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Simultaneous scheduling of front-end crude transfer and refinery processing

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ABSTRACT

Scheduling of front-end crude-oil transfer and refinery processing are two critically important and challenging tasks to petroleum refineries. However, the simultaneous scheduling of front-end crude-oil transfer and refinery operations has never been considered in previous studies due to the large scale and complexity of the resultant optimization problem. In this paper, a systematic methodology for simultaneous scheduling of front-end crude transfer and refinery processing has been developed. It provides a large-scale continuous-time based scheduling model for crude unloading, transferring, and processing (CUTP) to simulate and optimize the front-end and refinery crude-oil operations simultaneously. The CUTP model consists of a newly developed refinery processing sub model, a crude processing status transition sub-model, and a borrowed front-end crude transferring sub model. The objective is to maximize the total operational profit while satisfying various constraints such as operation and production specifications, inventory limits, and production demands. The efficacy of the proposed scheduling model has been demonstrated by an industrial-scale case study.

1. Introduction

The petroleum refinery is a leading segment of the entire petrochemical industry. It processes crude oils to produce various fuels such as gasoline, aviation kerosene, diesel, heavy fuel oil, and chemical raw materials such as naphtha and benzene. The petroleum refinery plays a vital role in the national economic development. It was reported by the Energy Information Administration (EIA) that U.S. crude oil and dry natural gas production levels have increased rapidly in recent years. From 2008 to 2013, the crude oil production grew from 5.0 million barrels per day to 7.4 million barrels per day. In 2014, 142 operable refineries in the U.S. processed 5.78 billion barrels of crude oil and produced 14.0 million barrels of petroleum and other liquids per day (EIA, 2014). Even in the slow market of 2015, the crude oil production associated with 140 operable refineries in U.S. reached 10.6 million barrels per day (EIA, 2015). Because of the increasingly strict economic competitions, refineries are eager to improve production efficiency and lower the operational cost to leverage profitability margins in current volatile oil markets.

Generally, the majority of a refinery's expenditure is used for crude oil purchasing. Thus, the crude availability and crude movement should be optimally integrated with the crude processing, so that the potential profitability of a refinery can be improved. This is also the reason why the front-end crude scheduling and planning is extremely important in the supply chain management of refineries, especially under current conditions of increasingly global competitions, more volatile feedstock/product markets, and stricter environmental regulations. As shown in Fig. 1, the scope of this study contains two major sections: (i) front-end crude transfer, which covers the crude unloading from vessels to portside storage tanks at onshore berths, and the crude transferring to charging tanks of an inland refinery to prepare blends for plant processing with satisfied property specifications; (ii) crude processing in the refinery, which includes crude distillation, reforming, cracking, hydrotreating, blending, gas processing, sulfur recovering facilities, as well as refinery product blending and storage illustrated in Appendix A. Obviously, the supply chain management for a petroleum refinery should consider the simultaneous scheduling of front-end crude transfers and in-plant processing. Lots of published studies have addressed these two major sections, separately.

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Nomenclature

Indices

$c \in C$ Crude types
$k \in K$ Key components
$n \in N$ Global time events
$unt \in UNT$ All the units including parcels, tanks, and CDUs
$v \in V$ Vessels
i, i' General process streams
j Raw material feed of a plant
$p \in PP$ Product of a plant
m Component
s, s' Process streams
u, v, w Process units in refinery plant
ui , uo Virtual plant input and output units

Sets

C Set of crude oil types
$CT \subset UNT$ Set of charging tanks
$DU \subset UNT$ Set of distillation CDUs
$IU \subset UNT$ Set of units as input unit sources: $IU = P \cup ST \cup CT$
$IU_{ct} \subset IU$ Set of input sources for charging tank
$IU_{du} \subset IU$ Set of input sources for CDU
$IU_{st} \subset IU$ Set of input sources for storage tank
K Set of key components (e.g. sulfur concentration)
N Set of global time events
$OU \subset UNT$ Set of output units: $OU = ST \cup CT \cup DU$
$OU_{ct} \subset OU$ Set of output units for crudes from charging tanks
$OU_{p} \subset OU$ Set of output units for crudes from parcels
$OU_{st} \subset OU$ Set of output units for crudes from storage tanks
$P \subset UNT$ Set of crude parcels
P_v Set of crude parcels carried by vessel v
$SCT = ST \cup CT$ Union of storage and charging tank sets
$SCT*$ Set of malfunctioning tanks
$ST \subset UNT$ Set of storage tanks
$UNT = P \cup ST \cup CT \cup DU$ Set of all the units including parcels, tanks, and CDUs
V Set of vessels
I Process stream set
J Raw material feed set of a plant
PP Plant product set
M General component set
$S_{v,u}$ Special stream set defined as $S_{v,u} = \left\{ s | \text{the} s\text{-th stream that flow from} v \text{to} u \right\}$
$S_{u,w}$ Special stream set defined as $S_{u,w} = \left\{ s | \text{the} s\text{-th stream that flow from} u \text{ to } w \right\}$
$S_{v,uo}$ Special stream set defined as output from unit v
$S_{ui,w}$ Special stream set defined as feedstock to unit w
SF_j Stream set that contains the j-th plant feed
SO_p Stream set that contains the p-th plant output
V_u Unit set defined as $V_u = \left\{ v | \text{units that have streams flowing to} u \right\}$
W_u Unit set defined as $W_u = \left\{ w | \text{units that have streams flowing from} u \right\}$
V_{uo} Unit set defined as output units
W_{ui} Unit set defined as feedstock units
$UALL$ All the units of the plant
$UINV$ Inventory unit set
$UMIX$ Mixer set
$USEP$ Separator set
$UREA$ Reactor set
$UTIT$ Utility generation unit set

Parameters

BST Brine settling and removal time
ETT Extra transitional time (RPST time) since charging tank change when feed a distilation column
$SPG(c)$ Specific gravity of crude c
C^{cho} Changeover cost for a CDU switching different feeds

$C^{inv}(unt)$ Inventory management cost for storage and charging tanks
C^{sea} Sea waiting cost
C^{set} Set-up costs for crude transfers from vessels to storage tanks or from storage to charging tanks
C^{uld} Parcel unloading cost
$FD(unt)$ Total demand for crude mixture from $unt \in CT$ throughout the scheduling horizon
$F^{lo}(unt', unt)/F^{up}(unt', unt)$ Lower/upper bounds of flow rate from units unt' to unt
H Scheduling time horizon
$Inv^0(unt)$ Initial inventory of a parcel or tank $unt \in P \cup SCT$
$Inv^{lo}(unt)/Inv^{up}(unt)$ Minimum/maximum allowable inventories of tank $unt \in SCT$
$T^{arr}(v)$ Arrival time of vessel v
$V^{t,up}$ Upper bound of the total transferred crude volume for an operation
$f^{com}(c,k)$ Fraction of key component k in crude c
$f^{com,\ lo}(unt,k)/f^{com,\ up}(unt,k)$ Minimum/maximum allowable fractions of key component k in charging tank $unt \in CT$
$f^{vol,p}(unt,c)$ Volume fraction of crude c in a parcel $unt \in P$
$f^{vol,0}(unt,c)$ Initial volume fraction of crude c in a tank $unt \in SCT$
PAR_n Process air unit price
PET_n Electricity unit price
$PFD_{j,n}$ Unit price for the j-th plant feed during time event n
$PPO_{p,n}$ Unit price for the p-th plant product during time event n
$PV_{u,\ n}$ Unit price of inventory in unit u during time event n
$\mathbf{P}W\mathbf{A}_n$ Unit price vector of various process water
$\mathbf{P}S\mathbf{W}_n$ Unit price vector of various steams
$\mathbf{P}F\mathbf{G}_n$ Unit price vector of various fuel oils
$\mathbf{P}R\mathbf{C}_n$ Unit price vector of various catalysts
Δt Time interval between time event n and time event $n-1$
$\delta_{i,i'}$ Interactive coefficient between stream i and i'

Continuous variables
$cost$ Total operating costs during the scheduling time horizon
$Inv^{ct,k}(unt,k,n)$ Inventory of key component k in a charging tank $unt \in CT$ at the end of time event n
$Inv^{p}(unt,n)$ Total inventory of a parcel $unt \in P$ at the end of time event n
$Inv^{p,c}(unt,c,n)$ Inventory of crude c in a parcel $unt \in P$ at the end of time event n
$Inv^{sct}(unt,n)$ Total inventory of a tank $unt \in SCT$at the end of time event n
$Inv^{sct,c}(unt,c,n)$ Inventory of crude c inside a tank $unt \in SCT$ at the end of time event n
$T^{s}(unt', unt, n)$ Starting time of a crude transfer from units unt' to unt at time event n
$T^{e}(unt', unt, n)$ Ending time of a crude transfer from units unt' to unt at time event n
$TP^{s}(unt)$ Starting time of unloading a parcel$unt \in P$during the scheduling horizon
$TP^{e}(unt)$ Ending time of unloading a parcel$unt \in P$during the scheduling horizon
$TV^{s}(v)$ Starting time of unloading a vessel v during the scheduling horizon
$TV^{e}(v)$ Ending time of unloading a vessel v during the scheduling horizon
$V^{c}(unt', unt, c, n)$ Volume of crude c transferred from units unt' to unt at time event n
$F^{c}(unt, c, n)$ Flow rate of crude c transferred from all charging tanks to distillation CDUs unt at time event n
$V^{t}(unt', unt, n)$ Total volume transferred from units unt' to unt at time event n
$f^{vol,n}(unt,c,n)$ Volume fraction of crude c in a tank $unt \in SCT$ at the end of time event n
$PC_{u,n}$ Processing capability of unit u during time event n
$PC_{u,n}^{\min}, PC_{u,n}^{\max}$ Lower and upper bounds for processing capability of u during time event n
$Cost\_FD_n$ Total cost for plant feedstock purchase during time event n
$Cost\_UD_n$ Total cost for plant utility purchase during time event n
$Cost\_OP_n$ Total operational cost for front-end crude oil transfer during time event n
f_i Flow rate of the i-th input stream to a mixer
fo Out flow rate of a mixer
$\mathbf{f}$ Flow rate vector defined as $\mathbf{f} = [\ldots\ , f_i\ ,\ \ldots]^T, \forall\ i \in I$
$F_{v,s,u,n}$ Flow rate of the s-th stream from v to u during time event n
$F_{u,s,w,n}$ Flow rate of the s-th stream from u to w during time event n
$F_{v,s,uo,n}$ Flow rate of output from unit$v$ during time event n
$F_{ui,s,w,n}$ Flow rate of feedstock to unit w during time event n
$F_{u,s,uo,n}$ Flow rate of the output waste steam from u during time event n
$FD_{j,\ n}$ Flow rate of the j-th plant feed during time event n
$FD_{j,n}^{\min}, FD_{j,n}^{\max}$ Lower and upper flow rate bounds of the j-th plant feed during time event n
$FP_{p,\ n}$ Flow rate of the p-th plant product during time event n
$FP_{p,n}^{\min}, FP_{p,n}^{\max}$ Lower and upper flow rate bounds of p-th plant product during time event n
$IV_{u,\ n}$ Inventory amount in unit u during time event n
$IV_{u,\ n}^{\min}, IV_{u,\ n}^{\max}$ Lower and upper limits of the inventory in unit u during time event n

$\Delta IV_{u,\ n}$ Inventory value increment
$\mathbf{Pam}_{u,n}$ Vector of operating parameters for unit u during time event n
$Sale\_PO_n$ Total sale value of plant products produced during time event n
$Sale\_UO_n$ Total sale value of plant utilities produced during time event n
$UAR^{in}_{u,n}, UAR^{out}_{u,n}$ Consumption and generation amount of process air for operating u during time event n
$UET^{in}_{u,n}, UET^{out}_{u,n}$ Consumed and generated amount of electricity for operating u during time event n
$\mathbf{UFG}^{in}_{u,n}, \mathbf{UFG}^{out}_{u,n}$ Consumed and generated fuel oil vectors for operating u during time event n
$\mathbf{URC}^{in}_{u,n}, \mathbf{URC}^{out}_{u,n}$ Consumed and generated catalyst vectors for operating u during time event n
$\mathbf{USW}^{in}_{u,n}, \mathbf{USW}^{out}_{u,n}$ Consumed and generated steam vectors for operating u during time event n
$\mathbf{UWA}^{in}_{u,n}, \mathbf{UWA}^{out}_{u,n}$ Consumed and generated process water vectors for operating u during time event n
$x^{\rho}_i, xo^{\rho}, x^{\rho}_{v,s,u,n}$ Density-based stream properties of the i-th stream, mixer output stream, and the s-th stream from v to u during time event n, respectively
$x^{v}_i, xo^{v}, x^{v}_{v,s,u,n}$ Volume-based stream properties of the i-th stream, mixer output stream, and the s-th stream from v to u during time event n, respectively
$x^{w}_i, xo^{w}, x^{w}_{v,s,u,n}$ Weight-based stream properties of the i-th stream, mixer output stream, and the s-th stream from v to u during time event n, respectively
$x^{sv}_i, xo^{sv}, x^{sv}_{v,s,u,n}$ Special volume-based stream properties of the i-th stream, mixer output stream, and the s-th stream from v to u during time event n, respectively
$x^{iv}_i, xo^{iv}, x^{iv}_{v,s,u,n}$ Interactive volume-based stream properties of the i-th stream, mixer output stream, and the s-th stream from v to u during time event n, respectively
$\mathbf{x}$ Property vector defined as $\mathbf{x} = [\ \ldots\ ,\ \mathbf{x}_i\ ,\ \ldots]^T, \forall\ i \in I$
$\mathbf{x}_i$ Property vector of the i-th input stream, defined as $\mathbf{x}_i = \left[x^{\rho}_i,\ x^{v}_i,\ x^{w}_i,\ x^{sv}_i,\ x^{iv}_i,\ \mathbf{z}_i\right]^T$
$\mathbf{x}o$ Property vector of a mixer output stream, defined as $\mathbf{x}o = \left[xo^{\rho},\ xo^{v},\ xo^{w},\ xo^{sv},\ xo^{iv}\ ,\ \mathbf{z}o\right]^T$
$\mathbf{X}_{v,s,u,n}$ Property vector of the s-th stream from v to u during time event n, defined as $\mathbf{X}_{v,s,u,n} = \left[x^{\rho}_{v,s,u,n},\ x^{v}_{v,s,u,n},\ x^{w}_{v,s,u,n},\ x^{sv}_{v,s,u,n},\ x^{iv}_{v,s,u,n},\ \mathbf{z}_{v,s,u,n}\right]^T, \forall\ s \in S_{v,u}$
$\mathbf{X}_{u,s,w,n}$ Property vector of the s-th stream from u to w during time event n, defined as $\mathbf{X}_{u,s,w,n} = \left[x^{\rho}_{u,s,w,n},\ x^{v}_{u,s,w,n},\ x^{w}_{u,s,w,n},\ x^{sv}_{u,s,w,n},\ x^{iv}_{u,s,w,n},\ \mathbf{z}u_{u,s,w,n}\right]^T, \forall\ s \in S_{u,w}$
$\mathbf{X}_{v,s,uo,n}$ Property vector of the s-th stream from v during time event n
$\mathbf{X}_{ui,s,w,n}$ Property vector of the s-th stream to w during time event n
$\mathbf{XD}_{j,n}$ Property vector of the j-th plant feed during time event n
$\mathbf{XP}_{p,n}$ Property vector of the p-th plant product during time event n
$\mathbf{XV}_{u,\ n}$ Property vector of inventory in unit u during time event n
$z^m_i, z^m_{v,s,u,n}$ The m-th component composition of the i-th input stream and the s-th stream from v to u during time event n, respectively
$zo^m, z^m_{u,s,w,n}$ The m-th component composition of the a mixer output stream and the s-th stream from u to w during time event n, respectively
$\mathbf{z}_i$ Component composition vector of the i-th input stream; defined as $\mathbf{z}_i = [\ldots\ ,\ z^m_i,\ \ldots], \forall\ m \in M$
$\mathbf{z}o$ Component composition vector of a mixer output stream; defined as $\mathbf{z}o = [\ldots\ ,\ zo^m,\ \ldots], \forall\ m \in M$
$\mathbf{z}_{v,s,u,n}$ Component composition vector of the s-th stream from v to u during time event n; defined as $\mathbf{z}_{v,s,u,n} = [\ldots\ ,\ z^m_{v,s,u,n},\ \ldots], \forall\ m \in M$
$\mathbf{z}_{u,s,w,n}$ Component composition vector of the s-th stream from u to w during time event n; defined as $\mathbf{z}_{u,s,w,n} = [\ldots\ ,\ z^m_{u,s,w,n},\ \ldots], \forall\ m \in M$
$\mathbf{UI}_{u,n}$ Utility input vector of unit u during time event n; defined as $\mathbf{UI}_{u,n} = \left[UET^{in}_{u,n},\ UAR^{in}_{u,n},\ \mathbf{UWA}^{in}_{u,n},\ \mathbf{USW}^{in}_{u,n},\ \mathbf{UFG}^{in}_{u,n},\ \mathbf{URC}^{in}_{u,n}\right]^T$
$\mathbf{UI}_{ui,\ n}$ Vector of purchased utilities by a plant during time event n
$\mathbf{UI}^{\min}_{ui,n},\ \mathbf{UI}^{\max}_{ui,n}$ Lower and upper bounds of purchased utility in a plant
$\mathbf{UO}_{u,n}$ Utility output vector of unit u during time event n; defined as $\mathbf{UO}_{u,n} = \left[UET^{out}_{u,n},\ UAR^{out}_{u,n},\ \mathbf{UWA}^{out}_{u,n},\ \mathbf{USW}^{out}_{u,n},\ \mathbf{UFG}^{out}_{u,n},\ \mathbf{URC}^{out}_{u,n}\right]^T$
$\mathbf{UO}_{uo,\ n}$ Vector of generated utilities by a plant during time event n
$\mathbf{UO}^{\min}_{uo,n},\ \mathbf{UO}^{\max}_{uo,n}$ Lower and upper bound vectors of utility generation in a plant during time event n
$\mathbf{\Omega F}_{v,u,n}$ Flow rate vector for all streams from v to u during time event n, defined as $\mathbf{\Omega F}_{v,u,n} = [\ \ldots,\ F_{v,s,u,n}\ ,\ \ldots]^T, \forall\ s \in S_{v,u}$
$\mathbf{\Omega X}_{v,u,n}$ Property vector for all streams from v to u during time event n, defined as $\mathbf{\Omega X}_{v,u,n} = [\ \ldots\ ,\ \mathbf{X}_{v,s,u,n},\ \ldots]^T, \forall\ s \in S_{v,u}$
$\mathbf{\Psi F}_{u,n}$ Input flow rate vector of u during time event n, $\mathbf{\Psi F}_{u,n} = \left[\ldots\ ,\ \mathbf{\Omega F}_{v,u,n}\ ,\ \ldots\right]^T, \forall\ v \in V_u$
$\mathbf{\Psi X}_{u,n}$ Input property vector of u during time event n, $\mathbf{\Psi X}_{u,n} = \left[\ldots\ ,\ \mathbf{\Omega X}_{v,u,n}\ ,\ \ldots\right]^T, \forall\ v \in V_u$
$\mathbf{\Gamma F}_{u,n}$ Output flow rate vector of u during time event n, $\mathbf{\Gamma F}_{u,n} = \left[\ldots\ ,\ \mathbf{\Omega F}_{u,w,n}\ ,\ \ldots\right]^T, \forall\ w \in W_u$
$\mathbf{\Gamma X}_{u,n}$ Output property vector of u during time event n, $\mathbf{\Gamma X}_{u,n} = \left[\ldots\ ,\ \mathbf{\Omega X}_{u,w,n}\ ,\ \ldots\right]^T, \forall\ w \in W_u$

