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To cite this article:
Xuan Chen, Simin Huang, Dejing Chen, Zhihai Zhang, Li Zheng, Ignacio Grossmann, Shihui Chen (2014) Hierarchical Decomposition Approach for Crude Oil Scheduling: A SINOPEC Case. Interfaces 44(3):269-285. http://dx.doi.org/10.1287/inte.2014.0744

Interfaces
Vol. 44, No. 3, May–June 2014, pp. 269–285
ISSN 0092-2102 (print) | ISSN 1526-551X (online)

http://dx.doi.org/10.1287/inte.2014.0744

Hierarchical Decomposition Approach for Crude Oil Scheduling: A SINOPEC Case

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This work addresses the large-scale crude oil scheduling problem of China's SINOPEC Maoming refinery that imports various types of crude oil from two terminals via bidirectional long-distance pipelines. We use a hierarchical decomposition approach to construct a two-stage model of the refinery operations. In the upper-level model, storage and charging tanks are aggregated to determine the inflows and outflows between the two terminals and the refinery plant. The lower-level submodels solve the detailed loading and unloading operations at storage and charging tanks inside the terminals and the refinery plant. To further improve the computational efficiency, we develop a rule-based tank-selection strategy to obtain a feasible schedule. Although state-of-the-art commercial solvers cannot obtain feasible solutions of the relaxed monolithic mixed-integer linear programming model within a reasonable time, our decomposition heuristic can generate schedules that are more flexible than manually generated schedules. It also provides the refinery with annual estimated cost savings of $30 million.

Keywords: crude oil scheduling; hierarchical decomposition; multiple terminals; long-distance pipelines.
History: This paper was refereed.

Crude oil scheduling is the first stage of the crude oil refining process. As Figure 1 shows, this process involves unloading crude oil from marine vessels to storage tanks, transferring it, mixing it in charging tanks, and generating a charging schedule for each crude oil mixture fed to the crude distillation units (CDUs) (Lee et al. 1996). Consequently, the scheduling decision involves selecting crude flows, allocating vessels to tanks and tanks to CDUs, and calculating crude compositions.

Optimal crude oil scheduling is critical to refineries. The many varieties of crude (e.g., light and heavy crude) vary widely in their properties, processing difficulties, and product yields. Most refineries procure and process several types of crude that yield various products and a wide range of profit margins (Reddy et al. 2004b). Optimal crude oil scheduling provides cost savings by intelligently using cheaper types of crude and minimizing crude changeovers. Studies from Honeywell (Kelly and Mann 2003a, b) have reported large economic benefits associated with better scheduling of crude oil blending. However, schedulers in most Chinese refineries have until now largely relied on their experience to make these decisions.

Researchers have developed many models and solution techniques for the crude oil scheduling problem; these techniques primarily involve mixed-integer linear programming (MILP) or mixed-integer nonlinear programming (MINLP) (Méndez et al. 2006). Depending on whether the events in the schedule can occur only at some predefined time or at any time during the schedule's horizon, models can be classified as discrete time formulations (Shah 1996, Lee et al. 1996, Wenkai et al. 2002, Reddy et al. 2004b) or continuous time formulations (Reddy et al. 2004a, Moro and Pinto 2004, Jia et al. 2003, Jia and Ierapetritou 2004), respectively.

In this paper, we discuss our solution for the large-scale crude oil scheduling problem of a multiregional refinery connected by bidirectional long-distance pipelines—a solution that has not been addressed in

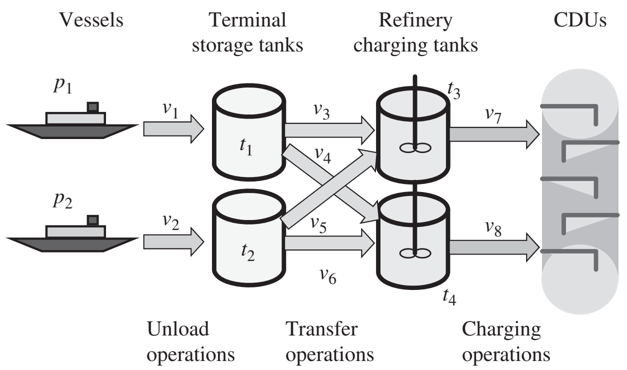

Figure 1: The diagram illustrates crude oil scheduling operations (Lee et al. 1996).

the literature. Although industrial applications based on mathematical programming techniques have been reported in the literature (Más and Pinto 2003, Magalhães and Shah 2003), the complexity of crude scheduling operations and the intractability of mathematical models have resulted in proposals for other exact and heuristic approaches; these include the event-tree search method (Zou et al. 2010), a combination of MILP models and expert systems (Bok et al. 2002, Pan et al. 2009), model-based decomposition heuristics (Kelly 2002, Kelly and Mann 2004), random search methods (Chryssolouris et al. 2005), and Petri net-based heuristics, which preassign a number of charging tanks to each CDU (Wu et al. 2007, 2010). None of these approaches is readily applicable to our problem. The multiproduct pipeline scheduling problem is also a fertile research field (Magatão et al. 2002, 2004; Lopes et al. 2010; Boschetto et al. 2010b, a; Cafaro and Cerdá 2010); however, to the best of our knowledge, the multi-regional crude oil scheduling (or tank-farm scheduling) problem integrated with bidirectional long-distance pipelines has not been reported. The scheduling of multiproduct pipelines (or pipeline networks) generally includes decisions on batch sizing and batch sequencing. In addition, the crude oil scheduling problem involves batch-mixing (i.e., the blending of crude) decisions and selecting batch operations (e.g., from the outlet tank to the inlet tank), making the problem significantly more complex. Therefore, we resort to a hierarchical decomposition methodology to obtain efficient and satisfactory solutions.

Crude Oil Scheduling in the SINOPEC Maoming Company

In this section, we present a brief introduction to the crude oil scheduling problem at the SINOPEC Maoming Company (SINOPEC) and discuss its distinct features and the decision process.

SINOPEC Maoming Company

SINOPEC, a subsidiary of China Petroleum & Chemical Corporation, is the largest petrochemical company in South China with an annual crude oil processing capacity of 96.5 million barrels and an annual ethylene processing capacity of 300,000 million tons; it also has the necessary support systems for its power supply, port handling, railway transport, crude and product oil transfer pipelines, and a 300,000-tonnage single-buoy mooring (SBM) offshore crude loading and unloading system. SINOPEC owns $5.5 billion of fixed assets and has 10,790 employees. In 2010, its annual tax was $3.1 billion and its annual profit was $740 million.

Figures 2 and 3 depict the refinery's geographical region and macro-level configuration, respectively. The refinery branch consists of the Zhanjiang (Z) terminal, the Beisanling (B) terminal, the Maoming (M) refinery plant, and two crude transfer pipelines that connect the two terminals and the plant—the Zhanmao (ZM) pipeline and the Bei-mao (BM) pipeline. Terminal Z is a natural deep harbor with two jetties (Jetty A and Jetty B) and limited storage capacity on its tank farm. Terminal B, although it has a much higher storage capacity, is not a natural deep-water

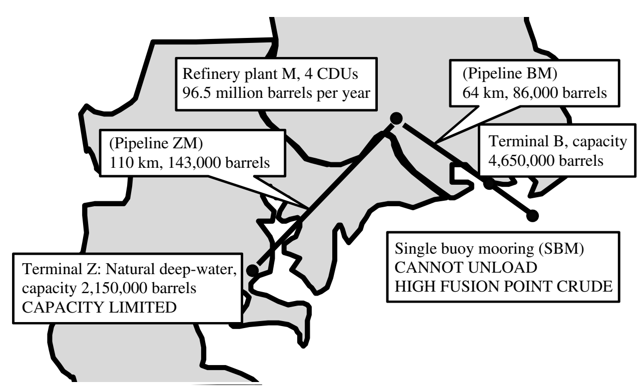

Figure 2: Long-distance, bidirectional pipelines from two terminals on the coast feed the inland refinery located at Maoming.

