Computers and Chemical Engineering 111 (2018) 225–240

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Expansion development planning of thermocracking-based bitumen upgrading plant under uncertainty

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ARTICLE INFO

Article history:
Received 10 October 2017
Revised 10 January 2018
Accepted 14 January 2018

Keywords:
Bitumen upgrading
Capacity expansion
Stochastic programming
Linear decision rule

ABSTRACT

Expansion development of upgrading plants is an important decision to make for the oil sands industry. In this paper, we propose a multistage stochastic expansion development method to tackle uncertain synthetic crude oil (*SCO*) and CO_2 tax prices. The linear decision rule based technique is applied to solve the proposed stochastic optimization model. Various analyses are conducted based on optimization results: (i) effects of the uncertainty set size, (ii) comparison of solutions for selected pessimistic, realistic, and optimistic scenarios, (iii) effects of different operating modes for an upgrading plant, and (iv) cost distribution. Results of this work demonstrate that the stochastic model provides a more flexible, economical, and robust solution compared to the deterministic solution. In addition, the CO_2 tax price affects the optimal solution negligibly compared to the *SCO* price. Finally, expansion development of the studied upgrading plant is economically beneficial even at the current market state.

1. Introduction

Crude oil is the global dominant energy source and the reliance of the world economy on it is expected to continue for a long time. It is estimated that the worldwide demand of crude oil will reach 111 million barrels per day by 2040, and approximately 25% of it will be contributed by North America, including Canada and the United States (World Oil Outlook, 2014). Due to the increasing scarcity of conventional oil reserves, oil industries and governments are interested in unconventional oil resources. Note that oil reserves that cannot be accessed using conventional drilling techniques are referred as unconventional oil. These reserves (e.g., tight oil, oil shale and bitumen) need novel methods for extraction (Demirbas et al., 2017; Wang et al., 2016). After Saudi Arabia and Venezuela, Canada has the third largest oil reserves with proven 168 billion barrels (Woynillowicz et al., 2005). Furthermore, nearly 97% of total Canadian oil reserves are in the form of oil sands, which are mainly distributed in the Athabasca, Cold Lake, and Peace River areas in northern Alberta (Woynillowicz et al., 2005).

Unconventional oil production in Canada is continuously increasing. The oil sands bitumen production in Alberta is projected to reach 3.8 million barrels per day by 2022, which will be two times the production as of 2012 (Lazzaroni et al., 2016). While oil price fluctuation affects profitability of the oil sands industry, important issue is how to adjust production and expansion planning under an uncertain market environment. Another major concern for the continuous development of the oil sands industry is the environmental management. Sustainable development with minimum environmental conservation is a concern of Alberta provincial and Canadian federal governments. To follow the international agreements (the United Nations Framework and Kyoto protocol), Canada is committed to mitigating its greenhouse gas (GHG) emissions. In Alberta, a carbon tax of \$15 per tonne of CO_2 was enacted in 2007 for the first time (Fact Sheet: Carbon Pricing Around the World, 2012). Recently, it was increased to \$20 and \$30 per tonne of CO_2 in 2016 and 2017 (Alberta Boosts Carbon Tax, 2015; Carbon Levy and Rebates, 2017). It is expected that the carbon tax rate will be increased; however, the exact future tax level is unknown. As it can be seen, the further development of the oil sands industry is accompanied with uncertainties in both the unpredictable oil price and changing environmental policies. Studying the development and expansion planning under uncertainties currently seems essential for the oil sands industry.

The uncertainty issue has received attention in various design and planning problems. The strategic planning of a bioethanol-sugar supply chain was studied under demand uncertainty (Kostin et al., 2012). A two-stage multi-scenario mixed-integer linear stochastic programming approach was proposed, and a decomposition technique was applied to solve it based on the sample average approximation technique. It was further shown that the stochastic model lead to more robust solution compared to

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https://doi.org/10.1016/j.compchemeng.2018.01.007

Nomenclature

Acronyms

ARMA	Auto Regressive Moving Average
DP	Deterministic Problem
DR	Diluent Recovery
el	Electricity
GHG	GreenHouse Gas
HGO	Heavy Gas Oil
HGOHT	Heavy Gas Oil HydroTreater
ht	Heat
HT	HydroTreater
LDR	Linear Decision Rule
LGO	Light Gas Oil
LGOHT	Light Gas Oil HydroTreater
NPH	Naphtha
NPHHT	Naphtha HydroTreater
NPV	Net Present Value
SAGD	Steam-assisted gravity Drainage
SCO	Synthetic Crude Oil
SOR	Steam-Oil-Ratio
SP	Stochastic Problem
st	Steam
TC	Thermocracker

Indices and sets

$p \in \mathcal{P}$	set of operating units
$u \in \mathcal{U}$	set of utilities
$t \in \mathcal{T}$	set of time periods
$c \in \mathcal{C}$	set of products
$\mathcal{MP}$	subset of mixer-type units (*NPHHT, LGOHT, HGOHT*)
$\mathcal{SP}$	subset of splitter-type units (*DR, TC*)
$\mathcal{PC}$	subset of matching between product and associated hydrotreater