Binary variables
$X(unt', unt, n)$ It is 1 if a unit unt' transfers crudes to another unit unt during time event n; otherwise, it is zero
$Bpe(unt, n)$ It is 1 if a parcel $unt \in P$ is completely unloaded at the end of time event n; otherwise, it is zero
$Z(unt', unt, n)$ It is 1 if a switchover of charging tanks $unt' \in CT$ occurs on a CDU $unt \in DU$ from time event n to $n+1$; otherwise, it is zero

$ZZ(unt', unt, n)$ It is 1 if a switchover of charging tanks $unt' \in CT$ occurs on a CDU $unt \in DU$ from time event n to $n+1$ and this tank is charging this CDU at time event n; otherwise, it is zero
$y_{u,n}$ Binary variable, it is 1 if u is in operation; otherwise, it is 0
$yd_{j,n}$ Binary variable, it is 1 if the j-th feed is purchased; otherwise, it is 0
$yp_{p,n}$ Binary variable, it is 1 if the p-th product is produced; otherwise, it is 0

Special functions
$\gamma(\cdot)$ Index approximation function of nonlinear property
$\chi_{u,n}(\cdot)$ Capacity calculating function for unit u during time event n
$\boldsymbol{\theta}(\cdot)$ Property mixing function
$\varphi_{u,n}(\cdot)$ Product flow rate distribution function for unit u during time event n
$\boldsymbol{\mu}_{u,n}(\cdot)$ Product property distribution function for unit u during time event n
$\boldsymbol{\tau}_{u,n}(\cdot)$ Calculating function for utility consumption for unit u during time event n
$\boldsymbol{\kappa}_{u,n}(\cdot)$ Calculating function for utility generation for running u during time event n

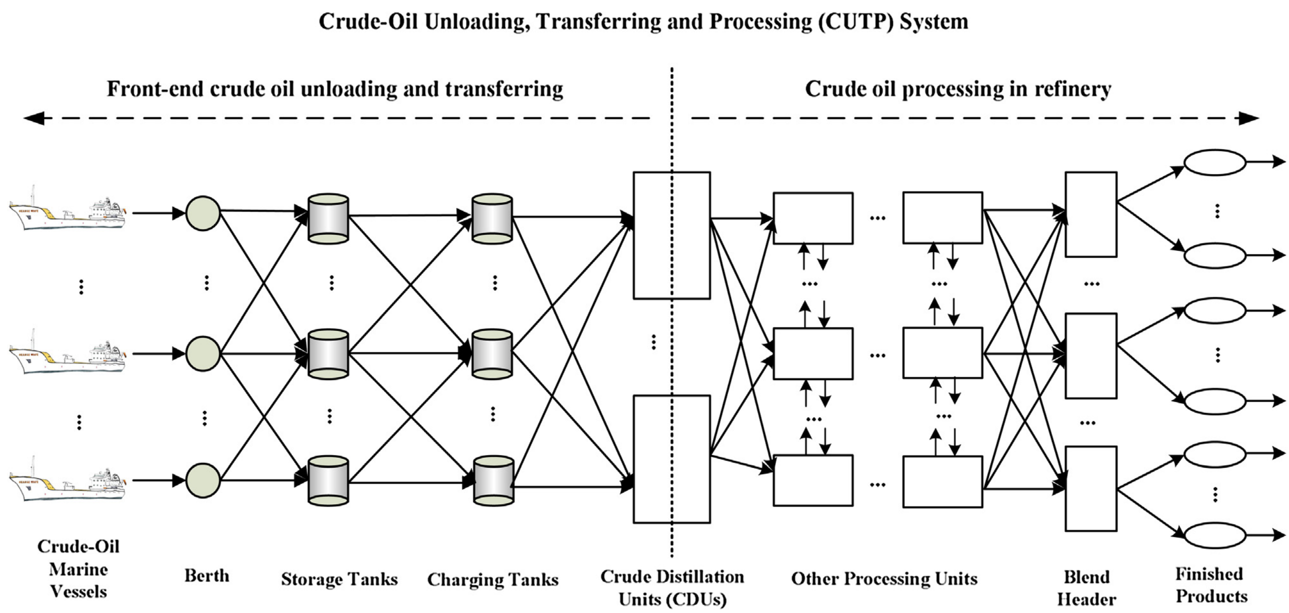

Fig. 1. Illustrative scheduling scope of the studied CUTP system.

There are two main categories of scheduling formulations for front-end crude scheduling: discrete-time and continuous-time formulations. For the crude scheduling with discrete-time formulations, Shah presented a discrete-time MILP (mixed-integer linear programming) model to address the production-driven crude oil scheduling (Shah, 1996). A decomposition approach was utilized to break the whole problem, which includes crude oil loading and unloading problems into upstream and downstream. Li et al. also proposed an MINLP (mixed-integer nonlinear programming) crude oil scheduling model based on discrete-time intervals for both inland and marine-access refineries (Wenkai et al., 2002). Lee et al. minimized operational costs for inland refineries by formulating a discrete-time based MILP model via linearization of bi-linear crude blending constraints (Lee et al., 1996). Reddy et al. pioneered the investigations on a new discrete-time model by using hybrid definition of time intervals, which includes various realistic operational features such as brine settling time, multi-parcel vessels, multiple jetties, and multi-tank feeding one or more CDUs (Reddy et al., 2004a,b).

For the continuous-time category, Ierapetritou and Floudas proposed a novel continuous-time formulation for short-term scheduling problems, which decoupled the task events from the unit events (Ierapetritou and Floudas, 1998a,b). Jia et al. used the continuous-time method to build an MILP scheduling model for inland refineries with both storage and charging tanks, in which non-linear constraints were relaxed to generate an MILP model (Jia et al., 2003; Jia and Ierapetritou, 2004). However, their material balance constraints only considered key components rather than individual crudes, and some important realistic operational features were not considered. Similarly, Reddy et al. presented continuous-time formulation for crude oil scheduling of refineries incorporating those real characteristics, including SBM station, multi-parcel vessels, brine settling, and multi-tank feeding one or more columns (Reddy et al., 2004a,b). An iterative algorithm was adopted to eliminate the crude composition discrepancy problem. Li et al. solved the developed scheduling model with a global optimization algorithm and considered 15 volume and weight based property indices that are linearly additive for marine-access refineries (Li et al., 2012). Besides all realistic characteristics mentioned above, Zhang et al. proposed an effective two-stage reactive scheduling methodology for short-term crude oil operations to manage crude movements from ship unloading to distillation processing under various uncertainties, such as shipping delay, crude mixture demand change, and tank unavailability (Zhang and Xu, 2014).

Refinery production scheduling addresses in-plant crude oil processing, which is also an important part of petroleum supply-chain management (Sear, 1993; Escudero et al., 1999; Dempster et al., 2000). Mendez et al. proposed a simultaneous optimization approach for blending and scheduling of refinery plant, which could be either a discrete or continuous formulation (Méndez et al., 2006). An iterative procedure is proposed to deal with non-linear gasoline properties and variable recipes to preserve the model's linearity. Thus, the solution of a very complex MINLP formulation is replaced by a sequential MILP approximation. Pinto et al. presented a general modeling framework for petroleum supply chain optimization (Pinto et al., 2000; Joly et al., 2002). The model framework could integrate oilfield, crude oil supply, petroleum processing, and products distribution models into a large supply-chain model. An integrated optimization model of refinery production has been proposed by Zhao et al. to decompose the integrated model of the two systems into a MILP model and a NLP model, which are then solved iteratively through variables transferring to further reduce the solution time (Zhao et al., 2015). Zhang et al. developed a general MINLP model to address the optimal crude oil blending and purchase planning in refinery plants under the uncertainty of crude oil shipping delays (Zhang et al., 2012). Very recently, a large-scale MILP model for strategic planning optimization was proposed by Elia et al. for a network of natural gas to liquids (GTL) systems, which was solved by a rolling horizon strategy (Elia et al., 2015). Meanwhile, Gao et al. studied refinery scheduling by employing a piecewise linear (PWL) partitioning and modeling strategy to help solve the original MINLP problem (Gao et al., 2015).

Due to the complexity of normal scheduling models, to apply large-scale scheduling models efficiently and effectively in reality, Kelly and his associates proposed hierarchical decomposition methods based on heuristic rules (Kelly, 2003; Kelly and Zyngier, 2008). To solve large-scale scheduling models efficiently, great efforts have been made on effective solution approaches like iterative decomposition algorithm, discretization approach, and improved rolling horizon algorithms. As demonstrated, iterative decomposition algorithms may fail to obtain a feasible solution even there exist many (Wenkai et al., 2002). The discretization approach approximates the MINLP problem into an MILP problem, which significantly increases the problem size and thus, cannot be generalized to industrial size problems (Moro and Pinto, 2004). Similarly, the improved version of rolling horizon algorithms equipped with intelligent strategies still cannot prove the global optimality of solutions (Li et al., 2007). Bilinear terms often exist in MINLP models for crude scheduling due to the presence of blending constraints. To efficiently solve large-scale systems without compromising problem complexity, outer-approximation (OA) algorithms and logic-based approaches have been developed. OA algorithms were investigated by Duran and Grossmann for convex MINLP problems in 1986 (Duran and Grossmann, 1986). Karuppiah et al. proposed an extended OA algorithm to accomplish global optimization of crude scheduling problems for inland refineries (Karuppiah et al., 2008). Also, a new continuous-time crude scheduling model has been developed by Zhang et al. to address the long-distance pipeline transportation and other realistic considerations for crude unloading using an OA-based iterative algorithm (Zhang and Xu, 2015).

It should be highlighted that the systematic study for simultaneous scheduling of front-end crude oil transfer and refinery operations is still lacking based on our conducted literature survey. On one hand, this presents a potential opportunity to improve the refinery profitability if the front-end crude oil transfer and refinery processing could be optimally integrated, because the two sections are inherently connected in the refinery supply-chain management. On the other hand, it also suggests the big challenge of the simultaneous scheduling initiative due to the tremendous complexity of development and integration of two different large-scale models.

In this paper, a systematic methodology for simultaneous scheduling of front-end crude transfer and refinery processing has been developed. It provides a large-scale continuous scheduling model to optimize crude unloading, transferring, and processing (CUTP) to simulate and optimize the front-end and refinery crude-oil operations simultaneously. The CUTP model consists of a newly developed refinery processing sub model, a crude processing status transition sub-model, and a borrowed front-end crude transferring sub model (Zhang and Xu, 2014). The objective of the proposed CUTP model is to maximize the total operational profit; meanwhile, operation and product specifications, inventory limits, and production demands have to be satisfied. The scheduling model is a large-scale mixed integer nonlinear programming problem (MINLP). An outer-approximation based decomposition method is implemented to obtain the optimal solution of the developed MINLP scheduling model. The efficacy of the proposed scheduling model has been demonstrated by an industrial-scale case study.

2. Problem statement

The scope of the studied CUTP scheduling process has been illustrated in Fig. 1. To help better understand the developed continuous-time methodology, several important terminologies in this study need to be clarified.

Time event: In this paper, the unit-to-unit time event is defined for point-to-point operations including crude unloading, transferring, and processing. To align time events on a continuous time base, any input/output operations associated with a unit at time event n occurs earlier than those arranged at time event $n+1$. Thus, the operating time window of event n for a unit will be determined by its scheduled input/output operations at time event n. In other words, the time event can be regarded as an "*identifier*" that facilitates the alignment of different activities along the scheduling time horizon. The more detailed explanation for time event can be found from the previous paper (Zhang et al., 2015).

Refinery processing status transition (RPST): During the CUTP scheduling, the blend type of crudes from charging tanks fed to refinery CDUs may change associated with different time events. The CDU feed type change will cause the refinery to have different operating statuses and production yields. Such a refinery processing status transition is called RPST. A RPST should take the whole refinery some time to complete the status transition, and it should satisfy crude mass balance during the transition. A fixed RPST time has been considered in our CUTP scheduling model.