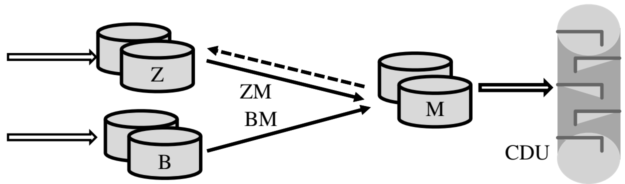

Figure 3: The graphic shows the configuration of the SINOPEC Maoming refinery.

terminal. Therefore, the refinery built a SBM 30 kilometers from terminal B and connected by a submarine pipeline. The SBM is a loading buoy anchored offshore, and serves as a mooring point and interconnect for tankers offloading crude oil. It is capable of handling any size ship, even very large crude carriers (VLCCs) when no alternative facility is available. Fifteen storage tanks are located in both terminals B and Z, and in refinery plant M. Pipeline ZM connects terminal Z and refinery M, is 110 kilometers long, and has a capacity of about 143,000 barrels. Pipeline BM connects terminal B and refinery M, is 64 kilometers long, and has a capacity of about 86,000 barrels. Because both are long-distance pipelines, the inlet and outlet flows of pipeline ZM and BM are asynchronous. Four CDUs and 15 charging tanks that feed crude oil to the CDUs are located at the inland refinery plant M. Each CDU is designed to process different types of crude with various specifications. In general, crude from terminal Z feeds CDU1 and CDU2, while crude from terminal B charges CDU3 and CDU4. If the crude from terminal Z is not sufficient, CDU1 and CDU2 process crude from terminal B. Other than for planned temporary shutdown of production (e.g., for maintenance), each CDU must operate continuously and the processing rate must be within a lower and upper limit. Frequent changeovers and process-rate fluctuations must also be avoided.

Refinery Features and Constraints

The refinery has the following distinct features and operational constraints.

- Crude storage segregation mode

—Tanks and CDUs usually store or process only specific types of crude, because crude types vary significantly in their properties and ability to be processed.

—Refineries reported in the literature (Lee et al. 1996, Reddy et al. 2004a, b) allow the mixing of crude prior to charging the CDUs. Based on our experiences at several refineries of SINOPEC and PetroChina, each CDU should process only specific types of crude. Consequently, storing different types of crude in the same tank or blending different types of crude before charging the CDUs is usually unnecessary and undesirable.

- Special treatment of crude oil transportation

—High-pour-point and high-viscosity crude oil (HPHVC) cannot be stored in storage tanks or transported via the long-distance pipeline without special treatment (e.g., heating, blending with a specified proportion of light crude, or both).

—Because of its aboveground unloading lines and heating devices for storage tanks, HPHVC can be unloaded at terminal Z. However, because the submarine pipeline connects the SBM and terminal B, HPHVC cannot be unloaded at the SBM. Other types of crude oil, including light oil, are usually unloaded at this terminal.

—To safely transfer certain types of HPHVC from terminal Z to plant M, blending HPHVC with light crude to avoid pipeline freezing is mandatory. More specifically, each type of high-pour-point, high-viscosity, or high-sulfur crude must be blended with a specified type and proportion of light crude, which the refinery's laboratory determines. The blending process is commonly finished inside the long-distance pipeline. That is, multiple tanks simultaneously store different types of crude and feed the pipeline by taking into account the operational constraints. The mixture of multiple types of crude inside the pipeline is denoted as a new type of crude.

- Bidirectional long-distance pipeline

—Similar to the system that Reddy et al. (2004a, b) discuss, crude arrives in either large multiparcel tankers or small single-parcel vessels. Because terminal Z's capacity is limited, this terminal is the system's bottleneck. Accordingly, VLCCs, which carry large amounts of light crude from the Middle East, cannot unload at terminal Z. Therefore, light crude needed at terminal Z is transferred from terminal B to plant M via pipeline BM, and then from plant M to terminal Z via pipeline ZM. We call the transfer operation from plant M to terminal Z, which takes place about once monthly, the backward or reverse transfer. It then follows that pipeline ZM is bidirectional.

—Although pipeline BM can always operate because its transfer rate can be adjusted according to the inventory level of plant M, pipeline ZM occasionally shuts down because the capacity of terminal Z is much smaller. When it is shut down, pipeline ZM should not be filled with high-viscosity crude to avoid pipeline freezing. Therefore, before the pipeline is shut down, an operation called cleaning transfer is performed to inject a specific amount of light crude into pipeline ZM to push out all the HPHVC inside the pipeline. This light crude would flow back to terminal Z if the follow-up operation is reverse transfer.

—Unless an operation to clean pipeline ZM or blend the light crude with high-pour-point, high-viscosity, or high-sulfur crude has occurred, terminal Z commonly does not feed light crude into pipeline ZM.

Figure 4 shows the forward transfer process, the pipeline stoppage, and the reverse transfer of pipeline ZM. During period $t-1$, the pipeline transfers forward the HPHVC. From period t to $t+5$, the cleaning transfer operation injects light crude into the pipeline to discharge the HPHVC inside the pipeline. After stoppage from period $t+6$ to $t+9$, the reverse transfer begins from period $t+10$ to $t+17$. The forward transfer then begins again from period $t+18$, and so forth.

Decision Procedure for the Refinery

Similar to the decision process described in Shah et al. (2009), plant M has two decision levels, that is, the quarterly plan level and the 10-day plan level. Given demand forecasts, the quarterly plan determines

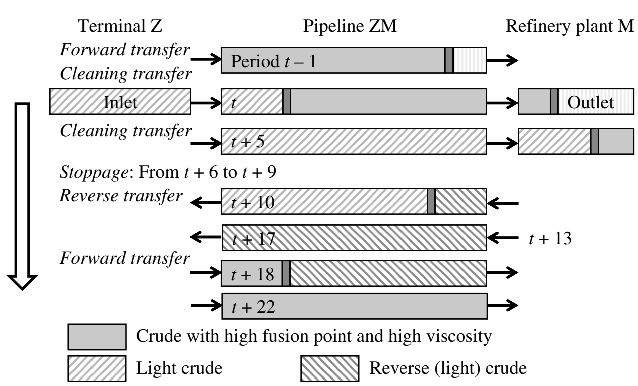

Figure 4: The figure shows an example of the transfer process of the bidirectional long-distance pipeline.

the variety and volume of crude oil needed for the upcoming three months, and the type and estimated quantities of final products to be ordered. Based on the quarterly-plan results, the 10-day plan determines the detailed schedule for unloading crude oil from vessels into storage tanks, transporting crude oil between terminals and the plant, and feeding the CDUs at various rates over time according to the production plan by considering the operational constraints.

