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Source-based discrete and continuous-time formulations for the crude oil pooling problem

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ABSTRACT

The optimization of crude oil operations in refineries is a challenging scheduling problem due to the need to model tanks of varying composition with nonconvex bilinear terms, and complicating logistic constraints. Following recent work for multiperiod pooling problems of refined petroleum products, a source-based mixed-integer nonlinear programming formulation is proposed for discrete and continuous representations of time. Logistic constraints are modeled through Generalized Disjunctive Programming while a specialized algorithm featuring relaxations from multiparametric disaggregation handles the bilinear terms. Results over a set of test problems from the literature show that the discrete-time approach finds better solutions when minimizing cost (avoids source of bilinear terms). In contrast, solution quality is slightly better for the continuous-time formulation when maximizing gross margin. The results also show that the specialized global optimization algorithm can lead to lower optimality gaps for fixed CPU, but overall, the performance of commercial solvers BARON and GloMIQO are better.

1. Introduction

Optimization of scheduling operations in refineries has been recognized as a relatively inexpensive and fast way to improve economical performance (Kelly and Mann, 2003). A distinctive feature of refinery scheduling problems is the blending of different types of crudes or liquid fuels and the need to meet strict quality specifications on process streams or customer orders. In most cases, they fall under the hood of nonconvex mixed-integer nonlinear programming (MINLP), which is one of the most complex and active fields in optimization (Trespalacios and Grossmann, 2014). Recent work has focused on both mathematical formulations and algorithms for the global optimal solution of refinery scheduling problems.

Most refinery scheduling models have focused on either upstream operations, from crude arrival up to distillation units (Shah, 1996; Lee et al., 1996; Jia et al., 2003; Reddy et al., 2004a,b; Furman et al., 2007; Li et al., 2007; Mouret et al., 2009; Li et al., 2012; Yadav and Shaik, 2012; Hamisu et al., 2013; Castro and Grossmann, 2014), or downstream operations, involving blending of hydrocarbon fractions to the storage and delivery of final product orders (Li et al., 2010; Li and Karimi, 2011; Kolodziej et al., 2013b; Castro, 2015b; Castillo-Castillo and Mahalec, 2016; Li et al., 2016; Cerdá et al., 2016). A major difference between the two problems concerns the type of blending process, occurring either discontinuously inside tanks, or continuously. The former needs to be modelled with nonlinear constraints while the latter can skip them whenever linear blending rules apply to qualities, which is not the case for research (RON) and motor octane numbers (MON) (Singh et al., 2000; Castillo-Castillo and Mahalec, 2016).

Blending tanks (pools) may have multiple fuels and we need to ensure that the compositions of the outlet streams match the compositions inside. A variety of alternative formulations have been proposed for the single period pooling problem (Haverly, 1978; Ben-Tal et al., 1994; Tawarmalani and Sahinidis, 2002; Alfaki and Haugland, 2013; Boland et al., 2016) with the one featuring total flows and composition variables being perhaps the most common when scheduling multiple time periods of operation (Lee et al., 1996; Li et al., 2007; Kolodziej et al., 2013b). However, recent work has shown that a source based formulation for the static multiperiod pooling problem of refined products, featuring variables for disaggregated volumes and split fractions, results in a tighter mixed-integer linear (MILP) relaxation of the MINLP (Lotero et al., 2016) and a better computational performance (Castro, 2015b).

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Nomenclature

Sets/Indices

B	Blending tanks
CD/cd	Crude oil distillation unit
CR/cr	Crude oil
CR_u	Crudes that can appear in unit u
CT/ct	Charging tank
MV/mv	Crude marine vessels
PR/pr	Crude oil property
ST/st	Storage tank
T/t	Time/event points of the single time grid
T^i_{mv}	Time/event points that can be assigned to harboring of vessel mv (\$/day)
T^o_{mv}	Time/event points that can be assigned to leaving of vessel mv (\$/day)
TK/tk	Storage and charging tanks
U/u	System units
$U_{u'}$	Units that can feed unit u'

Parameters

$ai^L_{tk,t}$	Lower bound of variables $AI_{tk,t}$ (kbbl)
$ai^U_{tk,t}$	Upper bound of variables $AI_{tk,t}$ (kbbl)
at_{mv}	Arrival time of marine vessel mv (day)
$c_{cr,pr}$	Composition of crude cr in property pr
c^{chg}	Cost involved for changing the crude feed to a distillation column (\$)
c^{harb}_{mv}	Harboring costs for unloading the crude from marine vessel mv (\$/day)
c^{inv}_{tk}	Inventory cost for tank tk (\$/kbbl/day)
$c^{\max}_{tk,pr}$	Maximum composition in blending tank tk for property pr
$c^{\min}_{tk,pr}$	Minimum composition in blending tank tk for property pr
c^{wsea}_{mv}	Sea waiting cost for marine vessel mv (\$/day)
$d^{\max}_{ct}$	Maximum demand of crude from charging tank ct (kbbl)
$d^{\min}_{ct}$	Minimum demand of crude from charging tank ct (kbbl)
ft_t	Time value for time point t for discrete-time formulation (day)
gap	Relative optimality gap
H	Time horizon (day)
$hb^{\min}_{mv}$	Minimum harboring time for marine vessel mv (day)
LB	Lower bound on value of objective function
p_{cr}	Gross margin of crude cr (\$/kbbl)
UB	Upper bound on value of objective function
$vt^{\max}_u$	Maximum volume that can be transferred from unit u (kbbl)
$vt^{\min}_u$	Minimum volume that can be transferred from unit u (kbbl)
δ	Duration of every time slot in grid of discrete-time formulation (day)
ε	Target relative optimality tolerance
$v^0_{u,cr}$	Initial volume inside unit u of crude cr (kbbl)
$v^L_{cr,u,t}$	Lower bound of variables $V_{cr,u,t}$ (kbbl)
$v^{\max}_{tk}$	Upper bound on total volume inside tank tk (kbbl)
$v^{\min}_{tk}$	Lower bound on total volume inside tank tk (kbbl)
$v^U_{cr,u,t}$	Upper bound of variables $V_{cr,u,t}$ (kbbl)
$\rho^{\max}_{u,u'}$	Maximum transfer flowrate between units u and u' (kbbl/day)
$\rho^{\min}_{u,u'}$	Minimum transfer flowrate between units u and u' (kbbl/day)
ψ	accuracy level of discretized variables, $\in \mathbb{Z}^-$

Variables

$Y_{u,u',t}$	Binary variable indicating flow between units u and u' during slot t
$Y^{noio}_{u,t}$	Binary variable indicating no active input or output flow for unit u during slot t
Y^{nomv}_t	Binary variable indicating that no vessel transfers crude during slot t
$Y^i_{t,mv}$	Binary variable indicating harboring of marine vessel mv. at event point t
$Y^o_{t,mv}$	Binary variable indicating departure of marine vessel mv at event point t
$Z^X_{u,u',t,j,k}$	binary variable assigning to discrete representation of $X_{u,u',t}$ digit j to position k
$Z^T_{t,j,k}$	binary variable assigning to discrete representation of λ_t digit j to position k
$AI_{tk,t}$	Average crude inventory in tank tk during slot t (kbbl)
$\hat{AI}_{tk,t,j,k}$	disaggregated variable from linearization of $AI_{tk,t}Z^T_{t,j,k}$ (kbbl)