Utility vectors: Most of refinery processing units will consume or generate utilities during their normal operations. Thus, utility vectors used in this paper represent utility consumptions and generations for an operating unit. They are functions of input and operating conditions of the associated unit. In this paper, six types of utilities are considered: electricity, process air, process water, various fuel oils or fuel gases, various catalysts, and steams.

Property vectors: Properties of a process stream are represented by a vector characterizing all the concerned physical and chemical features. In this paper, a property vector includes density-based, volume-based, and weight-based oil qualities, as well as component compositions.

The studied CUTP scheduling problem is summarized below:

Given information:

(1) Detailed CUTP configurations including process units/facilities and their connecting structures of the front-end crude transfer section and the refinery processing section. Note that major process facilities of a refinery have been illustrated by Appendix A.
(2) Initial operating status and process specifications of each CUTP units/facilities, such as tank capacities, crude transfer rate limits, and feed/product quality constraints of major refinery facilities;
(3) Crude shipping information including number of vessels, crude types and volumes of each crude parcel, and vessel arrival time;
(4) Properties of crude oils and blending products including densities, sulfur contents, light oil yields, and segregation policies such as property index ranges;
(5) Economic data including demurrage cost (tanker waiting cost), unloading cost, CDU changeover cost, utility costs, front-end tank set-up and inventory costs, and prices of crude oils, utilities, and refinery products.

Information to be determined:

(1) A detailed unloading schedule for each vessel, including information of transfer connections, timings, and volumes;
(2) A detailed crude transfer schedule from storage tanks to charging tanks and from charging tanks to refinery CDUs, including transfer connections, timings, volumes, and properties;
(3) Inventory and crude composition profiles at each storage and charging tanks;
(4) Operating schedules of various refinery processing facilities;
(5) Detailed refinery product quantity and quality profiles;
(6) CUTP economic results including front-end crude unloading, transferring, and storage costs, refinery processing costs, refinery product revenue, and total profit.

Operating constraints:

(1) A parcel can be unloaded to at most one storage tank at a time event; however, it can be unloaded into multiple tanks across consecutive time events;
(2) A storage or charging tank cannot simultaneously receive and send out crudes;
(3) A charging tank can feed at most one refinery CDU and a CDU can receive at most one feed from the charging tank at a time event;
(4) Properties of crudes fed to refinery CDUs should satisfy certain requirements;
(5) Refinery final products after blending operations should satisfy certain quality requirements.

Assumptions:

(1) Perfect mixing is assumed in crude storage and charging tanks as well as refinery blend headers;
(2) A fixed value of RPST time is assumed in the CUTP scheduling model.

3. Methodology framework

Fig. 2 gives the general framework of the developed CUTP scheduling methodology. Generally, the methodology starts from collecting economic, process, and initial operating data for the studied CUTP problem. Based on the collected data, a continuous time CUTP scheduling model will be developed. The model contains three parts: (i) front-end crude transfer model, (ii) RPST model, and (iii) refinery crude processing model. Among these three sub models, the front-end crude transfer model is mainly borrowed from Zhang and Xu with modest modifications (Zhang and Xu, 2014); the other two sub models are developed by this work. Details of the CUTP model will be illustrated in the next section.

After the CUTP scheduling model has been developed, it will be solved with an OA based decomposition method to generate a solution. Next, comprehensive analysis based on the scheduling results will be conducted to check the solution feasibility. Under the circumstance that any discrepancies occur, troubleshooting will be carried on to double check or refine the data collection, CUTP modeling and solving activities. Such troubleshooting may lead to multiple interactions among data, modeling, and solving stages until a final optimal solution for the studied CUTP problem has been identified. Note that to accommodate various design and operation modifications, the CUTP scheduling model should be developed in general and well structuralized, such that the expense of time and efforts for the model refinement can be saved to the maximum extent.

4. CUTP scheduling model

The whole scheduling model can be separated into three parts: (i) a front-end crude oil transfer model, which include equations and constraints covering crude movement from vessels to portside storage tanks, inland charging tanks, and refinery CDUs; (ii) a RPST model, which addresses issues of transitional time and mass balance because of the refinery operating status change associated with different refinery feeds; (iii) a refinery crude processing model, which addresses the detailed processing strategy based on the given input of crude blends.

4.1. Front-end crude transfer model

The front-end crude transfer scheduling model is mainly borrowed from one of the previous study (Zhang and Xu, 2014) with modest modifications. It involves integrality constraints for operating practices; logic constraints; transportation and capacity constraints; time

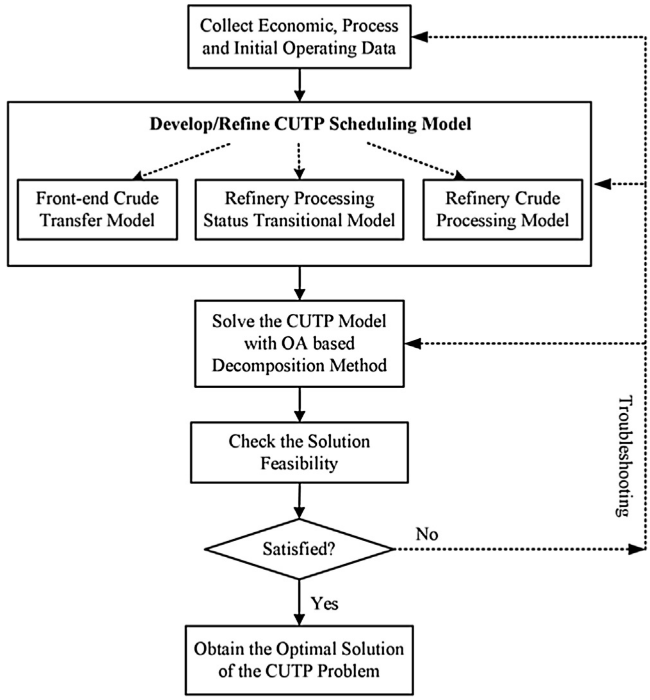

Fig. 2. General methodology framework.

constraints for vessels, parcels unloading, storage and charging tanks; and material balance constraints for crude parcels and tanks; as well as variable upper and lower bounds. Since the integrated crude scheduling model is very complicated, for conciseness, only those newly developed model equations from this study are elaborated in the following section. The detailed front-end crude scheduling model constraints similar to the previous study are summarized as Appendix B.

4.2. RPST model

4.2.1. Time constraints for CDUs

As described by Eqs. (1) and (2), if there is no crude changeover for a CDU, the starting time of charging operations at time event n + 1 will immediately follow the ending time of scheduled charging operations at time event n. Otherwise, a crude changeover does occur at time event *n*, which means the crude blend type changes at time event *n*, a RPST time should be given to allow the refinery facilities adjusting their processing statuses to reach a new steady state. In this paper, such a RPST time (*ETT*) is assumed as a fixed value. Note that the CDU must be continuously operated during the entire scheduling time horizon (*H*) as shown in Eq. (3). Eq. (4) expresses that the starting time of any charging operations to a CDU at a later time event (n′) should be arranged after the ending time of scheduled charging operations at an earlier time event n (n < n′).

$$T^s(unt', unt, n+1) \geq T^e(unt'', unt, n) - H(1 - X(unt'', unt, n)) + ETT * ZZ(unt'', unt, n) \forall unt', unt'' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (1)$$

$$T^s(unt', unt, n+1) \leq T^e(unt'', unt, n) - H(1 - X(unt'', unt, n)) + ETT * ZZ(unt'', unt, n) \forall unt', unt'' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (2)$$

$$\sum_{unt' \in IU_{du}} \sum_{n \in N, n \geq 1} \left(T^e(unt', unt, n) - T^s(unt', unt, n) + ETT * ZZ(unt', unt, n)\right) = H \, \forall unt \in DU \quad (3)$$

$$T^s(unt', unt, n') \geq T^e(unt'', unt, n) - H(1 - X(unt'', unt, n)) + ETT * ZZ(unt'', unt, n) \forall unt', unt'' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < n' \quad (4)$$

4.2.2. Refinery changeover constraints

As shown in Eqs. (5) and (6), a new *0–1* continuous variable $Z(unt', unt, n)$ is defined to denote whether or not a refinery switches feeds between charging tanks from n to $n+1$.

$$Z(unt', unt, n) \geq X(unt', unt, n) - X(unt', unt, n+1) \forall unt' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (5)$$

$$Z(unt', unt, n) \geq X(unt', unt, n+1) - X(unt', unt, n) \forall unt' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (6)$$

Another new *0-1* continuous variable $ZZ(unt', unt, n)$ is specially defined to denote whether there is a changeover at time event n ($ZZ(unt', unt, n) = 1$) or not (equal to 0). This means a CDU switches feeds between charging tanks from n to $n+1$; in the meantime, the transfer of crude between this charging tank and this CDU does exist at time event n. In fact, $Z(unt', unt, n)$ and $X(unt', unt, n)$ will determine the value of $ZZ(unt', unt, n)$. Their logic relation is that $Z(unt', unt, n) = 1$ and $X(unt', unt, n) = 1$ will result in $ZZ(unt', unt, n) = 1$. To formulate this rationale, Eqs. (7) through (9) are formed. Consequently, this variable of $ZZ(unt', unt, n)$can be incorporated into the objective function to calculate the refinery changeover cost.

$$ZZ(unt', unt, n) \geq Z(unt', unt, n) - X(unt', unt, n) \forall unt' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (7)$$

$$ZZ(unt', unt, n) \leq Z(unt', unt, n) \forall unt' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (8)$$

$$ZZ(unt', unt, n) \leq 1 - X(unt', unt, n) \forall unt' \in IU_{unt}; unt \in DU; n \in N, 1 \leq n < |N| \quad (9)$$

4.2.3. Volume to mass conversion for refinery feed

It should be noted that our front-end crude transfer model is volume based model; while the refinery crude processing model is mass based model. Thus, the conversion from volume to mass of the refinery feed should be performed at the CDU inlet. Eq. (10) gives the amount of crude c transferred from all charging tanks to each distillation CDU at time event n, which is equal to the product of specific gravity of crude c and the summation of transferred crude volumes from individual charging tanks at time event n. For example, the amount of crude 1 transferred to CDU 1 at time event n is equal to the specific gravity of crude 1 multiplying the summation over volumes of crude 1 transferred from all charging tanks at this time event.

$$F^c(unt, c, n) = SPG(c) \sum_{unit' \in CT} V^c(unt', unt, c, n), \forall unt \in DU; c \in C \quad (10)$$

4.2.4. CDU capacity constraints

As shown in Eqs. (11) and (12), if a charging tank is feeding a CDU, the total volume transferred will be constrained by the product of flow rate lower/upper bounds and the time durations used for transfer in which RPST time (*ETT*) is included; Otherwise, the constraints will be relaxed.

$$\begin{aligned} &F^{lo}(unt', unt)(T^e(unt', unt, n) - T^s(unt', unt, n)) - F^{lo}(unt', unt)H(1 - X(unt', unt, n)) \\ &+F^{lo}(unt', unt)(ETT * ZZ(unt', unt, n)) \leq V^t(unt', unt, n), \quad \forall unt' \in IU_{du}; unt \in DU; n \in N, n \geq 1 \end{aligned} \quad (11)$$

$$\begin{aligned} &V^t(unt', unt, n) \leq F^{up}(unt', unt)(T^e(unt', unt, n) - T^s(unt', unt, n)) + F^{up}(unt', unt)H(1 - X(unt', unt, n)) \\ &+F^{up}(unt', unt)(ETT * ZZ(unt', unt, n)), \forall unt' \in IU_{du}; unt \in DU; n \in N, n \geq 1 \end{aligned} \quad (12)$$

4.3. Refinery crude processing model

4.3.1. General description

A typical production unit has general input-output relations. From the definition, $F_{v,s,u,n}$ and $\mathbf{X}_{v,s,u,n}$ represent flow rate and property of the s-th stream flowing from unit v to unit u during time event n; By aggregation of all $F_{v,s,u,n}$ with respect to s, the vector of $\mathbf{\Omega F}_{v,u,n}$ represents flow rate vector from v to u. Similarly, by aggregation of all $\mathbf{X}_{v,s,u,n}$ with respect to$s$, the property vector of $\mathbf{\Omega X}_{v,u,n}$ will be defined. If all $\mathbf{\Omega F}_{v,u,n}$ and $\mathbf{\Omega X}_{v,u,n}$ are further aggregated respectively to every$v$, the vectors of $\mathbf{\Psi F}_{u,n}$ and $\mathbf{\Psi X}_{u,n}$ are defined, respectively. Note that $\mathbf{\Psi F}_{u,n}$ and $\mathbf{\Psi X}_{u,n}$ contain all inflow feed information of unit u, where process topology information are actually embedded. Similarly, $\mathbf{\Gamma F}_{u,n}$ and $\mathbf{\Gamma X}_{u,n}$ can be defined, which represent outflow product information of unit u.

Note that most of processing units will consume or generate utilities during their normal operations. Thus, vectors of $\mathbf{UI}_{u,n}$ and $\mathbf{UO}_{u,n}$ represent utility consumptions and generations for operating unit u. They are actually functions of input and operation conditions described by $\boldsymbol{\tau}_{u,n}(\cdot)$ and $\boldsymbol{\kappa}_{u,n}(\cdot)$, respectively. In this paper, six types of utilities are considered. They include electricity, process air (e.g., nitrogen), various process water (e.g., cooling water and the deoxygenated water), various fuel oils or fuel gases, various catalysts, and various grades of steams.

In a refinery scheduling model, stream property (quality) information is as important as flow rate (quantity) information. Since mixing occurs during several typical unit operations, a general property mixing module will be given first. After that, typical unit models including mixer, reactor, separator, plant feedstock, plant output, inventory, and utility generator models, as well as utility balance constraints will be presented, respectively.

4.3.2. Property mixing functions

A stream property is represented by a vector characterizing all the concerned physical and chemical features. In this paper, a property vector contains density-based, volume-based, and weight-based oil qualities, as well as component compositions. Obviously, the property of outflow stream is determined by inflow flow rates and their properties, which can be represented by Eq. (13).

$$\mathbf{x}o = \boldsymbol{\theta}(\mathbf{f}, \mathbf{x}) \tag{13}$$

Eq. (13) contains several property functions, which are quantitatively described by Eqs. (14) through (20).

$$fo = \sum_{i \in I} f_i \tag{14}$$

$$xo^{\rho} = \frac{\sum_{i \in I} f_i}{\sum_{i \in I} \frac{f_i}{x_i^{\rho}}} \tag{15}$$

$$xo^{v} = \frac{\sum_{i \in I} \left(\frac{f_i \quad x_i^{v}}{x_i^{\rho}} \right)}{\frac{\sum_{i \in I} f_i}{xo^{\rho}}} \tag{16}$$

$$xo^{w} = \frac{\sum_{i \in I} \left(f_i \quad x_i^{w} \right)}{\sum_{i \in I} f_i} \tag{17}$$

$$xo^{sv} = \gamma^{-1} \left(\frac{\sum_{i \in I} \left[\frac{f_i}{x_i^{\rho}} \quad \gamma\left(x_i^{v}\right) \right]}{\frac{fo}{xo^{\rho}}} \right) \tag{18}$$

$$xo^{iv} = \frac{\sum_{i \in I} \left(\frac{f_i \quad x_i^{v}}{x_i^{\rho}} \right) + \sum_{i \in I} \sum_{i' \in I, i' \neq i} \left(\delta_{i,i'} \quad \frac{f_i}{x_i^{\rho}} x_i^{v} \quad \frac{f_{i'}}{x_{i'}^{\rho}} x_{i'}^{v} \quad \left(\frac{xo^{\rho}}{fo} \right) \right)^2}{\frac{fo}{xo^{\rho}}} \tag{19}$$

$$zo^{m} = \frac{\sum_{i \in I} \left(f_i z_i^{m} \right)}{\sum_{i \in I} f_i}, \forall m \in M \tag{20}$$

where fo is the outlet flow rate of the mixer, f_i is the inlet flow rates of the mixer; xo^{ρ} and x_i^{ρ} in Eq. (15) are densities of the outflow and inflows; xo^{v} and x_i^{v} in Eq. (16) are volume-based properties (such as olefin content) of the outflow and inflows; xo^{w} and x_i^{w} in Eq. (17) are weight based properties (such as sulfur content); xo^{sv} is special volume-based property (e.g., pour point of diesel), which is given by Eq. (18). In this equation, a volume-based property needs to be projected to some quality index at first through a special function of γ. After some calculation procedure, the result should be retrieved back through the inverse function of γ. Another special type of property calculation involves interactive factors among input streams. Eq. (19) gives the formula for calculating interactive volume-based property xo^{iv} (e.g., octane number of gasoline). Finally, Eq. (20) shows calculation formula for outflow component compositionszo^{m}.