SINOPEC's manual 10-day plan has the following shortcomings. First, it is complicated, time consuming, and not flexible enough to allow rescheduling when supply chain disruptions occur. Obtaining the detailed crude oil schedule usually takes hours. Human errors and inconsistencies are easily introduced into the schedule. Second, because the schedule is developed in a user-driven simulation environment with Aspen ORION in the SINOPEC refinery, the overall process cannot be optimized from a system perspective. Therefore, we commonly see that (1) the CDUs run out of crude and the transportation of HPHVC is delayed because of a lack of light crude, or (2) the amount of crude is sufficient, but some CDUs must process the low-grade crude. In addition, manual schedules rely heavily on the scheduler's experience and skills.

Problem Definition

We now state SINOPEC's multiregional crude oil scheduling problem.

- Given the following:

—A refinery configuration and two terminals (i.e., numbers of CDUs, storage tanks, and berths, and the interconnections among them), as Figure 2 shows;

—Built-in system attributes, including the set of crude types, crude segregation mode of storage and processing, and upper and lower inventory levels of tanks;

—System operational parameters, including the start and end time of the scheduling horizon, the minimum crude settling time, limits on the number of simultaneously connected tanks for all operations, and flow-rate limits for all operations and resources;

—Initial state of the system, involving initial distribution of crude inside pipeline ZM (BM) and the initial transfer direction, initial crude types and initial inventory levels of terminal and refinery tanks, and initial crude type of distillation and processing rate of each CDU;

—Information on vessels at each terminal (i.e., system supply), including arrival times, crude types, volumes, and the unloading sequence of their parcels, updated in real time according to crude suppliers and shipping companies;

—Production plan of each CDU, based on higher-level planning decisions (i.e., system demand); and

—Economic parameters, including unit costs of various operations and crude distillation profits;

- Determine the

—Detailed unloading schedule for each vessel.

—Inventory levels and composition profiles of storage and charging tanks during the scheduling horizon.

—Detailed transfer schedule of pipeline ZM-BM, including the cleaning and reverse transfer operations.

—Detailed crude feeding profiles for CDUs.

- Objectives:

—Maximize the total crude distillation profit.

—Minimize the waiting time, and consequently the demurrage cost of each vessel.

—Minimize the changeover cost of tanks, pipelines, and CDUs.

—Minimize the cost of undesirable blending of various varieties of crude.

- Operational rules:

—The five categories of operating rules (constraints) are safety rule, interconnection rules, sequence rules of operations, mass and crude composition balance, and capacity limits. The appendix shows detailed constraints.

In summary, we study the scheduling of a system (see Figure 2) that differs substantially from previous work reported in the literature. The system consists of multiple regions distributing and sharing crude through long-distance, possibly bidirectional, pipelines. Mixing different varieties of crude oil should be avoided (except for required or planned blending) before delivering the crude to the CDUs. HPHVC can only be unloaded, transferred, or processed if special treatments have been applied. These practical constraints make the system difficult to model. However, the large number of discrete variables poses a challenge to solving the model. The various types of crude processed (up to 20), the number of CDUs (four CDUs, each of which is designed to distill different types of crude), and the number of storage and charging tanks (45 tanks) make this problem computationally intractable. Therefore, our objective is to obtain satisfactory and flexible solutions to the problem within reasonable time limits.

Practitioner Perspectives

Crude oil scheduling in actual (i.e., real-life) plants exhibits behavior that differs from the common assumptions used in the literature (Lee et al. 1996, Reddy et al. 2004b). Next, we present some of our industrial collaborators' work, based on their operating and management experiences at such plants.

The Scheduling Objective. The crude oil scheduling problem is inherently multiobjective. In their pioneering work, Lee et al. (1996) try to minimize operational costs, including sea-waiting costs and the costs of inventory, unloading marine vessels, and CDU changeovers. Magalhães and Shah (2003) minimize the deviation of the planned and scheduled amounts for crude when solving the crude oil scheduling problem at PETROBRAS' REFAP refinery in Brazil. Mouret et al. (2010) focus on maximizing crude distillation profit for the current scheduling period, as required by TOTAL in France. Reddy et al. (2004a, b) study the crude oil scheduling problem of coastal refineries based on the information provided by the Singapore Refining Company; they consider both profit and operational cost. However, when they execute the generated schedules, they include additional operational costs, such as the changeover costs of tanks and pipelines, utility costs of storing and transferring crude oil, and waste costs that result from undesirable crude mixtures. Including all these objectives in the objective function is unrealistic, because many of them are difficult to express in economic terms. For example, Shah and Ierapetritou (2011) consider the crude oil scheduling problem by incorporating logistic constraints. However, they add too many penalty items to the objective function, in which the weight coefficients are difficult to determine in actual plants. In addition, they consider the continuous and smooth production of the refinery to be the primary goal. That is, if CDU demands are not satisfied, the objectives that aim to reduce operational costs, such as minimizing pipeline changeovers and undesirable crude mixtures, are not relevant. From the viewpoint of the plant manager, a schedule that satisfies all the demands with minor unnecessary mixing is preferable to a schedule that avoids mixing but does not meet production demands. This reflects the soft constraints in real-world problems—not hard mathematical constraints; these objectives are hierarchical with different priorities. Optimizing them simultaneously would be inappropriate; objectives with different priorities should be optimized within different levels.

- First, safety should always be the highest priority. For example, the continuous operations of units should be guaranteed in case of equipment explosion, and the temperature of the crude inside the pipeline should not fall below its fusion point.
- Second, customer orders (i.e., demand) should be satisfied, including the demand flow in the inner subsystems. With this as a prerequisite, crude should be distilled intelligently to make as much profit as possible.
- Third, operational costs incurred from unloading, storage, transfer, and charge operations should be minimized. This includes the costs of vessel demurrage, utilities, undesirable crude mixtures, and changeovers.

Moreover, feasibility, which we can define as *satisfying the planning decisions* or *distilling different types of crude at their corresponding most-profitable CDUs*, rather than global optimality, is the major concern in practice. Consequently, a more straightforward optimization process is to first balance and optimize the amount of crude inflow and outflow globally; the mathematical model can optimize efficiently and globally. Detailed scheduling with a large number of discrete decisions can then be solved locally or heuristically to yield near-optimal solutions in significantly less CPU time than the current mixed-integer programming process, which cannot produce optimal or even feasible solutions within a reasonable computation time. Because this methodology mimics the practical two-level planning and scheduling decision process, it is more intuitive to schedulers. Incorporating the relaxed scheduling constraints into the upper-level planning model to avoid over-optimization of the planning layer and infeasibility of the lower-level problem is critical to implementing this methodology.

Modeling Crude Oil Blending. Models in the literature (Lee et al. 1996, Reddy et al. 2004b) generally use the blending setting to impose constraints on the upper and lower limits of the key-component concentration (e.g., the sulfur concentration) of tanks or CDU feedings. However, at SINOPEC, our industrial collaborators tend to use the crude-by-crude setting. Table 1 shows a typical refining schedule for a CDU. The CDU would process either a single type of crude (Crude A from Tank T127) or an instant blend of two types of crude (50 percent Crude A from Tank T127 and 50 percent Crude C from T182) or crude mixture (Crude B and Crude D, blended before transferring to Tank T129, possibly inside long-distance pipelines). Therefore, we need to define the quadruple-indexed binary variable to indicate whether a CDU distills a type of crude from a tank during a given period. Despite the large increase in the number of binary variables, the advantage of the crude-by-crude setting is that it conforms to the scheduler's experience. When supply chain disruptions occur (e.g., the late arrival of crude vessels), modifying the current schedule would be more intuitive and safer. Although the blending setting introduces no additional binary variables, its results are confusing to the scheduler. We know that the mathematical programming models tend to set the variables at their bounds to obtain optimal economic objective values. When disruptions occur (e.g., the insufficiency of a certain type of crude or key component caused by the delayed arrival of a vessel), the scheduler must decrease the processing rate or stop one of the units, producing production instability or an unsafe operation.

