real-time optimisation
Process control
Power consumption
Mixed integer linear programming

ABSTRACT

The development and application of an integrated real-time production scheduling and control strategy for a multiple cryogenic air separation unit (ASU) and compressor plant is discussed. Using a top-down optimisation approach, the operational targets for ASU production and compressor configuration are obtained for a given customer demand and subsequently managed using a real-time optimisation strategy. This is integrated with existing control to implement the steady-state configuration targets subject to process disturbances, power price fluctuations and against network change penalty weightings. Network material balance and network component operating constraints are met while simultaneously minimising plant reconfiguration costs during transient operation which occurs as a result of changing demands. Implemented using mixed integer linear programming, it is demonstrated that the two-stage optimisation strategy improves site operating costs by an average of 5% over the considered trial period (which would translate into substantial cost savings for such an energy intensive process).

1. Introduction

Cryogenic air separation is a highly energy intensive process,[1] with optimal operation critical to minimise energy consumption of sites; which often consist of an elaborate network of air separation units (ASUs) and compressors. This is particularly important where external market conditions, such as customer demand and power pricing, change, as the entire plant must be reconfigured to trade-off power consumption with specific demand requirements. In the literature, there are many examples of network optimisation by load and production sharing, see reviews by Cortinovis et al. (2016) and Xenos et al. (2015), where load sharing control can be effectively achieved after integration with existing control schemes.

However, only a few published papers have considered implementing a real-time optimisation (RTO) approach to manage the optimal load sharing of a network of compressors (and ASUs) and the subsequent integration with process control schemes. Cortinovis et al. (2016) note that only Xenos et al. (2015) and Paparella et al. (2013) have come close to the implementation of RTO; with Xenos et al. (2015) investigating the optimisation of cryogenic air separation networks (along with maintenance scheduling) using a mixed integer nonlinear programming (MINLP) network model and Paparella et al. (2013) examining RTO of natural gas compression station networks. Cortinovis et al. (2016) themselves develop a load sharing strategy based on the simulation of a large compression plant implemented as a MINLP problem but with high solving times. They also highlight requirement for the development of a computationally efficient method to consider network reconfiguration costs, such as the abortive power costs of changing product compression.

In other examples, Puranik et al. (2016) optimise an air separation plant configuration to meet changing demand requirements, where operating cost minimisation is the primary goal. They argue uncertainty in electricity price forecasts (perhaps due to increased uncertainty in renewable generation, demand and power market conditions, Merkert et al. (2014)) and unpredictable gas pipeline customer demands favour the use of RTO over discrete time optimal scheduling of future activities. Zhu et al. (2011) discuss optimisation of air separation plants with forecasts of variable power pricing. In addition, Zhou et al. (2017) discuss current limitations in the literature where works typically only focus on the scheduling of individual ASUs. The consideration of multiple ASUs that flex and load share over time to meet changing customer gas demands provides a more industrially relevant and challenging problem. Therefore, the novel site-wide steady-state optimisation

---

* Corresponding author.
E-mail addresses: richard.adamson1@newcastle.ac.uk (R. Adamson), mark.willis@newcastle.ac.uk (M.J. Willis).

[1] e.g. the Air Liquide Group's total electricity consumption in 2010 corresponded to more than one thousandth of the world's total electricity consumption, Li et al. (2011), and the industrial gas industry used approximately 3.5% of the total industrial electricity consumption of the US in 1998, Zhou et al. (2017).

http://dx.doi.org/10.1016/j.compchemeng.2017.04.001
0098-1354/

Nomenclature

Abbreviations

ASU	air separation unit
HCM	hundred cubic metres
IC	internally compressed
LO	liquid oxygen
MPC	model based predictive control
MP	medium pressure
SSO	steady-state optimisation
TGO	total gaseous oxygen demand
GO	gaseous oxygen
HP	high pressure
LN	liquid nitrogen
LP	low pressure
ME	model mean error (kW)
RTO	real-time optimisation
SWO	site-wide optimisation
TLO	total liquid oxygen