4.3.3. Unit models

4.3.3.1. Mixing unit model. Based on the above representation scheme, a general mixing unit model can be described by Eq. (21) for mass balance and Eq. (22) for outflow property identification. The property distribution is described by the property mixing functions and mixing unit model.

$$\sum_{v \in V_u} \sum_{s \in S_{v,u}} F_{v,s,u,n} = \sum_{w \in W_u} \sum_{s \in S_{u,w}} F_{u,s,w,n}, \forall u \in UMIX \tag{21}$$

$$\boldsymbol{X}_{u,s,w,n} = \boldsymbol{\theta}(\boldsymbol{\Psi F}_{u,n}, \boldsymbol{\Psi X}_{u,n}), \forall s \in S_{u,w}, \forall w \in W_u \tag{22}$$

where $F_{v,s,u,n}$ are flow rates of inlet streams of the unit u; $F_{u,s,w,n}$ are flow rates of outlet streams of the unit u; $\boldsymbol{\theta}(\cdot)$ has been defined by the property mixing function. $\mathbf{X}_{u,s,w,n}$ denotes properties of outlet streams of unit u. $\mathbf{\Psi F}_{u,n}$ denotes flow rates of all the inlet streams. $\mathbf{\Psi X}_{u,n}$ denotes properties of all the inlet streams. $\mathbf{UI}_{u,n}$ and $\mathbf{UO}_{u,n}$ of a mixing unit will be zero.

4.3.3.2. Reactor model. A general reactor model is described in Eqs. (23) through (29).

$$\sum_{v\in V_u}\sum_{s\in S_{v,u}} F_{v,s,u,n}=\sum_{w\in W_u}\sum_{s\in S_{u,w}} F_{u,s,w,n},\forall u\in UREA \tag{23}$$

$$\boldsymbol{\Gamma F}_{u,n}=\varphi_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in UREA \tag{24}$$

$$\boldsymbol{\Gamma X}_{u,n}=\boldsymbol{\mu}_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in UREA \tag{25}$$

$$PC_{u,n}=\chi_{u,n}(\boldsymbol{\Psi F}_{u,n},\ \boldsymbol{\Gamma F}_{u,n}),\forall u\in UREA \tag{26}$$

$$y_{u,n}PC_{u,n}^{\min}\le PC_{u,n}\le y_{u,n}PC_{u,n}^{\max},\forall u\in UREA \tag{27}$$

$$\boldsymbol{UI}_{u,n}=\boldsymbol{\tau}_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in UREA \tag{28}$$

$$\boldsymbol{UO}_{u,n}=\boldsymbol{\kappa}_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in UREA \tag{29}$$

where $\mathbf{\Psi F}_{u,n}$ denotes flow rates of all the inlet streams. $\mathbf{\Psi X}_{u,n}$ denotes properties of all the inlet streams. $\mathbf{Pam}_{u,n}$ denotes operating parameters (such as reaction temperature and pressure) of reactor u. $\mathbf{\Gamma F}_{u,n}$ denotes flow rates of all the outlet streams. $\mathbf{\Gamma X}_{u,n}$ denotes properties of all outlet streams. Eq. (23) describes the material balance; Eqs. (24) and (25) describe product flow rate distributions and property distributions after reaction. Since detailed reaction models should be developed case by case, for simplification, this paper only list a general form. It means the reaction outflow flow rate and property are function of input ($\mathbf{\Psi F}_{u,n}$ and $\mathbf{\Psi X}_{u,n}$) and operating strategy ($\mathbf{Pam}_{u,n}$). Eq. (26) identifies a processing capacity data $PC_{u,n}$, which is a function of all inflow rates of $\mathbf{\Psi F}_{u,n}$ and all outflow rates of $\mathbf{\Gamma F}_{u,n}$. The process capacity should be bounded by processing limits as described by Eq. (27). $PC_{u,n}^{\min}$ and $PC_{u,n}^{\max}$ are lower and upper limits of the processing capacity. $y_{u,n}$ is a binary variable that denotes whether or not the unit is in operation. Eqs. (28) and (29) describe the utility consumption of $\mathbf{UI}_{u,n}$ and utility generation of $\mathbf{UO}_{u,n}$, respectively.

4.3.3.3. Separator model. A general model for separator unit is described in Eqs. (30) through (37). Generally, the separator model is similar to the reactor model, except the component mass balance should be considered, which is highlighted in Eqs. (30) and (31).

$$\sum_{v\in V_u}\sum_{s\in S_{v,u}} F_{v,s,u,n}=\sum_{w\in W_u}\sum_{s\in S_{u,w}} F_{u,s,w,n},\forall u\in USEP \tag{30}$$

$$\sum_{v\in V_u}\sum_{s\in S_{v,u}}\left(F_{v,s,u,n}z_{v,s,u,n}^{m}\right)=\sum_{w\in W_u}\sum_{s\in S_{u,w}}\left(F_{u,s,w,n}z_{u,s,w,n}^{m}\right),\forall m\in M \tag{31}$$

$$\sum_{m\in M} z_{u,s,w,n}^{m}=1,\forall u\in USEP,\forall w\in W_u,\forall s\in S_{u,w} \tag{32}$$

$$\boldsymbol{\Gamma X}_{u,n}=\boldsymbol{\mu}_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in USEP \tag{33}$$

$$PC_{u,n}=\chi_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Gamma F}_{u,n}),\forall u\in USEP \tag{34}$$

$$y_{u,n}PC_{u,n}^{\min}\le PC_{u,n}\le y_{u,n}PC_{u,n}^{\max},\forall u\in USEP \tag{35}$$

$$\boldsymbol{UI}_{u,n}=\boldsymbol{\tau}_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in USEP \tag{36}$$

$$\boldsymbol{UO}_{u,n}=\boldsymbol{\kappa}_{u,n}(\boldsymbol{\Psi F}_{u,n},\boldsymbol{\Psi X}_{u,n},\mathbf{Pam}_{u,n}),\forall u\in USEP \tag{37}$$

where $z_{v,s,u,n}^{m}$ and $z_{u,s,w,n}^{m}$ are compositions of inlet and outlet streams.

4.3.3.4. Plant feedstock model. Plant feedstock model is a virtual model, which does not exist in reality. However, by assuming all the plant inputs (include raw materials and purchased utilities) must pass through the feedstock model, we could easily model and account all plant feedstock costs. The feedstock unit is designated as ui. The stream set containing the j-th feedstock is SF_j. Each feedstock or utility stream simply passes through the unit with the same flow rate and property. Thus, the model is described by Eqs. (38) through (42).

$$FD_{j,n}=\sum_{w\in W_{ui}}\sum_{s\in S_{ui,w}\cap SF_j} F_{ui,s,w,n},\forall j\in J \tag{38}$$

$$\boldsymbol{X}_{ui,s,w,n}=\boldsymbol{XD}_{j,n},\forall s\in S_{ui,w}\cap SF_j,\forall w\in W_{ui} \tag{39}$$

$$yd_{j,n}FD_{j,n}^{\min}\le FD_{j,n}\le yd_{j,n}FD_{j,n}^{\max},\forall j\in J \tag{40}$$

$$\mathbf{UI}_{ui,n}=\mathbf{UO}_{ui,n} \tag{41}$$

$$\mathbf{UI}_{ui,n}^{\min}\le\mathbf{UI}_{ui,n}\le\mathbf{UI}_{ui,n}^{\max} \tag{42}$$

where $FD_{j,n}$ is the flow rate of feedstock j; $F_{ui,s,w,n}$ is flow rate of feedstock to unit w; $FD_{j,n}^{\min}$ and $FD_{j,n}^{\max}$ are lower and upper limits of the capacity. Eq. (38) gives the mass balance. Eq. (39) suggests property propagations, which means properties $\mathbf{X}_{ui,s,w,n}$ are equal to properties $\mathbf{XD}_{j,n}$ of feedstock j. Eq. (40) sets plant input capacity limits, where binary variables, $yd_{j,n}$, are employed. $yd_{j,n}$ equals to 1 if the$j$-th feed is purchased. Eqs. (41) and (42) describe utility balance and utility import limits. $\mathbf{UI}_{ui,n}$ denotes the quantity of input utilities of the plant. $\mathbf{UO}_{ui,n}$ denotes the quantity of utilities to be distributed to all units in the plant.

4.3.3.5. Plant output model. Plant output model is another virtual model, which assumes all the plant output (e.g., products, wastes, or sold utilities) has to pass through an output unit of *uo*. Similar to plant feedstock model, the model equations are shown in Eqs. (43) through (47).

$$FP_{p,n} = F_{v,s,uo,n}, s \in S_{v,uo} \cap SO_p, v \in V_{uo}, \forall p \in PP \quad (43)$$

$$\boldsymbol{XP}_{p,t} = \boldsymbol{X}_{v,s,uo,t}, s \in S_{v,uo} \cap SO_P, v \in V_{uo}, \forall p \in PP \quad (44)$$

$$yp_{p,n} FP^{\min}_{j,n} \le FP_{p,n} \le yp_{p,n} FP^{\max}_{p,n}, \forall p \in PP \quad (45)$$

$$\mathbf{UO}_{uo,\ n} = \mathbf{UI}_{uo,\ n} \quad (46)$$

$$\mathbf{UO}^{\min}_{uo,\ n} \le \mathbf{UO}_{uo,\ n} \le \mathbf{UO}^{\max}_{uo,\ n} \quad (47)$$

where $FP_{p,n}$ is the flow rate of output p; $F_{v,s,uo,n}$ is the flow rate of unit v to output; $FP^{\min}_{j,n}$ and $FP^{\max}_{j,n}$ are lower and upper limits of the capacity. The mass balance is given by Eq. (43). The property propagation is given by Eq. (44), which suggests properties, $\mathbf{XP}_{p,n}$, of the output streams are equal to properties of $\mathbf{X}_{v,\ s,\ uo,n}$. Eq. (45) sets plant output capacity limits, where binary variable $yp_{p,n}$ is employed. $yp_{p,n}$ equals to 1 if the$p$-th product is produced. Eqs. (46) and (47) describe the utility balance and utility export limits, where $\mathbf{UO}_{uo,\ n}$ denotes the quantity of output utilities of the plant; and $\mathbf{UI}_{uo,\ n}$ denotes the quantity of utilities sent to output of the plant. The flow rate (yield) distribution is described by the mixing unit model along with the plant feedstock model and plant output model.

4.3.3.6. inventory unit model. Inventory unit model is specifically considered because inventory changes with respect to time event should be clarified in the refinery crude processing model. The model is described through Eqs. (48) through (52).

$$F_{v,s,u,n}\Delta t + IV_{u,n-1} = \left(\sum_{w \in W_u}\sum_{s \in S_{u,w}} F_{u,s,w,n}\right)\Delta t + IV_{u,n}, u \in UINV \quad (48)$$

$$IV^{\min}_{u,n} \le IV_{u,n} \le IV^{\max}_{u,n}, u \in UINV \quad (49)$$

$$\boldsymbol{X}_{u,s',w,n} = \boldsymbol{\theta}\left([F_{v,s,u,n}\Delta t,\ IV_{u,n-1}],\ [\mathbf{X}_{v,s,u,n},\ \boldsymbol{XV}_{u,n-1}]\right), \forall s' \in S_{u,w}, \forall w \in W_u, u \in UINV \quad (50)$$

$$\boldsymbol{UI}_{u,n} = \boldsymbol{\tau}_{u,n}(F_{v,s,u,n},\ IV_{u,n},\ \mathbf{Pa}\boldsymbol{m}_{u,n}), u \in UINV \quad (51)$$

$$\boldsymbol{UO}_{u,n} = \boldsymbol{\kappa}_{u,n}(F_{v,s,u,n},\ IV_{u,n},\ \mathbf{Pa}\boldsymbol{m}_{u,n}), u \in UINV \quad (52)$$

where Δt is the interval of a time period; $F_{v,\ s,\ u,\ n}$ is the inlet stream to inventory unit u; $F_{u,s,w,\ n}$ is the output stream to inventory unit u; $IV_{u,\ n-1}$ and $IV_{u,\ n}$ are inventories at the time event n-1 and n; $IV^{\min}_{u,\ n}$ and $IV^{\max}_{u,\ n}$ are lower and upper limits of the inventory unit u. Eq. (48) means total input plus previous inventory should be equal to total output plus the new inventory amount. Eq. (49) keeps the updated inventory constrained. Eq. (50) suggests property output from an inventory unit should consider new inflow and previous inventory influence. Eqs. (51) and (52) calculate utility consumptions and generations, respectively.

4.3.3.7. Utility generator model. A utility generator usually consumes fuel oil/fuel gas to generate steam, electricity, and process water. It is worth noting that the waste gas is directly sent to the plant output unit, so as to leave out of the plant. Its model equations include:

$$\sum_{v \in V_u}\sum_{s \in S_{v,u}} F_{v,s,u,n} = \sum_{s \in S_{u,uo}} F_{u,s,uo,n}, u \in UTIT \quad (53)$$

$$\boldsymbol{\Gamma F}_{u,n} = \boldsymbol{\varphi}_{u,n}(\boldsymbol{\Psi F}_{u,n}, \boldsymbol{\Psi X}_{u,n}, \mathbf{Pa}\boldsymbol{m}_{u,n}), \forall u \in UTIT \quad (54)$$

$$\boldsymbol{\Gamma X}_{u,n} = \boldsymbol{\mu}_{u,n}(\boldsymbol{\Psi F}_{u,n}, \boldsymbol{\Psi X}_{u,n}, \mathbf{Pa}\boldsymbol{m}_{u,n}), \forall u \in UTIT \quad (55)$$

$$PC_{u,n} = \chi_{u,n}(\boldsymbol{\Psi F}_{u,n}, \boldsymbol{\Gamma F}_{u,n}), u \in UTIT \quad (56)$$

$$y_{u,n} PC^{\min}_{u,n} \le PC_{u,n} \le y_{u,n} PC^{\max}_{u,n}, u \in UTIT \quad (57)$$

$$\boldsymbol{UI}_{u,n} = \boldsymbol{\tau}_{u,n}(\boldsymbol{\Psi F}_{u,n}, \boldsymbol{\Psi X}_{u,n}, \mathbf{Pa}\boldsymbol{m}_{u,n}), u \in UTIT \quad (58)$$

$$\boldsymbol{UO}_{u,n} = \boldsymbol{\kappa}_{u,n}(\boldsymbol{\Psi F}_{u,n}, \boldsymbol{\Psi X}_{u,n}, \mathbf{Pa}\boldsymbol{m}_{u,n}), u \in UTIT \quad (59)$$

where the mass balance shown in Eq. (53), which indicates the output waste steam is sent to *uo*; Eqs. (54) and (55) describe product flow rate and property distribution after the processing; Eqs. (56) and (57) calculate and constrain unit processing capacity; Eqs. (58) and (59) calculate utility consumptions and generations, respectively. Note that even for a utility generator, the operation itself may consume some utilities for processing assistance.