Crude	Crude A	Crude A + Crude C	Crude mixture B + D
Tank	T127	T127 (50%) + T182 (50%)	T129
Tank vol.	5,722		
Start	2011-7-29 5:15	2011-7-29 22:00	2011-8-1 19:40
End	2011-7-29 22:00	2011-7-31 14:23	2011-8-5 13:38

Table 1: This example of a typical refining schedule for a CDU shows the crude-by-crude setting.

The Decomposition Framework

We initially tried to apply different models from the literature (Reddy et al. 2004a, b; Jia et al. 2003) to solve the problem. We excluded constraints that make the problem difficult to model, such as the bidirectional feature of the pipeline, bilinear terms results from crude oil blending (i.e., variable volume multiplied by variable concentration), and unavoidable tank bottoms. Despite these simplifications, the state-of-the-art commercial

MILP solvers could not obtain a feasible solution for the large-scale monolithic model in several hours. We were unable to obtain a feasible 10-day schedule of the refinery plant subproblem without considering the two terminals.

To reduce the computational time, we break the monolithic model into two levels (see Figure 5). In principle, the upper-level model (solved by XPRESS-MP) determines high-level decisions of distributing crude resources among regions (i.e., the refinery plant and two terminals) in a tank-aggregated way, whereas the lower-level problem allocates these crude resources to specific tanks. Given some parameter values, the upper-level problem determines the transfer schedule of the long-distance pipelines (i.e., the type and amount of crude each region receives or feeds during each period) and the charging schedule of the CDUs (i.e., the type and amount of crude each CDU processes during each period). Based on these schedules, the lower-level subproblems determine the feeding and receiving schedule of tanks in each region and the unloading schedule of marine vessels at terminals. If the lower-level subproblems are infeasible, we can adjust the parameters of the upper-level model accordingly.

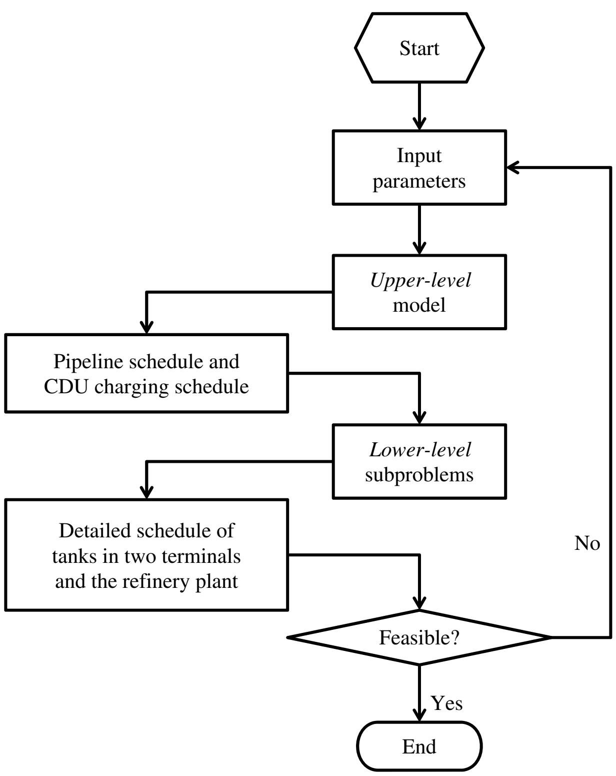

Figure 5: The flowchart shows the framework of the hierarchical decomposition methodology.

Next, we list all constraints of the upper-level model; in the appendix, we present the complete upper-level MILP model (the numbers in parentheses refer to the item numbers in the appendix).

- CDU constraints
  —Processing rate limits. (1)
  —Processing rate smoothness. (2)
  —Processing variety. (3)
  —Processing variety continuity. (4)
  —Safety stock of crude for each CDU. (5)
- Refinery plant constraints
  —Upper limit of crude inventory of refinery plant M. (6)
  —Lower limit of crude inventory of refinery plant M. (7)
- Terminal constraints
  —Upper and lower limits of inventory of terminals Z and B. (8)
  —Safety stock of light crude in terminal Z. (9)
- Pipeline constraints
  —Changeovers of pipeline. (10)
  —Transfer stability of pipelines. (11)
  —Transfer rate limits of pipeline BM. (12)
  —Transfer rate limits of pipeline ZM (forward). (13)
  —Transfer rate limits of pipeline ZM (reverse). (14)
  —Smoothness of transfer rate of pipelines ZM and BM. (15)
  —Reverse transfer of pipeline ZM. (16)
  —Pipeline ZM reverse transfers at most once. (17)
  —Stoppage and forward transfer of pipeline ZM. (18)
  —Initial holdups inside pipelines ZM and BM. (19)

In the upper-level model, the high-level economic objectives, we consider only the resource balance (among two terminals and the refinery plant M) and do not involve the lower-level operations of the storage and charging tanks. Reasonably aggregating the demands of the refinery and the two terminals is key to this process. The basic concepts are as follows.

- We employ a buffer-time vessel-unloading parameter to aggregate the terminals' supply. Parameters S_{BM}^{UL} and S_{ZM}^{UL} in item (8) in the appendix represent the estimated time of vessel unloading in terminals B and Z, respectively. The upper-level model, although it omits the detailed unloading operations of vessels into storage tanks in terminals, considers that the crude carried by vessels arriving at terminal B (Z) is available for use in the refinery plant S_{BM}^{UL} (S_{ZM}^{UL}) periods after the vessel arrivals.

- We incorporate the storage and charging tank inventory capacity constraints in the upper-level model in a tank-aggregated way; see items (5)–(9) in the appendix. We use η_M, the maximum inventory ratio for all the charging tanks in the refinery plant, and other safety stock parameters (e.g., S_u^V, S_M^V, S_Z^{VLC}) to control the inventory of crude in the two terminals and the refinery plant, indirectly regulating the transferred types of crude and the transfer rate of pipelines.
- We introduce the buffer time parameters of pipeline transportation and changeover to implicitly model the complex constraints of the pipelines. The buffer time parameters (S_{BM}, S_{ZM}, and S_{MZ}) denote that the timing of crude oil transported from the terminal to the refinery plant is adjusted to consider the transportation time, as in Shah (1996).

—Item (16) models the changeover from reverse transfer to forward transfer (possibly going through stoppage after reverse transfer) of pipeline ZM. Instead of modeling the details of the transfer operations of pipeline ZM, we allocate a few periods ($S_{MZ} + S_{ZM}$ periods) to such operations, and therefore treat the long-distance pipeline as instant inlet and outlet. Consider Figure 4 as an example. The reverse light crude injected into the pipeline from period $t+13$ to $t+17$ returns to refinery plant M during period $t+18$ to $t+22$. By eliminating period $t+13$ to $t+22$, the changeover from reverse transfer to forward transfer is instantaneous.