Parameters

$\hat{b}$	model co-efficient
C_{kW}	spot power cost (£/MWh)
C_s	liquid use cost (£/m^3)
h	compressor off penalty (£)
P_{Dj}	discharge pressure (bar)
$\hat{W}$	power consumption estimation (kW)
τ	compression change penalty (£)
σ	ASU change penalty (£)
β	max ramp rate (m^3/h^2)
C_{LO}	liquid make cost (£/m^3)
g	compressor on penalty (£)
J	cost function (£/h)
W	power consumption (kW)
μ	average
ρ	control error penalty (£)
φ	LP spill penalty (£)

Variables

δ	binary co-efficient
y	total flow/binary auxiliary variable
F	flow rate (m^3/h)
z	penalty auxiliary variable

Subscript/superscripts

c	compressor
k	pseudo-machine number
max	maximum capacity limit
$RAMP$	ramping customer demand
s	liquid back-up supply
t	discrete time point
v	valve
j	compressor or ASU number
m	model number
min	minimum capacity limit
REQ	requested customer demand
SW	site-wide
u	unit (ASU)
RT	real-time

(SSO) deployed in Adamson et al. (2017) requires extension into a robust RTO strategy to ensure optimal network management at all times, i.e. during demand changes and accounting for process disturbances such as variable power pricing and pipeline pressures.

The cooperation of site-wide optimisation (SWO) and the lower level control systems is an important field of research which has practical significance. The importance of the current work is highlighted by a recent funding call, European Commission (2015), noting the current shortcomings in integration of dedicated local control systems with overarching real-time optimisation scheduling systems for the control and monitoring of processes. The review by Baldea and Harjunkoski (2014) proposes the fact that the scheduling and control fields evolved separately, along with current inefficiencies in communication and solving strategies, as the reason for why efforts to integrate these strategies have only recently begun. Lotero et al. (2017) suggest the scheduling community focussed on online scheduling and the control community only considered closed loop implementations, with the methods not converging. Combined RTO and control strategies must simultaneously consider production, operational and control law constraints as well as defining the overall objective function goal. Recent works to integrate the strategies include, Marchetti et al. (2014), Tatjewski (2010) and Hovd (2007) whom all suggest the use of an end-point target optimiser to generate set point optimisation goals and an additional (normally linear) RTO layer to minimise actual to target set point errors. Marchetti et al. (2014) describe how the outputs of SSO can be used a target for other layers of control to achieve optimal economic operation. In their work, they note that in the face of the disturbances the SSO may not correspond to a currently feasible operation therefore a further RTO layer is required prior to implementation via model based predictive control (MPC). Tatjewski (2010) describes a method to model uncertainty in the RTO layer enabling economic optimisation subject to modelled process constraints. Finally, Hovd (2007) note that RTO can be used to find a feasible operating point close to the SSO target using current disturbance data therefore reducing model errors caused by process uncertainties changing the optimal operating point. One example of the application of multilayer control with SSO targets is Singh et al. (2015) who adopt an integrated moving horizon based approach to optimise a continuous compaction tablet manufacturing process.

This paper reports the successful development and application of a novel RTO strategy to a real multiple cryogenic ASU and compressor plant demonstrating optimal load and production sharing in conjunction with optimal reconfiguration timing, implemented to achieve a significant financial benefit. Our RTO strategy is like the economic MPC approaches of Würth et al. (2009), Engell (2009) and Heidarinejad et al. (2012), where the tracking objective function of standard MPC is replaced by an economics based (usually nonlinear) objective function. However, as opposed to integrating this with MPC, this is used at steady-state (with steady-state models) to co-ordinate the load sharing optimisation problem, i.e. co-ordinate the set points transmitted to the individual MPCs, efficiently.

Work detailed in Pattison et al. (2016), describes the need for scheduling and MPC control strategies which operate at different frequencies to react to economic information changing at dissimilar rates. They suggest the need for detailed dynamics to be included in an RTO strategy, with scale-bridging models used to tie the optimisation and control layers for real-time solvability. However, this is at variance with our work as there was no possibility of investigating modifications to the well-established MPC proprietary software; so the layers had to remain separate and further work is required to challenge our assumption that unmodelled dynamics affect model robustness. Furthermore, as our results demonstrate, dynamics are not required to be captured in the RTO layer as (a) the model based and supervisory control schemes already in place can control high frequency dynamic disturbances to ensure stable plant operation and (b) the RTO strategy tracks the output of the scheduling layer following a contractually agreed ramping policy.

We develop a computationally efficient mixed integer linear programming (MILP) approach to RTO designed to cooperate with