4.3.4. Plant utility balance constraints

Material balance equations have been included in equipment models, but utility balance constraints from the plant-wide level still need to be addressed. As shown in Eq. (60), the difference between plant purchased and sold utilities should be equal to the summation of difference between inflow and outflow utilities at each unit.

$$\mathbf{UI}_{ui,\ n} - \mathbf{UO}_{uo,\ n} = \sum_{u \in UALL}(\mathbf{UI}_{u,\ n} - \mathbf{UO}_{u,\ n}) \quad (60)$$

where $\mathbf{UI}_{ui,\ n}$ denotes utilities purchased by the plant; $\mathbf{UO}_{uo,\ n}$ denotes utilities sold outside by the plant; $\mathbf{UI}_{u,\ n}$ and $\mathbf{UO}_{u,\ n}$ are utilities consumed and generated by unit u.

4.4. Objective function of CUTP model

The objective function of the CUTP model is to maximize total process profit, which is defined in Eq. (61). It contains three main items. The first summation item of Eq. (61) represents the total refinery revenue, which includes plant product sale income and utility sale income. The second summation item of Eq. (61) represents the total refinery cost, which includes feedstock costs, utility costs, and plant inventory costs. The third summation item of Eq. (61) represents the front-end crude operational cost.

$$\max Profit = \sum_{n}(Sale\_PO_n + Sale\_UO_n) \ -\sum_{n}\left(Cost\_FD_n + Cost\_UD_n + \sum_{u\in UINV}\Delta IV_{u,n}\right) \ -\sum_{n}(Cost\_OP_n) \quad (61)$$

where various items in Eq. (61) are formulated in details as below:

$$Sale\_PO_n = \sum_{p\in PP} PPO_{p,n} \quad FP_{p,n} \quad (62)$$

$$Sale\_UO_n = PET_n UET^{out}_{uo,n} + PAR_n UAR^{out}_{uo,n} + \mathbf{PWA}^T_n \mathbf{UWA}^{out}_{uo,n} + \mathbf{PSW}^T_n \mathbf{USW}^{out}_{uo,n} + \mathbf{PFG}^T_n \mathbf{UFG}^{out}_{uo,n} + \mathbf{PRC}^T_n \mathbf{URC}^{out}_{uo,n} \quad (63)$$

$$Cost\_FD_n = \sum_{j\in J} PFD_{j,n} FD_{j,n} \quad (64)$$

$$Cost\_UD_n = PET_n UET^{in}_{ui,n} + PAR_n UAR^{in}_{ui,n} + \mathbf{PWA}^T_n \mathbf{UWA}^{in}_{ui,n} + \mathbf{PSW}^T_n \mathbf{USW}^{in}_{ui,n} + \mathbf{PFG}^T_n \mathbf{UFG}^{in}_{ui,n} + \mathbf{PRC}^T_n \mathbf{URC}^{in}_{ui,n} \quad (65)$$

$$\Delta IV_{u,\ n} = PV_{u,\ n} \quad (IV_{u,n} - IV_{u,\ n-1}) \quad ,(66)$$

where Eqs. (62) and (63) give the product and utility sale incomes. Eqs. (64) and (65) give purchased feedstock and utility costs. Eq. (66) accounts for the inventory value changes for inventory units. In the above equations,$PPO_{p,n}$ is unit price of the product p; $FP_{p,n}$ is the flow rate of the product p; PET_n, PAR_n, $\mathbf{PWA}^T_n$, $\mathbf{PSW}^T_n$, $\mathbf{PFG}^T_n$, and $\mathbf{PRC}^T_n$ are unit price of utilities; $UET^{in}_{ui,n}$, $UAR^{in}_{ui,n}$, $\mathbf{UWA}^{in}_{ui,n}$, $\mathbf{USW}^{in}_{ui,n}$, $\mathbf{UFG}^{in}_{ui,n}$, $\mathbf{URC}^{in}_{ui,n}$ $UET^{out}_{uo,n}$, $UAR^{out}_{uo,n}$, $\mathbf{UWA}^{out}_{uo,n}$, $\mathbf{USW}^{out}_{uo,n}$, $\mathbf{UFG}^{out}_{uo,n}$, and $\mathbf{URC}^{out}_{uo,n}$ are quantities of utilities; $PFD_{j,n}$ is unit price of feedstock j; $FD_{j,n}$ is the flow rate of feedstock j; $PV_{u,\ n}$ is the price of inventory u; $IV_{u,\ n-1}$ and $IV_{u,\ n}$ are inventories at the time event n-1 and n. The superscript T means vector transposition. For instance, $\mathbf{PWA}^T_n \quad \mathbf{UWA}^{out}_{uo,n}$ represents the dot product of two vectors.

Eq. (67) summarizes the front-end crude operational cost. In Eq. (67), the first term calculates demurrage costs caused by the delay of vessel unloading; the second term expresses unloading costs; the third term represents changeover costs incurred by switching column feeds among different charging tanks; the forth term sums up setup costs for crude transferring from vessels to storage tanks and from storage tanks to charging tanks; and the last term is an approximation of average inventory costs for all tanks throughout the scheduling time horizon.

$$\begin{aligned} Cost\_OP_n =\ & C^{sea}\sum_{v\in V}(TV^s(v) - T^{arr}(v)) + C^{uld}\sum_{v\in V}(TV^e(v) - TV^s(v)) \\ & + C^{cho}\sum_{unt'\in IU_{unt}}\sum_{unt\in DU}\sum_{n\in N,n\geq 1} Z(unt', unt, n) + C^{set}\sum_{unt'\in IU_{unt}}\sum_{unt\in SCT}\sum_{n\in N,n\geq 1} X(unt', unt, n) \\ & + \frac{H}{|N|+1}\sum_{unt\in SCT}\left(C^{inv}(unt)\left(\sum_{n\in N,n\geq 1} Inv^{sct}(unt, n) + Inv^0(unt)\right)\right) \end{aligned} \quad (67)$$

In summary, the entire CUTP scheduling model includes Eqs. (1) through (67) and Eqs. (68) through (123) in Appendix B.

5. Case study

5.1. Given data

The developed scheduling methodology has been demonstrated through an industrial-size CUTP problem. The problem consists of three single-parcel vessels carrying their respective crudes, one single docking berth, four storage tanks (ST), four charging tanks (CT), and a refinery plant starting from two CDUs. The detailed crude oil transfer network is presented in Fig. 3. The refinery process includes crude distillation, reforming, cracking, hydrotreating, blending, gas processing, and sulfur recovering facilities, which has been shown in Fig. 4. For simplicity, the case study has neglected the inventory change of each refinery processing unit. Major process facilities of the refinery are illustrated by Appendix A. The specified scheduling time horizon is 15 days. The brine settling time (BST) for front-end tank operations is 0.1 day. The front-end crude unloading and transferring data, crude property data, refinery product specifications, and economic data of the studied CTUP case have been provided by Tables 1–4.

Based on our study, the obtained CUTP model is an MINLP model. It has been programmed and solved in GAMS v23.9.1 on Intel 3.4 GHz Windows PC with 16.0 GB memory. The optimization solver DICOPT (solver based on the extensions of the outer-approximation algorithm) is adopted to solve the MINLP problems (Grossmann et al., 2002), with CPLEX and BARON respectively employed as the sub-solvers for MIP and NLP sub problems. The optimal solution gives the maximum total gross profit of $ 105,105.49 K. The model has 3101 constraints, 1841 continuous variables and 74 binary variables. The solving time for case study is 25.94 s.

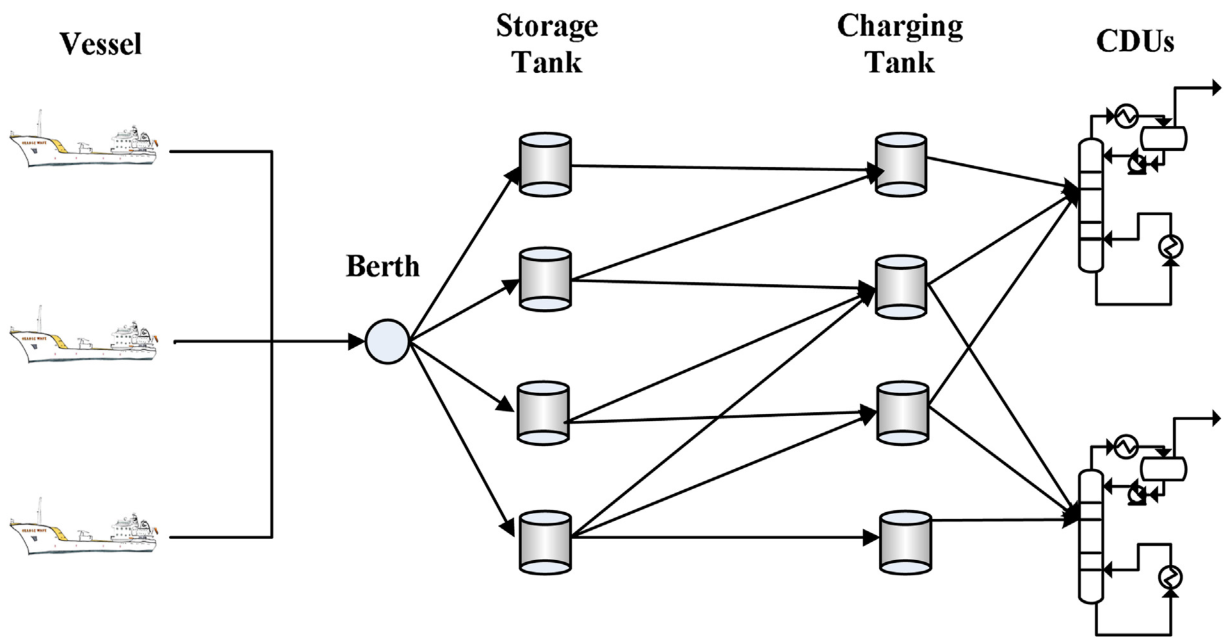

Fig. 3. Schematic diagram of the studied front-end crude transfer process.

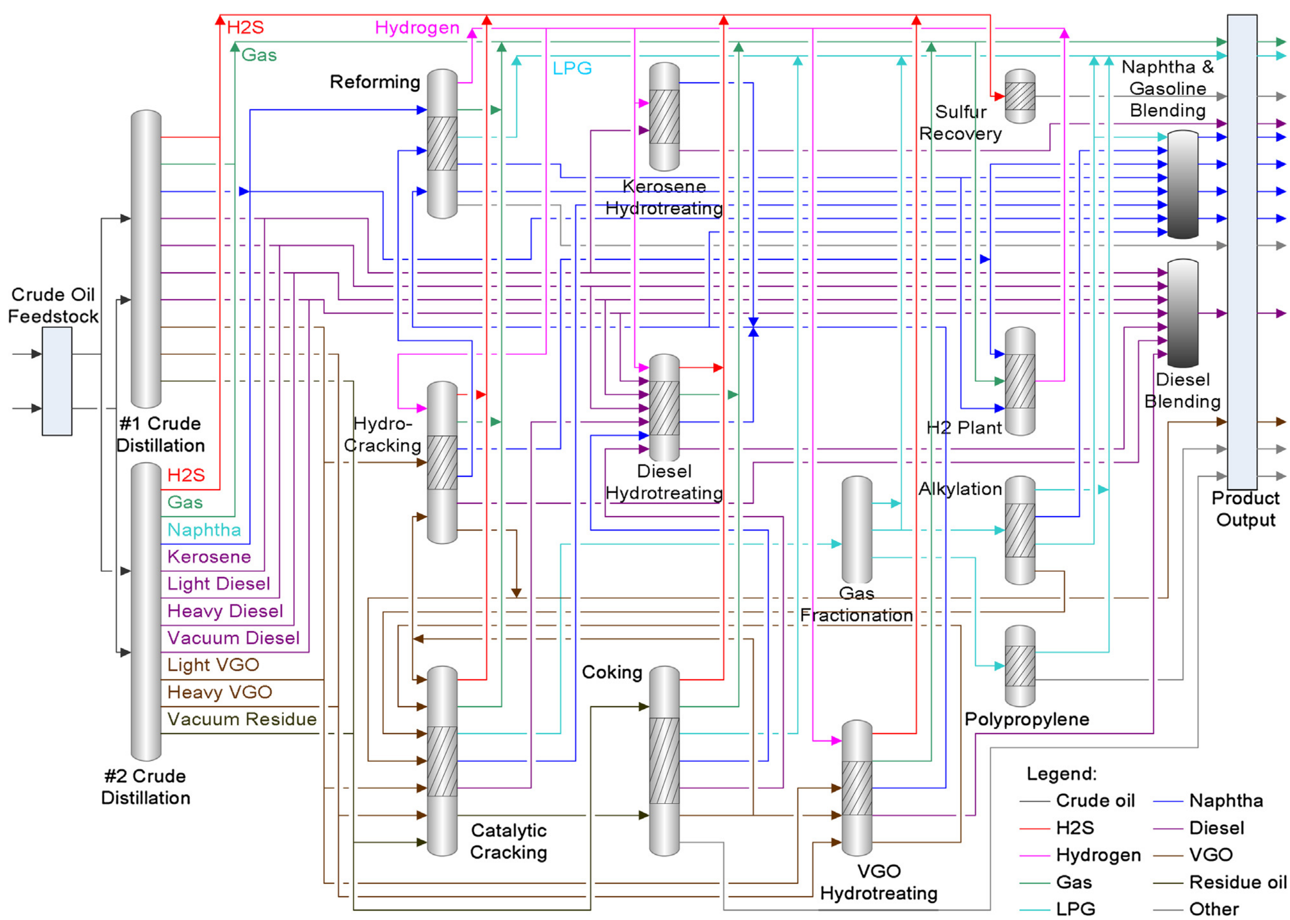

Fig. 4. Schematic diagram of the studied refinery plant.

5.2. Operating results analysis

5.2.1. Results of front-end crude scheduling

The optimal Gantt chart for the CUTP scheduling model with RPST time is presented in Fig. 5. As shown, the scheduling time is adopted as the horizontal axis, and crude “receiving units” are adopted as the vertical category axis. The numbers close to the schedule bars represent

Table 1
Front-end Crude Unloading and Transfer Data for the Studied CUTP Case.

Vessels	**Arrival time (day)**	**Crude composition**	**Volume (Mbbl)**
vessel 1	0	100% CR1	1000
vessel 2	5	100% CR2	1000
vessel 3	10	100% CR1	1000
Storage tanks	**Capacity (Mbbl)**	**Initial composition**	**Initial inventory (Mbbl)**
ST 1	[100,1600]	100% CR1	1000
ST 2	[100,2000]	100% CR2	200
ST 3	[100,2000]	100% CR1	900
ST 4	[100,2000]	100% CR2	700
Charging tanks	**Capacity (Mbbl)**	**Initial composition**	**Initial inventory (Mbbl)**
CT 1 (for mixture X)	[0,1500]	100% CR1	90
CT 2 (for mixture Y)	[0,1500]	100% CR2	900
CT 3 (for mixture Z)	[0,1500]	100% CR1	550
CT 4 (for mixture W)	[0,1500]	100% CR2	550
Crude mixtures	**Sulfur Content**	**Demand (Mbbl)**	
X	[0.000, 0.200]	1000	
Y	[0.000, 0.200]	1000	
Z	[0.000, 0.200]	1000	
W	[0.000, 0.200]	1000	
Unloading flow rate (Mbbl/day)	[0,900]	Inter-tank transfer flow rate (Mbbl/day)	[0,900]
Charging flow rate (Mbbl/day)	[20,900]		

Table 2
Crude Properties of the Studied CUTP Case.