Parameters

α	significance level
$\alpha_{p,c}^{yield}$	yield coefficient of splitter-type units
$\alpha_p^{H_2}$	hydrogen requirement coefficients ($\frac{tonne}{m^3}$)
α_p^{HT}	yield coefficient of mixers
$\beta_{p,\ u}$	energy requirements coefficient ($\frac{energy}{tonne}$)
γ^{CO_2}	carbon tax economic coefficient ($\frac{\$}{tonne\ \mathrm{CO}_2}$)
$\gamma^{Bitumen}$	Bitumen price ($\frac{\$}{bbl}$)
γ_u^E	energy requirements economic coefficients ($\frac{\$}{energy}$)
γ^{H_2}	hydrogen requirement economic coefficients ($\frac{\$}{tonne}$)
γ^{MAINEX}	maintenance economic coefficient
γ^{SCO}	*SCO* price ($\frac{\$}{bbl}$)
Γ	a scalar to control the uncertainty set size
δ_u^E	GHG emission coefficient of Energy sources ($\frac{tonne\ \mathrm{CO}_2}{energy}$)
δ^{H_2}	GHG emission coefficient of Hydrogen ($\frac{tonne\ \mathrm{CO}_2}{tonne}$)
δ^{SCO}	GHG emission coefficient of *SCO* production ($\frac{tonne\ \mathrm{CO}_2}{tonne}$)
ϵ_t	uncertainties for *SCO* price
ζ_t	uncertainties for CO_2 tax price
θ_q	*ARMA* ARMA model coefficients
ρ_p	density ($\frac{tonne}{m^3}$)
ϕ_p	*ARMA* ARMA model coefficients
$\bar{\Omega}_t^{Investment}$	capital investment limitation corresponding to period t (M\$)
$\underline{\Omega}^M$	upper bound for the inlet to the upgrading plant ($\frac{tonne}{hr}$)
$\underline{\Omega}_p^Q$	lower bound for percentile of capacity usage (%)
$\underline{\Omega}_p^{spec}$	lower bound for percentile of each product in final blend (%)
$\underline{\Omega}_p^X$, $\bar{\Omega}_p^X$	lower and upper bounds for expansion capacity (*bpd*)
a_p	gradient of linear capital cost equation
A_t^{SCO}	constant coefficients vector of reformulated *ARMA* model at year t
b_p	intercept of linear capital cost equation (M\$)
B_t^{SCO}	constant coefficients scalar of reformulated *ARMA* model at year t
d	depreciation time (*yr*)
h	the coefficients vector of general uncertainty set
ir	annual real debt interest rate (%)
OT	operating time (*hr*)
P_t	truncate matrix at year t
r	discount rate (%)
UC_1	unit conversion from cubic meter per hour into barrel per day ($\frac{bpd}{\frac{m^3}{hr}}$)
UC_2	unit conversion from \$ to M\$ ($\frac{\mathrm{M\$}}{\$}$)
W	coefficient matrix of general uncertainty set
$z_{1-\alpha}$	$1-\alpha$ quantile of standard normal distribution

Decision variables

Λ	variable stemmed from dual counterpart of inequality constraint
C_t^{CAPEX}	capital cost investment of year t (M\$)
$Y_{p,\ t}$	binary capacity expansion decision for process p in the year t
$M_{p,t}^{H2}$	mass flow rate of hydrogen in hydrotreater p at year t ($\frac{tonne}{hr}$)
$M_{p,c,t}^{out}$	mass flow rate of outlet product c from splitter p at year t ($\frac{tonne}{hr}$)
$M_{p,t}^{in}$	mass flow rate of inlet to splitter p at year t ($\frac{tonne}{hr}$)
$M_{p,t}^{HTout}$	mass flow rate of outlet from hydrotreater p at year t ($\frac{tonne}{hr}$)
$M_{p,t}^{H2}$	mass flow rate of hydrogen in hydrotreater p at year t ($\frac{tonne}{hr}$)
M_t^{SCO}	total mass flow rate of *SCO* at year t ($\frac{tonne}{hr}$)
$E_{u,\ t}$	energy consumption of utility u at year t ($\frac{energy}{hr}$)
$X_{p,\ t}$	capacity expansion of process p to be installed in period t (*bpd*)
$Q_{p,\ t}$	total capacity of process p in period t (*bpd*)

the deterministic model. The strategic investment planning of a multi-product, multi-period supply chain problem was investigated (Oliveira et al., 2013). To address the demand uncertainty, a two-stage mixed-integer linear stochastic programming model with risk consideration was taken into account to reduce the chances of very large objective function values during minimization. A two-stage mixed-integer linear stochastic programming was applied for the expansion planning of electricity generation plants (Park and Baldick, 2015). Various power generation techniques (coal, combustion turbine, nuclear, combined cycle and wind generator) were considered. The load and wind availabilities were the uncertain parameters which were defined as independent and identically distributed random variables. Environmental regulations (including carbon tax and a renewable portfolio standard) were imposed on the model as well. This model was solved using the L-shaped method based on the Monte Carlo simulation.