—Item (18) depicts the transfer stoppage and the cleaning transfer operation between two consecutive forward transfer operations (i.e., the forward-stoppage-forward transfer state of pipeline ZM, the last few periods of the forward transfer operation before stoppage injects light crude into the pipeline to avoid pipeline freezing; we refer to this as cleaning transfer). Consequently, the first few periods (S_{ZM}^{CL} periods, or the periods until the end of the scheduling horizon) of the forward transfer operation after stoppage discharge light crude oil into refinery plant M.

Next, we discuss the lower-level problem. Following the resource balance stage, the primary objective of the lower-level subproblems is to determine detailed tank operations (i.e., to allocate the (already-known) resource demands to specific tanks). The lower-level model is similar to the model in Reddy et al. (2004b). We do not include the lower-level subproblems because of space limitations. However, they are available upon request.

The lower-level subproblems can be solved by commercial MILP solvers. However, because of the large number of discrete decision variables with triple indices (e.g., crude type, tank, period), the solution time is usually too long for industrial applications. Therefore, we propose a heuristic tank-allocation policy, based on the experience of the scheduler from the M refinery to efficiently obtain pragmatic and reliable schedules. The lower-level problem involves only the decisions of selecting tanks to receive or feed crude. These decisions are made period by period on the basis of operating rules (e.g., we give priority to tanks filled with the same or similar types of crude, or empty tanks) to avoid undesirable crude mixtures and degradation.

Implementation and Applications

SINOPEC is a state-owned company. We had the full support of its senior management to do the work we present in this paper. In early 2009, the company's general manager, aware that modern operations research tools could improve SINOPEC's competitiveness, contacted our department to propose launching this project to optimize crude oil scheduling. Figure 6 and the decomposition framework in Figure 5 illustrate how

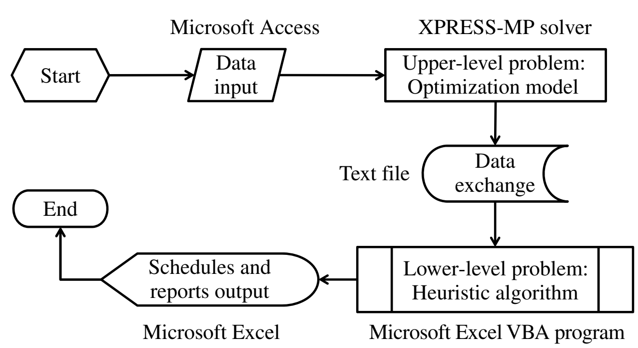

Figure 6: The flowchart illustrates the implementation of the proposed decomposition approach.

we developed an implementable solution for the optimization problem. Our scheduling software employs a hierarchical decomposition approach using Excel VBA. The program's output includes detailed schedules of vessel unloading, pipeline transfer, and CDU charging, and inventory profiles of vessels and tanks. Relevant data are exported from the company's existing enterprise resource planning (ERP) and Aspen ORION systems. In addition to the Aspen ORION system, an Excel VBA program serves as a decision support tool. As the direct end user of the program, the scheduler expressed support for the program, which reduced his workload and also helped to systematically optimize the crude oil scheduling process. Our approach was more efficient than the manual scheduling process that took an experienced scheduler about one day using the ORION system.

In this paper, we present three problem instances corresponding to three scheduling horizons of the refinery (the last 10-day period of August 2009 and the middle and last 10-day periods of December 2009). In all problem instances, all types of crude were distilled at their corresponding most-profitable CDUs (see Table 2). Although we cannot discuss the precise cost savings because of a confidentiality agreement, the conservative estimated annual cost reduction is $30 million, four percent of SINOPEC's annual profit in 2010.

Next, we present the detailed results of the first 10-day period of December 2009 as an example.

	Aspen ORION	Proposed method
Last Aug-2009		
Pipeline	15	6
CDU	12	9
Tank	25	22
Middle Dec-2009		
Pipeline	20	17
CDU	9	11
Tank	34	30
Last Dec-2009		
Pipeline	12	9
CDU	9[a]	6
Tank	32	26

Table 2: A comparison of our schedules to manually obtained schedules shows that the total number of changeovers of pipelines, tanks, and CDUs was reduced on average by 19.05 percent.
[a]CDU3 is shut down.

We solved this instance on a Pentium M processor with 1.60 GHz and 1.99 GB memory using the upper-level model, and the lower-level submodels or the heuristic tank-allocation algorithm. In this scheduling horizon, CDU3 can either be shut down for annual inspection or kept in production. Although the scheduler's actual refinery schedule, generated using the spreadsheet-based ORION system, specified shutting down CDU3, the plant manager could analyze other scenarios to facilitate decision making, thus allowing the proposed method to easily generate two schedules.

1. All CDUs operated continuously, and we solved each model with XPRESS-MP 2008 with a gap smaller than one percent. The upper-level model had 9,075 equations, 4,133 variables, and 1,265 discrete variables. Note that the number of equations and discrete variables increases approximately linearly with the number of types of crude (10 in this instance) and the number of periods (40 in this instance). The total CPU time of the upper-level and three lower-level submodels was 1,873 seconds (31.2 minutes). Because we can concurrently solve the three lower-level submodels, the total CPU time for solving the problem was 1,361 seconds (22.7 minutes).

2. CDU3 was shut down and pipeline ZM did not reverse transfer as specified in the scheduler's refinery schedule. We solved the upper-level model with XPRESS-MP 2008 in 600 seconds and solved the lower-level subproblems using the heuristic tank-allocation algorithm in about three seconds. Figure 7 shows the detailed schedule of refinery plant M, as generated by our model and the Excel VBA program. Each crude type is represented by a color (not shown in the black-and-white representation in Figure 7), and cell blocks of the same color indicate that during these periods, both the type and amount of crude fed or received by the unit (tank or CDU) do not change. Numbers in the cell indicate the flow rate (i.e., the amount of crude charged each period); F denotes feed, R denotes receive, U denotes unload, Line 1 denotes pipeline ZM, and Line 2 denotes pipeline BM.

Conclusion

This study focused on a large-scale multiregional crude oil scheduling problem at SINOPEC; this problem was not previously addressed in the literature. We proposed a two-stage decomposition scheme that generates