	Specific Gravity	**Sulfur Content**	**Aromatics Content**	**Paraffin Content**	**Pour Point**	**Flash Point**	**Cetane Index**
CR1-Naphtha	0.6955	0.0069	2.5431	97.050	–	–	–
CR1-Kerosene	0.7858	0.0132	–	–	−52.200	40.000	48.900
CR1-Light Diesel	0.8122	0.0382	–	–	−0.4000	70.000	59.700
CR1-Heavy Diesel	0.8443	0.0760	–	–	18.900	80.000	58.000
CR1-Vacuum Diesel	0.8551	0.0884	–	–	21.100	100.00	56.000
CR1-Light VGO	0.8701	–	–	–	–	–	–
CR1-Heavy VGO	0.8994	–	–	–	–	–	–
CR1-Vacuum Residue	0.9553	–	–	–	–	–	–
CR2-Naphtha	0.7224	0.0069	6.3293	94.200	–	–	–
CR2-Kerosene	0.8006	0.0243	–	–	−55.000	42.000	42.016
CR2-Light Diesel	0.8475	0.3043	–	–	−5.0000	75.000	51.559
CR2-Heavy Diesel	0.8863	0.7047	–	–	10.000	88.000	45.494
CR2-Vacuum Diesel	0.8906	0.7782	–	–	20.000	100.00	40.000
CR2-Light VGO	0.9184	–	–	–	–	–	–
CR2-Heavy VGO	0.9295	–	–	–	–	–	–
CR2-Vacuum Residue	0.9878	–	–	–	–	–	–

Table 3
Refinery Product Specifications of the Studied CUTP Case.

	Specific Gravity	**Sulfur Content**	**Aromatics Content**	**Paraffin Content**	**Pour Point**	**Flash Point**	**Cetane Index**	**Diesel Oil Number**	**Olefin Content**	**Relative Vapor Pressure**
Gasoline	[0.7, 0.75]	[0,0.0005]	[0,42]	–	–	–	–	>87	[0,18]	[0,86]
Medium Gasoline	[0.7, 0.75]	[0,0.0005]	[0,42]	–	–	–	–	>90	[0,18]	[0,86]
Premium Gasoline	[0.7, 0.75]	[0,0.0005]	[0,42]	–	–	–	–	>94	[0,18]	[0,86]
Diesel	[0.82, 0.84]	[0,0.005]	–	–	<3	> 8	>46	–	–	–
Naphtha	[0.7, 0.8]	[0,0.005]	[0,20]	>60	–	–	–	–	–	–

the total volumes (Mbbl) transferred. Here, various filling patterns indicate the source units of crude transfers; while different colors denote specific time events when particular operations occur. Overall, four time events are adopted for the CUTP scheduling case. For example, as for the first green schedule bar in the figure, it means at time event 1, a total volume of 1000 MbbL crude oil is fed from parcel 1 to storage tank 2 from day 0 to day1.1.

It can be seen in the optimal Gantt chart that two refinery CDUs have received different types of crude blends from charging tanks at different time events. Thus, a RPST time is located between any pair of these time events. Note that both CDU1 and CDU2 utilize all four time events. It is possible that a CDU may skip certain time events, but it still can ensure its continuous operations with the left non-successive time events. Comparatively, crude movements from parcels to storage tanks and from storage tanks to charging tanks take a smaller portion of the entire scheduling time horizon. Tank inventory profiles based on storage tanks and charging tanks are illustrated in Fig. 6(a) and (b), respectively. As illustrated in these two figures, both storage tank and charging tank inventory change with time events but within their capacity constraints.

Table 4
Economic Data of the Studied CUTP Case.

Crude Oil Price ($/barrel)			
Crude Oil 1		56.29	
Crude Oil 2		48.68	
Front-end Economic Data			
Unloading cost ($/day)	10,000	Demurrage cost ($/day)	5000
Storage tank inventory cost ($/day Mbbl)	40	Charging tank inventory cost [$/day Mbbl]	80
CDU changeover cost ($)	50,000	Inter-tank transfer setup cost ($)	30,000
Product Sale Price (k$/kt)			
Gasoline	617.30	Sulfur	105.80
Medium Gasoline	634.90	Catalytic Coking	0
Premium Gasoline	652.60	Hydrogen Fuel Gas	0
Diesel	652.60	Loss	0
Kerosene	705.50	Utility Fuel Gas	0
Dry Gas	123.50	Utility Fuel Oil	0
Liquefied Petroleum Gas	740.70	Propane	529.10
Polypropylene	1,375.70	N-butane	529.10
Benzene	1,093.50	Topped Oil	529.10
Naphtha	617.30	Hydrotreating Naphtha	529.10
Hydrocracking Oil	211.60	1# Distilation Naphtha	529.10
Commercial Fuel Oil	246.90	2# Distilation Naphtha	529.10
Petroleum Coke	105.80	Hydrocracking Heavy Naphtha	529.10
Utility Unit Cost (k$/kt)		**Utility Sale Price** (k$/kt)	
Fresh Water	5.29	Fresh Water	0.26
Desalinated Water	3.53	Desalinated Water	0.18
Recycled Water	0.018	Recycled Water	0.00089
Condensed Water	0.177	Condensed Water	0.0088
Deoxygen Water	7.06	Deoxygen Water	0.35
Low-pressure Steam	1.76	Low-pressure Steam	0.88
Medium-pressure Steam	2.65	Medium-pressure Steam	1.24
High-pressure Steam	3.53	High-pressure Steam	1.76
Electricity ($/kW h)	0.088	Electricity(KWh/t)	0.036
Utility Fuel Gas	211.60	Utility Fuel Gas	10.58
Utility Fuel Oil	423.30	Utility Fuel Oil	14.11
Auxiliary Materials	4.39	Auxiliary Materials	0.0088

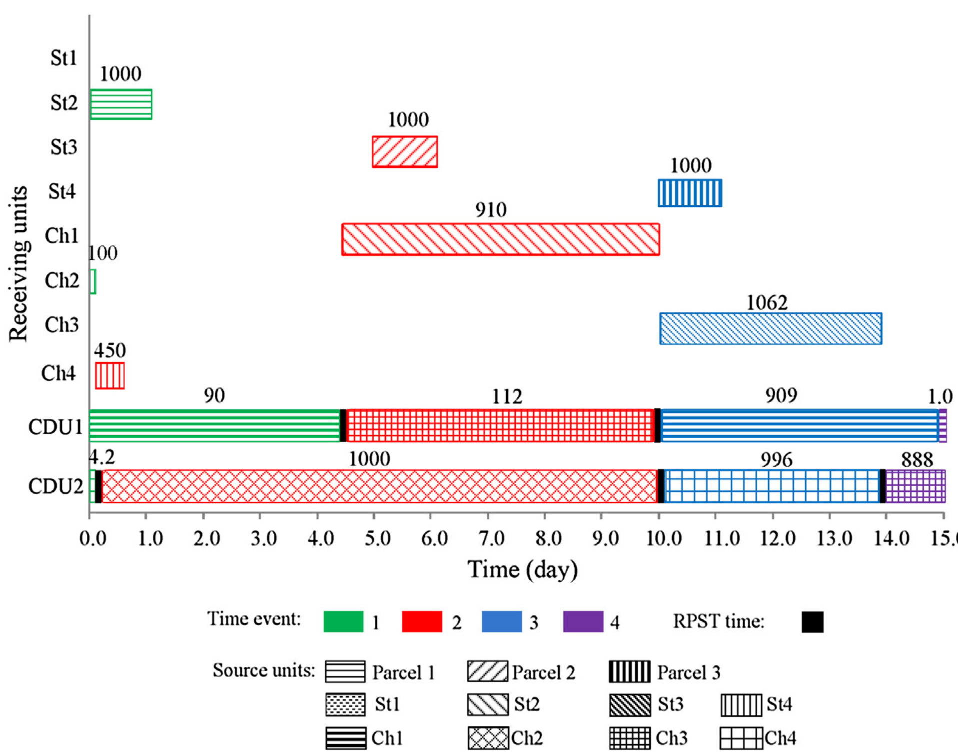

Fig. 5. Scheduling result by considering the RPST time.

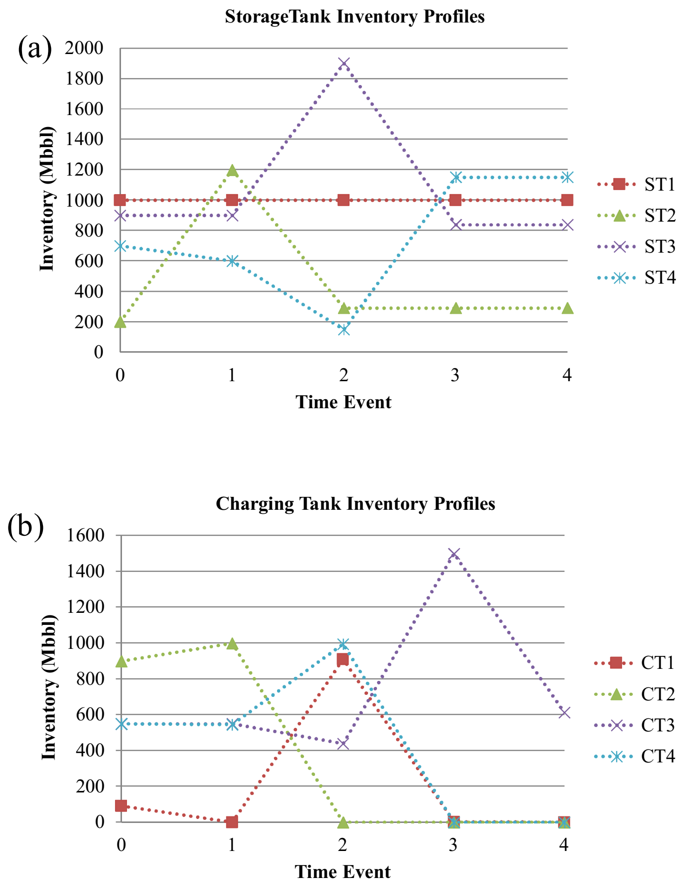

Fig. 6. Front-end inventory profiles of (a) storage tanks and (b) charging tanks.

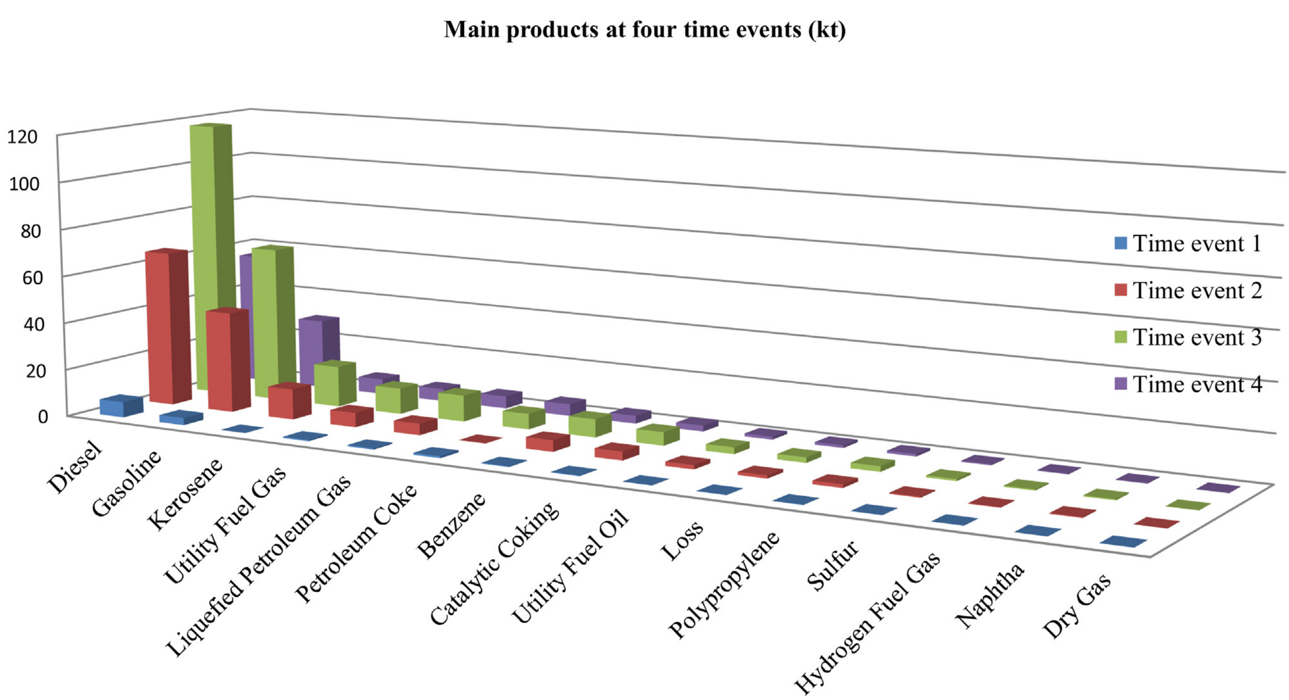

Fig. 7. Optimization results of main refinery products for four time events.

5.2.2. Results of refinery processing

The scheduling result of refinery imports and exports for the CUTP case is presented in Table 5. The refinery main imports contain two types of crude oils and various utilities such as four types of water, two grades of steam and electricity. The refinery main exports include major products such as gasoline, diesel, kerosene, and benzene and utilities like condensed water and high-pressure steam. Fig. 7

Table 5
Scheduling Result of Refinery Imports and Exports.

Time Event	1	2	3	4
Crude Oil				
Crude Oil 1	11.95	14.85	100.57	74.10
Crude Oil 2	0.56	131.49	150.86	43.53
Main Product				
Gasoline	3.03	42.72	65.81	29.68
Diesel	6.56	66.08	117.91	56.08
Kerosene	0	12.91	17.31	6.46
Dry Gas	0.05	0	0.07	0.16
Liquefied Petroleum Gas	0.51	4.88	11.12	5.21
Polypropylene	0.10	1.47	2.26	1.02
Benzene	0.32	4.77	7.62	3.36
Naphtha	0	0.33	0.44	0.17
Petroleum Coke	0.82	0.07	6.56	5.01
Sulfur	0.05	0.42	0.82	0.42
Catalytic Coking	0.26	3.64	5.60	2.53
Hydrogen Fuel Gas	0.03	0.22	0.48	0.26
Utility Fuel Gas	0.12	1.27	2.27	1.10
Utility Fuel Oil	0.56	6.09	10.93	5.23
Main Utility Import				
Fresh Water	2.97	46.10	72.42	31.43
Desalinated Water	1.12	8.98	18.17	9.31
Recycled Water	280.56	3,243.51	5,535.40	2,611.00
Deoxygen Water	2.31	30.65	48.25	22.10
Low-pressure Steam	0.16	3.08	3.85	1.64
Medium-pressure Steam	0.63	2.88	7.94	4.65
Electricity (MW h)	618.34	7,130.22	1,2116.84	5,761.46
Main Utility Export				
Condensed Water	1.31	11.69	21.90	11.09
High-pressure Steam	0.03	0.19	0.42	0.22

The unit of these solution results is kiloton if not specified.