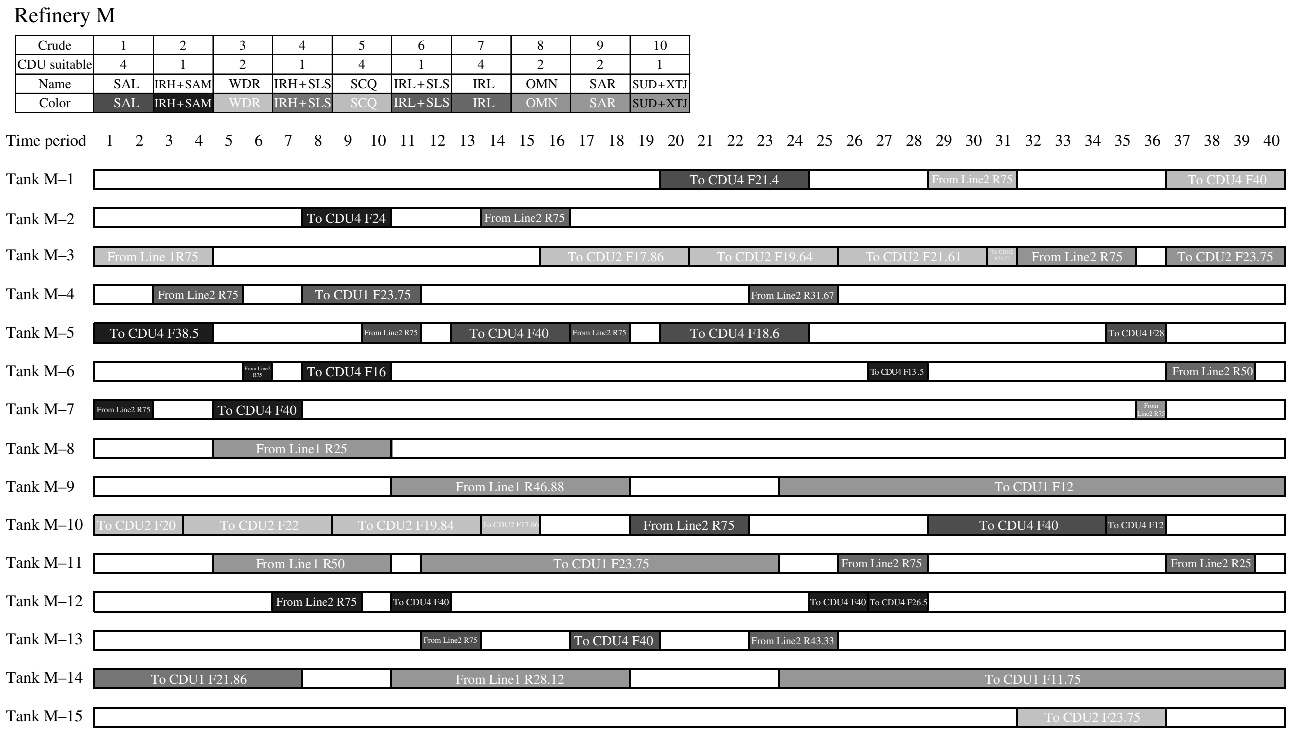

Figure 7: A Gantt chart of refinery plant M is shown for the first 10-day period of December 2009.

smaller tractable subproblems. Based on a uniform discrete-time representation, the upper-level model allocates different types of crude oil among multiple regions, optimizing economic objectives. The lower-level submodels are then solved to obtain detailed schedules within each region, focusing on feasible operations. We adopted a rule-based tank-allocation algorithm to efficiently obtain pragmatic schedules. In this way, the scheduler can focus on strategic decisions and leave the tedious process of generating detailed schedules to the software, which systematically generates optimal schedules.

Appendix. The Upper-Level Model

We present the upper-level model using the decomposition framework shown in Figure 5. The uniform discrete-time representation is used to partition the scheduling horizon into N_T identical periods ($t = 1, 2, \ldots, N_T$), with the time interval of each period as six hours. As Wassick and Ferrio (2011) point out, industrial practitioners tend to use the discrete-time representation because it is simple and applicable to general processes.

Our main assumptions are as follows: the changeover time between different tasks at each unit is negligible, the crude flow in any pipeline is plug flow (i.e., the velocity of the crude is assumed to be constant across any cross-section of the pipe perpendicular to the axis of the pipe), and crude mixing is applicable in long-distance pipelines. Furthermore, to model the rule that each tank can store at most one type of crude at a time while maintaining the tank bottom, the initial inventory in each tank in the proposed model equals the real inventory minus the heel, and the maximum storage capacity equals the real capacity minus the heel, with the minimum crude level as zero. In this way, we maintain linearity and the model developed is a MILP problem.

Nomenclature

Key notations

$bm/zm/mz$	Denotes the forward transfer of pipeline BM, the forward transfer of pipeline ZM, and the reverse transfer of pipeline ZM, respectively.
i/o	Denotes the inlet and outlet operations of pipelines.
Prefix f	Denotes variables of crude oil amount.
Prefix F	Denotes parameters of crude oil amount per period.

Prefix x Denotes binary variables of the operating states (unloading, transfer, and charging).
Prefix y Denotes changeovers.

Indices and sets

$B/Z/M$ Set of tank $b/z/m$ at terminal B/terminal Z/refinery plant M.
C Set of crude c.
C_L Set of light crude c_L, $C_L \subseteq C$.
C_u Set of crude that can be processed by CDU u, $C_u \subseteq C$.
$P_A/P_B/P_C$ Set of parcel $p_A/p_B/p_C$ carried on vessels arriving at Jetty A of terminal Z/Jetty B of terminal Z/terminal B.
P_AC Set of (p_A, c) satisfying that parcel p_A carries crude c; P_BC and P_CC are similar.
P_AT Set of (p_A, t) satisfying that the arrival time of p_A is no later than t; P_BT and P_CT are similar.
T Set of period t, $t = 1, 2, \ldots, N_T$.
U Set of CDU u.

Parameters

η_M Upper limit on the utilization ratio of the total storage capacity of the refinery plant M.
γ_u^U Upper limit on the fluctuation of processing rates of CDU u in two adjacent periods.
$\tau_{c',c}$ Proportion of c to c' when pipeline ZM is transferring c' (e.g., c' is a blend of c and some other type of crude; Table A.1 shows an example).
C^{set} (\$) Cost per pipeline changeover.
C_{uc}^{prof} (\$/kbbl) Unit profit margin of processing crude c in CDU u, where kbbl represents 1,000 barrels.
$[\underline{F}_{BM}, \bar{F}_{BM}]$ (kbbl) Lower and upper limit of the amount of crude transferred each period if pipeline BM is transferring; $[\underline{F}_{ZM}, \bar{F}_{ZM}]$ and $[\underline{F}_{MZ}, \bar{F}_{MZ}]$ are similar.
F_{ZM}^{CL} (kbbl) Amount of light crude fed to pipeline ZM each period when forward cleaning pipeline ZM; F_{MZ}^{CL} is similar for reverse cleaning.
$[\underline{F}_u^U, \bar{F}_u^U]$ (kbbl) Lower and upper limit of the amount of crude processed by CDU u.
F_{u0}^U (kbbl) Amount of crude processed by CDU u during the last period of the previous horizon.
N_{CT} Minimum number of periods during which the type of crude transferred in the long-distance pipeline does not change.
$P_{p_A}^S$ (kbbl) Size of parcel p_A; $P_{p_B}^S$ and $P_{p_C}^S$ are similar.
S_{BM} Number of periods between flow in and out of pipeline BM; S_{ZM} and S_{MZ} are similar.
S_{ZM}^{CL} Number of periods needed when cleaning pipeline ZM.
S_u^{CT} Number of periods between two changeovers on CDU u.
S_b^T Number of periods for settling of tank b after receiving crude; ST_m and ST_z are similar.
S_M^T Number of periods for settling of each tank at the refinery plant M after receiving crude; S_Z^T is similar.
S_{BM}^{UL} Safety transfer time (number of periods) of crude from any vessel just arriving at terminal B to tank farm at the refinery plant M; S_{ZM}^{UL} is similar.
$\underline{V}_M$ (kbbl) Safety inventory level for the refinery plant M at the end of the scheduling horizon.
$\underline{V}_u$ (kbbl) Lower limit on the total inventory of crude, which is suitable for processing in CDU u at the refinery plant M at the end of the scheduling horizon.
$\underline{V}_Z^{LC}$ (kbbl) Safety inventory of light crude for terminal Z at the end of the scheduling horizon.
V_{bc0}^{CT} (kbbl) Initial inventory of crude c in tank b; V_{mc0}^{CT} and V_{zc0}^{CT} are similar.
$[\underline{V}_m^T, \bar{V}_m^T]$ (kbbl) Lower and upper limit on the inventory level of tank m.

Variables

Binary variables

x_t^{bm} If refinery M is receiving crude from pipeline BM during period t and the crude comes from terminal B, then it equals 1, otherwise 0; x_t^{zm} (forward) and x_t^{mz} (reverse) are similar.
x_{ct}^{fcimz} If refinery M is feeding crude c reversely to pipeline ZM during period t to transfer it to terminal Z, then it equals 1, otherwise 0; x_{ct}^{fcobm} and x_{ct}^{fcozm} are similar.
x_{uct}^{fctu} If refinery M is feeding crude c to CDU u during period t, then it equals 1, otherwise 0.
x_t^{roizm} If during the latest transfer period before t (including t), pipeline ZM is forward transferring, then it equals 1, otherwise 0.

0-1 *continuous variables*

y_{ut}^{tu} If a changeover occurs on CDU u at the start of period t, then it equals 1, otherwise 0.
y_t^{fcimz} If the type of crude fed to pipeline ZM by refinery M changes at the start of period t, then it equals 1, otherwise 0; y_t^{fcobm} and y_t^{fcozm} are similar.
y_{ut}^{fcu} If the type of crude processed in CDU u changes at the start of period t, then it equals 1.
y_t^{fimz} If refinery M starts or stops to feed crude to pipeline ZM at the start of period t, then it equals 1, otherwise 0; y_t^{fobm} and y_t^{fozm} are similar.

Continuous variables

f_{ct}^{cibm} (kbbl) The amount of crude c fed by tank farm at terminal B to pipeline BM during period t; f_{ct}^{cimz}, f_{ct}^{cizm}, f_{ct}^{cobm}, f_{ct}^{comz}, and f_{ct}^{cozm} are similar.
f_{uct}^{cu} (kbbl) The amount of crude c fed to CDU u during period t.
f_t^{ibm} (kbbl) The amount of crude fed by tank farm at terminal B to pipeline BM during period t; f_t^{imz}, f_t^{izm}, f_t^{obm}, f_t^{omz}, and f_t^{ozm} are similar.

f^u_{ut} (kbbl) The amount of crude fed to CDU u during period t.
r^{timz}_t Latest period before t (including t) when refinery M is reverse feeding crude to pipeline ZM to transfer it to terminal Z.
r^{tozm}_t Latest period before t (including t) when refinery M is receiving crude that comes from terminal Z from pipeline ZM.
v^{ctm}_{ct} (kbbl) The inventory of crude c in tank farm at refinery M at the end of period t.

Model

In the upper-level model, the scheduling objectives are to maximize the crude processing profit and to minimize changeovers of the two pipelines:

$$\text{minimize}\left\{-\sum_{u\in U}\sum_{c\in C}\sum_{t\in T}C^{\text{prof}}_{uc}\cdot f^{cu}_{uct} + C^{\text{set}}\sum_{t\in T}(y^{fozm}_t + y^{fobm}_t)\right\}. \quad (1)$$

Constraints of the upper-level model are listed next.

1. The total amount of crude feeds to each CDU during each period should be bounded:

$$f^u_{ut} = \sum_{c\in C} f^{cu}_{uct}, \quad u\in U,\ t\in T, \quad (2a)$$

$$\underline{F}^U_u \le f^u_{ut} \le \bar{F}^U_u, \quad u\in U,\ t\in T. \quad (2b)$$

2. To maintain a smooth production state, the total amount of feed to CDU u during each period is allowed to vary within the limits ($\pm\gamma^U_u$) from the previous period:

$$(1-\gamma^U_u)f^u_{ut} \le fu_{u(t+1)} \le (1+\gamma^U_u)f^u_{ut}, \quad u\in U,\ t<N_T, \quad (3a)$$

$$(1-\gamma^U_u)F^U_{u0} \le fu_{u1} \le (1+\gamma^U_u)F^U_{u0}, \quad u\in U. \quad (3b)$$

3. During each period, each CDU is allowed to process only one type of crude:

$$f^{cu}_{uct} \le \bar{F}^U_u \cdot x^{fctu}_{uct}, \quad u\in U,\ c\in C,\ t\in T, \quad (4a)$$

$$\sum_{c\in C} x^{fctu}_{uct} \le 1, \quad u\in U,\ t\in T. \quad (4b)$$

4. The following constraints require that the processing of a type of crude should last for at least S^{CT}_u periods in CDU u before switching to another type:

$$y^{fcu}_{ut} \ge x^{fctu}_{uct} - x^{fctu}_{uc(t-1)}, \quad u\in U,\ c\in C,\ t>1, \quad (5a)$$

$$y^{fcu}_{ut} \ge x^{fctu}_{uc(t-1)} - x^{fctu}_{uct}, \quad u\in U,\ c\in C,\ t>1, \quad (5b)$$

$$y^{fcu}_{u1} = 1, \quad u\in U, \quad (5c)$$

$$\sum_{k=0}^{\min\{S^{CT}_u-1,\, N_T-t\}} y^{fcu}_{u(t+k)} \le 1, \quad u\in U,\ t\in T. \quad (5d)$$

We further constrain that the processing rate cannot change when processing the same type of crude to stabilize the production process:

$$f^u_{ut} - f^u_{u(t-1)} \le \bar{F}^U_u \cdot y^{fcu}_{ut}, \quad u\in U,\ t>1, \quad (6a)$$

$$f^u_{u(t-1)} - f^u_{ut} \le \bar{F}^U_u \cdot y^{fcu}_{ut}, \quad u\in U,\ t>1. \quad (6b)$$

5. At the end of the scheduling horizon, the total inventory level of the types of crude for CDU u cannot lie below the safety inventory $\underline{V}_u$, and the total inventory level of all types of crude cannot be below the total safety inventory $\underline{V}_M$:

$$\sum_{c\in C_u} v^{ctm}{}_{cN_T} \ge \underline{V}_u, \quad u\in U, \quad (7a)$$

$$\sum_{c\in C} v^{ctm}{}_{cN_T} \ge \underline{V}_M. \quad (7b)$$

6. The total amount of crude in the tank farm at refinery M cannot exceed the total storage capacity of all tanks. Parameter η_M, which denotes the maximum utilization of the overall storage capacity at refinery M, is adopted to ensure feasibility of the lower-level problem:

$$v^{ctm}_{ct} = \sum_{m\in M} V^{CT}_{mc0} + \sum_{k=1}^{t}\left(f^{cozm}_{ck} + f^{cobm}_{ck} - f^{cimz}_{ck} - \sum_{u\in U} f^{cu}_{uck}\right), \quad c\in C,\ t\in T, \quad (8)$$

$$\sum_{c\in C} v^{ctm}_{ct} \le \eta_M \cdot \sum_{m\in M}\bar{V}^T_m, \quad t\in T. \quad (9)$$