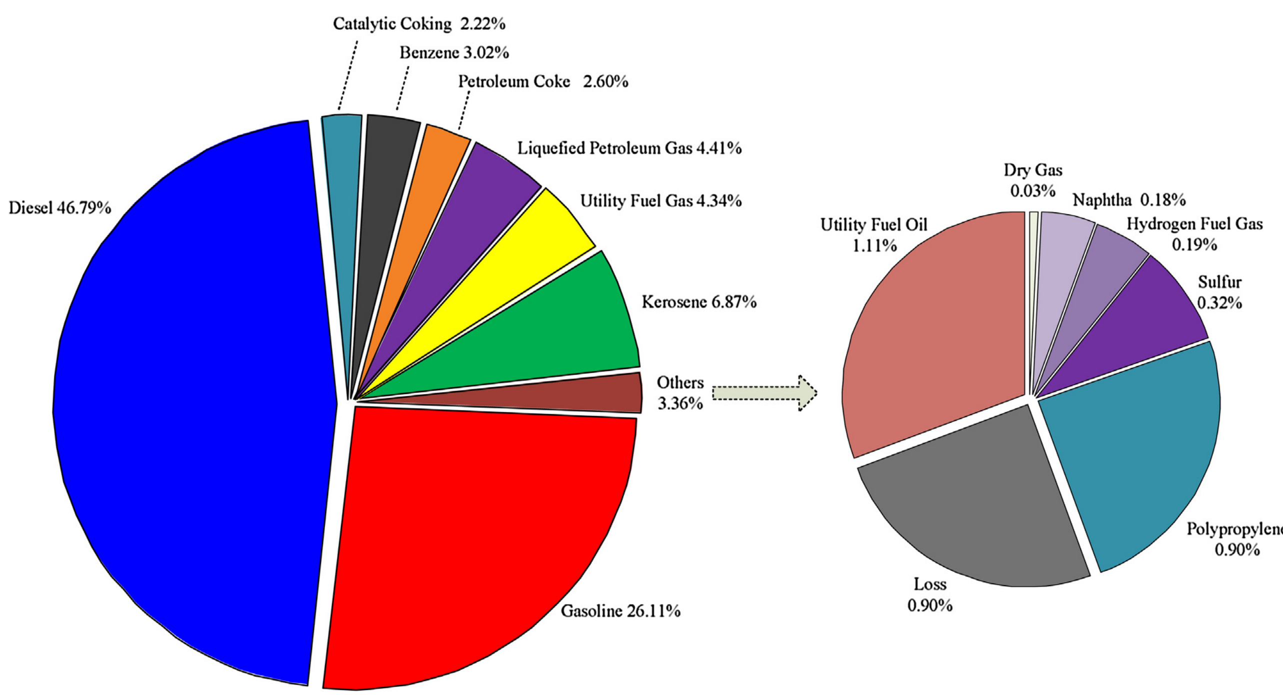

Fig. 8. Refinery main product distribution in time event 3.

showed the scheduling result based on main products produced for all four time events. It can be seen that diesel and gasoline are main products of this refinery comparing to others like kerosene, liquefied petroleum gas, utility fuel gas, and etc. Meanwhile, it can be seen that productions from time events 2 and 3 are more than those from time events 1 and 4. To show the main product distribution in a time event, Fig. 8 gives an example for time event 3. It shows diesel and gasoline have covered almost three quarters of the pie chart. Other products include: kerosene, liquefied petroleum gas, utility fuel gas, petroleum coke, benzene, catalytic coking, utility fuel oil, polypropylene, sulfur, hydrogen fuel gas, naphtha, dry gas and etc.

Table 6
Refinery Economic Results.

Time Event	1	2	3	4
Crude Oil Buy				
Crude Oil 1	−5,066.14	−6,295.26	−42,639.25	−31,414.80
Crude Oil 2	−205.47	−48,680.02	−55,849.51	−16,116.72
Subtotal	−5,271.60	−54,975.28	−98,488.76	−47,531.52
Main Product Sell				
Gasoline	1,872.27	26,373.53	40,621.43	18,323.93
Diesel	4,281.71	43,121.85	76,950.68	36,595.85
Kerosene	0	9,110.12	12,210.09	4,558.94
Dry Gas	6.05	0	8.27	20.01
Liquefied Petroleum Gas	379.24	3,617.58	8,235.84	3,861.27
Polypropylene	143.07	2,018.15	3,107.71	1,401.84
Benzene	351.01	5,214.90	8,335.75	3,675.25
Naphtha	0	204.33	274.08	102.47
Petroleum Coke	86.44	7.62	693.73	529.85
Sulfur	5.18	44.44	86.23	43.91
Subtotal	7,124.98	89,712.51	150,523.80	69,113.32
Main Utility Buy				
Fresh Water	−15.70	−243.88	−383.10	−166.28
Desalinated Water	−3.95	−31.69	−64.13	−32.87
Recycled Water	−4.94	−57.09	−97.42	−45.95
Deoxygen Water	−16.28	−216.22	−340.38	−155.89
Low-pressure Steam	−0.28	−5.44	−6.80	−2.89
Medium-pressure Steam	−1.67	−7.61	−21.00	−12.29
Electricity	−54.54	−628.89	−1,068.70	−508.16
Subtotal	−97.35	−1,190.80	−1,981.54	−924.33
Main Utility Sell				
Condensed Water	0.01	0.10	0.19	0.10
High-pressure Steam	0.05	0.33	0.73	0.39
Subtotal	0.06	0.43	0.93	0.49
Economic Performance Summary				
Crude Oil Buy		206,267.16	Profit	105,105.49
Product Sell		316,474.61	Profit/Sell	33.21%
Operation Cost		5,100.44	Utility/Sell	1.33%
Front-end Operation Cost		908.33	Crude/Sell	65.18%

Unit of these economic results is k$.

5.3. Economic results analysis

Table 6 gives economic solution results for the studied CUTP case. Detailed economic results in terms of crude oil buy, main product sell, main utility buy, and main utility sell in different time events are shown in this table. The sub-total results of each category in different time event also presented in Table 6. Based on the proposed CUTP methodology, the optimal solution gives the maximum total gross profit of $ 105,105.49 K. It results from the total revenue from products sale of $ 316,474.61 K, minus crude oil purchase of $ 206,267.16 K, and minus operational cost of $ 5,100.44 K, in which the front-end operational cost is $ 908.33 K. In comparison, ratios of the gross profit, total net utility income, and crude purchasing cost over the total revenue are 33.21%, 1.33%, and 65.18%, respectively. It matches the reality that the major expenditure of a refinery is for crude purchasing. It should be noted that this profit is gross profit because it does not consider some direct costs like labor, supervision, payroll, maintenance, and royalties, as well as indirect costs like depreciation, taxes, and insurances.

6. Concluding remarks

In this paper, a systematic methodology for simultaneous scheduling of front-end crude transfer and refinery processing has been developed. It provides a large-scale continuous scheduling model to simultaneously simulate and optimize the crude unloading, transferring, and processing (CUTP). The model consists of a newly developed refinery processing sub model, a refinery processing status transition (RPST) sub model, and a borrowed front-end crude transferring sub model. Compared to recent studies, this paper has two major contributions: (1) the simultaneous scheduling of front-end crude transfer and refinery processing has been achieved; (2) RPST has been considered in the CUTP model for seamlessly connecting both front-end crude transfer and refinery processing models. The efficacy of the proposed methodology and CUTP model has been demonstrated by an industrial-scale case study.

Acknowledgements

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Appendix A. General Introduction of Major Refinery Facilities

A typical refinery process includes crude distillation, reforming, cracking, hydrotreating, blending, gas processing, and sulfur recovering facilities. Introductions of each facility in terms of its general functionality are given below.

Crude distillation. Compounds in crude oil can be separated according to the principle that the longer the carbon chain, the higher the temperature at which the compounds will boil. A crude distillation facility is used to heat the crude oil into gas mixtures and split them into gas, naphtha, kerosene, diesel, vacuum gas oil (VGO), and vacuum residues by atmospheric and vacuum distillation columns. All these intermediate products will be further processed by downstream facilities.

Reforming. A reforming facility is used to convert low-octane-number naphtha to high-octane-number gasoline. Its naphtha input comes from crude distillation, hydrocracking, and hydrotreating facilities. After reforming operation, some hydrocarbon molecules from naphtha are restructured to more complex molecular shapes; and some others are broken into smaller molecules, which make overall product having higher octane values. It also generates byproducts of low-purity (about 80%) hydrogen and dry gas, which are partially used as heating utilities by other facilities.

Cracking. Cracking facilities include fluid catalytic cracking (FCC), hydrocracking, and coking operations. With the help of catalysts, FCC facility convert VGO and vacuum residue oil into gas, liquefied petroleum gas (LPG), gasoline, and diesel. A hydrocracking facility employs hydrogen to crack light VGO into gas, naphtha, and diesel. For the vacuum residue, the heaviest intermediate product from crude distillation columns, a coking facility has to be employed to crack it into gas, LPG, naphtha, and diesel.

Hydrotreating. Hydrotreating facilities include kerosene, diesel, and VGO hydrotreating. They are designed to use hydrogen to remove contaminants such as sulfur, nitrogen, condensed ring aromatics, or metals from feedstock. The kerosene hydrotreating facility refines kerosene feedstock to produce aviation kerosene; while the diesel hydrotreating facility refines diesel and coking naphtha. The VGO hydrotreating facility refines VGO to reduce its sulfur content and make VGO suitable for FCC processing. Hydrotreating facilities use fuel gas as heating utilities, which cause emissions.

Blending. Blending facilities are used for crude oil blending and product blending which including naphtha, gasoline, kerosene, diesel, and fuel oil blending operations. Inflows of blenders come from upstream facilities. Thus, product blending always belongs to the final processing facilities of a refinery plant. Blending operations should satisfy both product quantity and quality requirements.

Gas processing. Gas processing facilities include gas fractionation, alkylation, and hydrogen plant. The gas fractionation separates LPG from catalytic cracking facility into propane, propylene, butane and butylene. The alkylation facility uses LPG from catalytic cracking, which mainly contains isobutene, to produce high-octane and branched-chain paraffins. The hydrogen plant facility uses dry gas from other facilities to produce high-purity (99%) hydrogen used for hydrocracking and hydrotreating facilities. For safety considerations, surplus hydrogen, dry gas, or LPG should be sent to flare system for destruction.

Sulfur recovery. Sulfur recovery facilities include sulfurated hydrogen (H_2S) removing and sulfur recovering facilities. The H_2S removing facility scrubs H_2S from dry gas and LPG streams to reduce air pollutions before they are burned. The sulfur recovering facility converts H_2S into sulfur products. Usually, emissions of H_2S and its oxides (SO_X) are very small during refinery normal productions.

Appendix B. Scheduling Model of Frond-end Crude Transfer

B.1 Integrality constraints for operating practices

The binary variable of $X(unt',unt,n)$ is used to denote whether or not a unit (unt') transfers crudes to another unit (unt) during time event n. It is forbidden that simultaneous inflow and outflow operations occur for a tank, which is formulated by Eq. (68). Eq. (69) restricts that a parcel p can be unloaded to no more than one storage tank at the same time event n; And Eq. (70) enforces that at the time event n, a storage tank can receive at most B parcels depending on the number of available berths. Eqs. (71) and (72) impose that a storage tank can send out crudes to at most one charging tank or a charging tank can receive feed from at most one storage tank at the same time event, respectively. Eqs. (73) and (74) indicate that at a time one charging tank can send out crudes to at most one CDU; and a CDU can accept at most one charging tank feed.

$$X(unt', unt, n) + X(unt, unt'', n) \leq 1 \forall unt' \in IU_{unt}; unt \in SCT; unt'' \in OU_{unt}; n \in N, \quad n \geq 1 \tag{68}$$

$$\sum_{unt' \in OU_{unt}} X(unt, unt', n) \leq 1, \quad \forall unt \in P; n \in N, \quad n \geq 1 \tag{69}$$

$$\sum_{unt' \in IU_{unt}} X(unt', unt, n) \leq B, \quad \forall unt \in ST; n \in N, \quad n \geq 1 \tag{70}$$

$$\sum_{unt' \in OU_{unt}} X(unt, unt', n) \leq 1, \forall unt \in ST; n \in N, \quad n \geq 1 \tag{71}$$

$$\sum_{unt' \in IU_{unt}} X(unt', unt, n) \leq 1, \quad \forall unt \in CT; n \in N, \quad n \geq 1 \tag{72}$$

$$\sum_{unt' \in OU_{unt}} X(unt, unt', n) \leq 1, \quad \forall unt \in CT; n \in N, \quad n \geq 1 \tag{73}$$

$$\sum_{unt' \in IU_{unt}} X(unt', unt, n) \leq 1, \quad \forall unt \in DU; n \in N, \quad n \geq 1 \tag{74}$$

B.2 Logic constraints

The total volume transferred during an operation should be constrained within the lower and upper bounds. Eq. (75) expresses that if a crude transfer is not selected, the total volume transferred should be zero under "*M*"; Otherwise, it must have a nonzero value above "*S*".

$$S \cdot X(unt', unt, n) \le V^t(unt', unt, n) \le M \cdot X(unt', unt, n) \forall unt' \in IU_{unt}; unt \in SCT \cup DU; n \in N, n \ge 1 \tag{75}$$

B.3 Transportation capacity constraints

As shown in Eqs. (76) and (77), if a storage or charging tank is selected for an operation, the total volume transferred will be constrained by the product of flow rate lower/upper bounds and the time durations used for transfer; Otherwise, the constraints will be relaxed.

$$\begin{aligned} &F^{lo}(unt', unt)(T^e(unt', unt, n) - T^s(unt', unt, n)) - F^{lo}(unt', unt)H(1 - X(unt', unt, n)) \le V^t(unt', unt, n), \\ &\forall unt' \in IU_{st} \cup IU_{ct}; unt \in SCT; n \in N, n \ge 1 \end{aligned} \tag{76}$$

$$\begin{aligned} &V^t(unt', unt, n) \le F^{up}(unt', unt)(T^e(unt', unt, n) - T^s(unt', unt, n)) + F^{up}(unt', unt)H(1 - X(unt', unt, n)), \\ &\forall unt' \in IU_{st} \cup IU_{ct}; unt \in SCT; n \in N, n \ge 1 \end{aligned} \tag{77}$$

B.4 Time constraints

B.4.1 Time constraints for vessel unloading

The starting and ending times of unloading a parcel p are constrained by Eqs. (78) and (79), respectively. Eq. (80) defines the order of parcels to be unloaded under the circumstance that only one berth is available. Thus, the parcel arriving earlier will be completely unloaded before the one arriving later. When multiple berths are considered, Eq. (80) will be excluded.

$$TP^s(unt) \le T^s(unt, unt', n) + H(1 - X(unt, unt', n)) \forall unt \in P; unt' \in OU_{unt}; n \in N, n \ge 1 \tag{78}$$

$$TP^e(unt) \ge T^e(unt, unt', n) - H(1 - X(unt, unt', n)), \forall unt \in P; unt' \in OU_{unt}; n \in N, n \ge 1 \tag{79}$$

$$TP^s(unt) \ge TP^e(unt'), \forall unt, unt' \in P, unt > unt'; n \in N, n \ge 1 \tag{80}$$

Eqs. (81) and (82) constrain the starting and ending time of unloading a vessel, respectively.

$$TV^s(v) \le TP^s(unt), \forall v \in V; unt \in P_v \tag{81}$$

$$TV^e(v) \ge TP^e(unt), \forall v \in V; unt \in P_v \tag{82}$$

B.4.2 Time constraints for parcels unloaded across multiple time events

A *0-1* continuous variable, *Bpe(unt,n)*, is used to denote whether a parcel has been emptied (completely unloaded) at the end of time event n. In this work, parcel is allowed to be unloaded into storage tanks at multiple time events; and if this is true, it has to be unloaded at consecutive time events. Hence, Eq. (83) constrains that if a parcel p is unloaded at time event n but not unloaded at $n+1$, then it must have been completely unloaded at the end of time event n. By analogy, as shown in Eq. (84), if a parcel p is unloaded at two adjacent time events of n and $n+1$, then it must have some leftover volume at the end of time event n.

$$Bpe(unt, n) \ge \sum_{unt' \in OU_{unt}} X(unt, unt', n) - \sum_{unt'' \in OU_{unt}} X(unt, unt'', n+1) \forall unt \in P; n \in N, 1 \le n < |N| \tag{83}$$

$$Bpe(unt, n) \le 2 - (\sum_{unt' \in OU_{unt}} X(unt, unt', n) + \sum_{unt'' \in OU_{unt}} X(unt, unt'', n+1)) \forall unt \in P; n \in N, 1 \le n < |N| \tag{84}$$

Eq. (85) shows that each individual parcel p has to be completely unloaded throughout the scheduling time horizon. Eq. (86) is used to denote the situation that parcel p has to be completely unloaded no later than the last time event N.

$$\sum_{n \in N, 1 \le n} Bpe(unt, n) = 1, \forall unt \in P \tag{85}$$

$$Bpe(unt, n) \ge \sum_{unt' \in OU_{unt}} X(unt, unt', n), \forall unt \in P; n =' N' \tag{86}$$

For parcels that are unloaded at consecutive time events, Eq. (87) imposes that the starting time of unloading parcel p to storage tanks at time event $n+1$ should follow right after the ending time of unloading parcel p to storage tanks at time event n.

$$T^s(unt, unt', n+1) \ge T^e(unt, unt'', n) - H(1 - X(unt, unt'', n)) \forall unt \in P; unt', unt'' \in OU_{unt}; n \in N, 1 \le n < |N| \tag{87}$$

B.4.3 Time constraints for storage and charging tanks

As shown in Eqs. (88) through (91), tank operations should follow the way that any input or output operations of a tank at time event $n+1$ should start after those operations for the same tank at time event n. Specifically, each output operation from a tank should wait until brine is settled as revealed in Eq. (89).

$$T^s(unt', unt, n+1) \geq T^e(unt, unt'', n) - H(1 - X(unt, unt'', n)) \forall unt' \in IU_{unt}; unt \in SCT; unt'' \in OU_{unt}; n \in N, 1 \leq n < |N| \quad (88)$$

$$T^s(unt, unt', n+1) \geq T^e(unt'', unt, n) - H(1 - X(unt'', unt, n)) + BST\ X(unt'', unt, n))$$
$$\forall unt \in SCT; unt' \in OU_{unt}; unt'' \in IU_{unt} n \in N, 1 \leq n < |N| \quad (89)$$

$$T^s(unt', unt, n+1) \geq T^e(unt'', unt, n) - H(1 - X(unt'', unt, n)) \forall unt', unt'' \in IU_{unt}; unt \in SCT; n \in N, 1 \leq n < |N| \quad (90)$$

$$T^s(unt, unt', n+1) \geq T^e(unt, unt'', n) - H(1 - X(unt, unt'', n)) \forall unt \in SCT; unt', unt'' \in OU_{unt}, unt' \neq unt''; n \in N, 1 \leq n < |N| \quad (91)$$

B.4.4 Auxiliary time constraints

Eq. (92) constrains that the ending time of input and output operations for storage/charging tanks should be after their respective starting time, and Eq. (93) shows that empty time intervals (i.e., starting time equals ending time) will be enforced on a given time event of an operation if it doesn't happen.

$$T^e(unt', unt, n) \geq T^s(unt', unt, n), \forall unt' \in IU_{unt}; unt \in SCT \cup DU; n \in N, n \geq 1 \quad (92)$$

$$T^e(unt', unt, n) - T^s(unt', unt, n) \leq H \cdot X(unt', unt, n) \forall unt' \in IU_{unt}; unt \in SCT \cup DU; n \in N, n \geq 1 \quad (93)$$

B.5 Material balance constraints

B.5.1 Material balance constraints for crude parcels

Eq. (94) shows that crude parcels have to be completely unloaded during the scheduling time horizon. As shown in Eq. (95), if a parcel p is completely unloaded at the end of time event n ($Bpe(unt,n)=1$), then its inventory should be equal to zero.

Eq. (96) expresses that the inventory of crude c contained in parcel p at the end of time event n is equal to that at the time event n-1 minus outflow volume of crude c during time event n. Eq. (97) establishes the initial inventories of each crude oil for each parcel. As shown in Eq. (98), the summation of individual crude inventories contained in parcel p at the end of time event n is equal to the total inventory of parcel p at the end of time event n.

$$\sum_{unt' \in OU_{unt}} \sum_{n \in N, n \geq 1} V^t(unt, unt', n) = Inv^0(unt), \forall unt \in P \quad (94)$$

$$Inv^p(unt, n) \leq Inv^0(unt)(1 - Bpe(unt, n)), \forall unt \in P; n \in N, n \geq 1 \quad (95)$$

$$Inv^{p,c}(unt, c, n) = Inv^{p,c}(unt, c, n-1) - \sum_{unt' \in OU_{unt}} V^t(unt, unt', n) f^{vol,p}(unt, c) \forall unt \in P; c \in C; n \in N, n \geq 1 \quad (96)$$

$$Inv^{p,c}(unt, c, n) = Inv^0(unt) f^{vol,p}(unt, c), \forall unt \in P; c \in C; n =' 0' \quad (97)$$

$$Inv^p(unt, n) = \sum_{c \in C} Inv^{p,c}(unt, c, n), \ \forall unt \in P; n \in N \quad (98)$$

B.5.2 Material balance constraints for tanks

Eq. (99) expresses that the inventory of crude c inside a storage/charging tank at the end of time event n is equal to the inventory at time event n-1 adjusted by inflow/outflow of crude c during time event n. Eq. (100) establishes the initial inventories for each storage/charging tanks.

$$Inv^{sct,c}(unt, c, n) = Inv^{sct,c}(unt, c, n-1) + \sum_{unt' \in IU_{unt}} V^c(unt', unt, c, n) - \sum_{unt'' \in OU_{unt}} V^c(unt, unt'', c, n), \forall unt \in SCT; c \in C; n \in N, n \geq 1 \quad (99)$$

$$Inv^{sct,c}(unt, c, n) = Inv^0(unt) f^{vol,0}(unt, c), \forall unt \in SCT; c \in C; n =' 0' \quad (100)$$

Eq. (101) gives the total inventory of a storage or charging tank at the end of time event n, which is equal to the summation over individual crude inventories inside the tank. Similarly, as shown in Eq. (102), the total crude volume transferred by an output operation from a storage or charging tank is equal to the summation over transferred volumes of individual crudes.

$$Inv^{sct}(unt, n) = \sum_{c \in C} Inv^{sct,c}(unt, c, n), \forall unt \in SCT; n \in N \quad (101)$$

$$v^t(unt, unt', n) = \sum_{c \in C} V^c(unt, unt', c, n), \forall unt \in SCT; unt' \in OU_{unt}; n \in N, n \geq 1 \quad (102)$$

Eq. (103) specifies demands of crude mixes from different charging tanks. Eq. (104) calculates inventories of key components (e.g., sulfur content) for charging tanks at the end of time event n, and Eq. (105) enforces the allowable ranges for key components inside charging tanks.

$$\sum_{unt' \in OU_{unt}} \sum_{n \in N, n \geq 1} V^t(unt, unt', n) = FD(unt), \forall unt \in CT \tag{103}$$

$$Inv^{ct,k}(unt, k, n) = \sum_{c \in C} f^{com}(c, k) Inv^{sct,c}(unt, c, n), \forall unt \in CT; k \in K; n \in N \tag{104}$$

$$f^{com,lo}(unt, k) Inv^{sct}(unt, n) \leq Inv^{ct,k}(unt, k, n) \leq f^{com,up}(unt, k) Inv^{sct}(unt, n) \forall unt \in CT; k \in K; n \in N \tag{105}$$

Eq. (106) calculates volume fractions of individual crudes inside a storage or charging tank ($V^{t,up}$) at the end of time event n. Eq. (107) ensures that the outflow volume of an individual crude ($f^{com}(c, k)$) is proportional to the total outflow volume ($f^{com,\ lo}(unt, k)/f^{com,\ up}(unt, k)$) according to the individual crude volume fraction inside the source tank ($unt \in CT$). Note that in these two equations, two continuous variables are multiplied together, which leads to bi-linear terms.

$$Inv^{sct,c}(unt, c, n) f^{vol,n}(unt, c, n) Inv^{sct}(unt, n), \forall unt \in SCT; c \in C; n \in N \tag{106}$$

$$v^c(unt, unt', c, n) = V^t(unt, unt', c, n) f^{vol,n}(unt, c, n-1), \forall unt \in SCT; unt' \in OU_{unt}; c \in C; n \in N, n \geq 1 \tag{107}$$

B.6 Variable bounds

The following constraints (Eqs. (108) through (123)) impose variable bounds.

$$0 \leq Inv^p(unt, n) \leq Inv^0(unt) \tag{108}$$

$$0 \leq Inv^{sct}(unt, n) \leq Inv^{up}(unt) \tag{109}$$

$$0 \leq Inv^{p,c}(unt, c, n) \leq Inv^0(unt) \tag{110}$$

$$0 \leq Inv^{sct,c}(unt, c, n) \leq Inv^{up}(unt) \tag{111}$$

$$0 \leq V^t(unt', unt, n) \leq V^{t,up} \tag{112}$$

$$0 \leq V^c(unt', unt, c, n) \leq V^{t,up} \tag{113}$$

$$0 \leq f^{vol,n}(unt, c, n) \leq 1 \tag{114}$$

$$0 \leq f^{vol,l}(l, c) \leq 1 \tag{115}$$

$$T^{arr}(v) \leq TV^s(v) \leq H \tag{116}$$

$$T^{arr}(v) \leq TV^e(v) \leq H \tag{117}$$

$$0 \leq TP^s(unt) \leq H \tag{118}$$

$$0 \leq TP^e(unt) \leq H \tag{119}$$

$$0 \leq T^s(unt', unt, n) \leq H \tag{120}$$

$$0 \leq T^e(unt', unt, n) \leq H \tag{121}$$

$$0 \leq Z(unt', unt, n) \leq 1 \tag{122}$$

$$0 \leq ZZ(unt', unt, n) \leq 1 \tag{123}$$

Appendix C. Detailed Scheduling Model of Hydrocracking Unit (An Example of the Developed Refinery Unit Models)

In the developed refinery model, it includes 23 different units as shown in Fig. 4. It covers processing of crude distillation, cracking, coking, reforming, hydrotreating, product blending and component recovery. Table 7 lists all these processing units and the number of model equations for each processing unit. The refinery model has 358 equations in total, not including all economic calculations in the objective function. Note that some model equations are very lengthy and complicated.

If all model equations were listed in detail plus their explanations, the paper could be extremely lengthy and dilute its merits. Note that the major contribution of our paper is the development of a scheduling model for CUTP to simulate and optimize the front-end and refinery crude-oil operations simultaneously. For considerations of general readers, we give the hydrocracking unit as an example to show its detailed model equations.

A hydrocracking unit employs hydrogen to crack light VGO into gas, naphtha, and diesel. For the vacuum residue, the heaviest intermediate product from crude distillation columns, a coking unit has to be employed to crack it into gas, LPG, naphtha, and diesel. The Gas oil feed to the hydrocracking unit includes CR1-light VGO, CR2-light VGO, CGO and CR1-catalytic heavy diesel, which comes from crude distillation units. CR1 and CR2 refer to crude oil 1 and crude oil 2 fed to the refinery, respectively. The flow rate (yield) distribution data of the hydrocracking unit has been provided by Table 8.

Based on Table 8, the detailed hydrocracking unit feedstock and output model can be described by the following equations:

$$F_{in,Feed} = F_{in,GasOilFeed} + F_{in,Hydrogen} \tag{124}$$

Table 7
Crude Processing Units inside the Refinery.

Unit Index	Unit Description	No. of Equations
1	Crude Distillation #1	40
2	Crude Distillation #2	42
3	Crude Distillation Blending	7
4	Catalystic Reforming	18
5	Hydrocracking	19
6	Catalystic Cracking	18
7	Delayed Coking	19
8	Kerosene Hydrotreating	13
9	Diesel Hydrotreating	35
10	Gas Fractionation	12
11	Alkylation	11
12	Sulfur Recovery	8
13	Vacuum Gas Oil Hydrotreating	22
14	Polypropylene	16
15	Hydrogen Plant	11
16	Dry Gas	1
17	Liquefied Petroleum Gas	1
18	Utility Fuel Gas	2
19	Fuel Oil	6
20	H_2 Pooling	3
21	Gasoline Blending	36
22	Diesel Blending	10
23	Naphtha Blending	8

Table 8
Flow Rate (yield) Distribution Data of Hydrocracking Unit.

Flow rate (yield) distribution coefficient		
Feed	Gas Oil Feed: (1) CR1-light VGO; (2) CR2-light VGO; (3) CGO; (4) CR1-catalytic heavy diesel.	0.9941
	Hydrogen	0.0059
Product	H_2S	0.0050
	Cracked Dry Gas	0.0220
	Light Naphtha	0.1215
	Heavy Naphtha	0.1467
	Diesel	0.1384
	Residue/Uncracked Heavy Component	0.5634
	Loss	0.0089

$$F_{in,GasOilFeed} = F_{in,Feed} \times 0.9941 \tag{125}$$

$$F_{in,Hydrogen} = F_{in,Feed} \times 0.0059 \tag{126}$$

$$F_{in,GasOilFeed} = F_{in,CR1-LightVGO} + F_{in,CR2-LightVGO} + F_{in,CGO} + F_{in,CR1-CatalyticHeavyDiesel} \tag{127}$$

$$F_{in,GasOilFeed} + F_{in,Hydrogen} = F_{out,H_2S} + F_{out,CrackedDryGas} + F_{out,LightNaphtha} + F_{out,HeavyNaphtha} + F_{out,Diesel} + F_{out,Residue} + F_{out,Loss} \tag{128}$$

$$F_{out,H_2S} = F_{in,Feed} \times 0.0050 \tag{129}$$

$$F_{out,CrackedDryGas} = F_{in,Feed} \times 0.0220 \tag{130}$$

$$F_{out,LightNaphtha} = F_{in,Feed} \times 0.1215 \tag{131}$$

$$F_{out,HeavyNaphtha} = F_{in,Feed} \times 0.1467 \tag{132}$$

$$F_{out,Diesel} = F_{in,Feed} \times 0.1384 \tag{133}$$

$$F_{out,Residue} = F_{in,Feed} \times 0.5634 \tag{134}$$

$$F_{out,Loss} = F_{in,Feed} \times 0.0089 \tag{135}$$

Note that the hydrogen feed the hydrocracking unit comes from the catalytic reforming unit and hydrogen plant. The property calculations are already described in the sections of the property mixing functions and mixing unit model, as shown in Eqs. (13) through (22) in the paper context. Crude property data of this study has been given in Table 2. In addition, to model the utility consumption and generation of the hydrocracking unit, utility consumption and generation coefficients have been provided by Table 9, where positive and negative sign denote utility consumption and generation, respectively.

Based on Table 9, the model equations for the calculation of utility consumption and generation of the hydrocracking unit are listed below.

$$F_{in,FreshWater} = F_{in,Feed} \times 0.2284 \tag{136}$$

$$F_{in,DesalinatedWater} = F_{in,Feed} \times 0.0384 \tag{137}$$

Table 9
Utility Consumption and Generation Data of Hydrocracking Unit.

Utility consumption and generation coefficient	
Fresh Water (t/t)	0.2284
Desalinated Water (t/t)	0.0384
Recycled Water (t/t)	17.026
Low-pressure Steam (t/t)	−0.0464
Medium-pressure Steam (t/t)	0.1367
Electricity (KWh/t)	31.055
Utility Fuel Gas (t/t)	0.0199

$$F_{in,RecycledWater} = F_{in,Feed} \times 17.026 \quad (138)$$

$$F_{out,Low-pressureSteam} = F_{in,Feed} \times 0.0464 \quad (139)$$

$$F_{in,Medium-pressureSteam} = F_{in,Feed} \times 0.1367 \quad (140)$$

$$F_{in,Electricity} = F_{in,Feed} \times 31.055 \quad (141)$$

$$F_{in,UtilityFuelGas} = F_{in,Feed} \times 0.0199 \quad (142)$$

To summarize the overall utility consumptions and generations, as shown in Eq. (60), the difference between plant purchased and sold utilities should be equal to the summation of difference between inflow and outflow utilities at each unit.

$$\mathbf{UI}_{ui,\ n} - \mathbf{UO}_{uo,\ n} = \sum_{u \in UALL} (\mathbf{UI}_{u,\ n} - \mathbf{UO}_{u,\ n}) \quad (60)$$

where $\mathbf{UI}_{ui,\ n}$ denotes utilities purchased by the plant; $\mathbf{UO}_{uo,\ n}$ denotes utilities sold outside by the plant; $\mathbf{UI}_{u,\ n}$ and $\mathbf{UO}_{u,\ n}$ are utilities consumed and generated by unit u.

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