7. The accumulated inventory for crude type c at refinery M at the end of period t, defined as the left side of Equation (10), should be nonnegative. For production robustness, we also require that the accumulated inventory at the end of each period should be sufficiently large to ensure that the processing in CDU u lasts for another S^{CT}_u periods without crude refill. Accordingly, the summation of item $\sum_{u\in U} f^{cu}_{ucs}$ of the right side of constraint (10) is from 1 to $t+S^{CT}_u-1$. Because each tank requires some time (S^T_M) for brine settling and removal after receiving crude in the detailed lower-level decisions, both items f^{cozm}_{ck} and f^{cobm}_{ck} are summed from 1 to $t-S^T_M$:

$$\sum_{m\in M} V^{CT}_{mc0} + \sum_{k=1}^{t-S^T_M}(f^{cozm}_{ck} + f^{cobm}_{ck}) - \sum_{j=1}^{t} f^{cimz}_{cj} \ge \sum_{s=1}^{\min\{t+S^{CT}_u-1,\, N_T\}}\sum_{u\in U} f^{cu}_{ucs}, \quad c\in C,\ t>S^T_M, \quad (10)$$

$$\sum_{m\in M} V^{CT}_{mc0} - \sum_{j=1}^{t} f^{cimz}_{cj} \ge \sum_{s=1}^{\min\{t+S^{CT}_u-1,\, N_T\}}\sum_{u\in U} f^{cu}_{ucs}, \quad c\in C,\ t\le S^T_M. \quad (11)$$

8. Similar to the refinery setting, before the end of period t, the total amount of each type of crude received from each

terminal should not exceed the maximum available supply. For terminal Z, an extra constraint is required to guarantee that the total amount of light crude reverse transferred to terminal Z should be sufficient to ensure the safe transfer of high-pour-point, high-viscosity, and high-sulfur crude in pipeline ZM:

$$\sum_{c'\in C}\sum_{k=1}^{t} f_{c'k}^{cozm}\cdot\tau_{c'c} \le \sum_{z\in Z} V_{zc0}^{CT} + \sum_{\substack{(p_A,c)\in P_A C,\\ (p_A,t-S_{ZM}^{UL})\in P_A T}} P_{p_A}^{S} + \sum_{\substack{(p_B,c)\in P_B C,\\ (p_B,t-S_{ZM}^{UL})\in P_B T}} P_{p_B}^{S} + \sum_{s=1}^{t-S_{MZ}-S_Z^T} f_{cs}^{cimz}, \quad c\in C,\ t > S_{MZ}+S_Z^T, \quad (12)$$

$$\sum_{c'\in C}\sum_{k=1}^{t} f_{c'k}^{cozm}\cdot\tau_{c'c} \le \sum_{z\in Z} V_{zc0}^{CT} + \sum_{\substack{(p_A,c)\in P_A C,\\ (p_A,t-S_{ZM}^{UL})\in P_A T}} P_{p_A}^{S} + \sum_{\substack{(p_B,c)\in P_B C,\\ (p_B,t-S_{ZM}^{UL})\in P_B T}} P_{p_B}^{S}, \quad c\in C,\ t\le S_{MZ}+S_Z^T, \quad (13)$$

$$\sum_{k=1}^{t} f_{ck}^{cobm} \le \sum_{b\in B} V_{bc0}^{CT} + \sum_{\substack{(p_C,c)\in P_C C,\\ (p_C,t-S_{BM}^{UL})\in P_C T}} P_{p_C}^{S}, \quad c\in C,\ t\in T. \quad (14)$$

Table A.1 lists an instance of parameter $\tau_{c'c}$, where crude SUD_XTJ is obtained by blending 70 percent of crude SUD with 30 percent of crude XTJ. In general, if c' and c are the same type of crude, then $\tau_{c'c}$ equals 1. If c' is a type of blended crude, then $\tau_{c'c}$ equals the specified proportion of the amount of c blending in c' to guarantee transportation safety. In other cases, $\tau_{c'c}$ equals 0. Because terminal Z may receive light crude from refinery M while terminal B does not, the extra term $\tau_{c'c}$ in constraints (12) and (13) is not included in constraint (14). For crude type c, which is pure, parameters V_{zc0}^{CT}, V_{bc0}^{CT}, $P_{p_A}^{S}$, $P_{p_B}^{S}$, and $P_{p_C}^{S}$ are the initial crude inventory levels or parcel sizes at terminal Z or B. For crude type c, which is a blend, parameters V_{zc0}^{CT}, V_{bc0}^{CT}, $P_{p_A}^{S}$, $P_{p_B}^{S}$, and $P_{p_C}^{S}$ are computed as adjusted crude inventory levels or adjusted parcel sizes by considering the proportion of each pure type of crude in the blend.

9. Before the end of period t, the total inventory level of light crude at terminal Z should be above the safety inventory for cleaning pipeline ZM. In three cases, we need to clean pipeline ZM: (1) forward transfer-stop-forward transfer, (2) forward transfer-reverse transfer, and (3) forward transfer-stop until the end of the scheduling horizon. Because pipeline ZM is allowed to reverse transfer at most once during the scheduling horizon, case (3) can also happen at most once. We set the safety inventory level for cleaning pipeline ZM to be the amount of light crude ($S_{ZM}^{CL}\cdot F_{ZM}^{CL}$) for a complete clean:

$$\sum_{c\in C_L}\sum_{k=1}^{t} f_{ck}^{cimz} \ge \sum_{c\in C_L}\sum_{c'\in C}\sum_{s=1}^{t} f_{c's}^{cozm}\tau_{c'c} - \sum_{c\in C_L}\sum_{z\in Z} V_{zc0}^{CT} + S_{ZM}^{CL}\cdot F_{ZM}^{CL}, \quad t\in T. \quad (15)$$

In addition, at the end of the scheduling horizon, the total inventory level of light crude at terminal Z cannot be lower than the safety inventory of light crude ($\underline{V}_Z^{LC}$) for terminal Z:

$$\sum_{c\in C_L}\sum_{t\in T}\left(f_{ct}^{cimz} - \sum_{c'\in C} f_{c't}^{cozm}\cdot\tau_{c'c}\right) + \sum_{z\in Z}\sum_{c\in C_L} V_{zc0}^{CT} \ge \underline{V}_Z^{LC}. \quad (16)$$

10. Variables y_t^{fozm}, y_t^{fobm}, and y_t^{fimz} are defined as in the following example. If x_t^{zm} does not equal x_{t-1}^{zm} (i.e., pipeline ZM changes the transfer state from forward transfer to stoppage (or reverse transfer), or from stoppage (or reverse transfer) to forward transfer, at the beginning of period t), then $y_t^{fozm} \ge 1$:

$$y_t^{fozm} \ge x_t^{zm} - x_{t-1}^{zm}, \quad t>1, \quad (17a)$$
$$y_t^{fozm} \ge x_{t-1}^{zm} - x_t^{zm}, \quad t>1, \quad (17b)$$
$$y_1^{fozm} = 0, \quad (17c)$$
$$y_t^{fobm} \ge x_t^{bm} - x_{t-1}^{bm}, \quad t>1, \quad (17d)$$
$$y_t^{fobm} \ge x_{t-1}^{bm} - x_t^{bm}, \quad t>1, \quad (17e)$$
$$y_1^{fobm} = 0, \quad (17f)$$
$$y_t^{fimz} \ge x_t^{mz} - x_{t-1}^{mz}, \quad t>1, \quad (17g)$$
$$y_t^{fimz} \ge x_{t-1}^{mz} - x_t^{mz}, \quad t>1, \quad (17h)$$
$$y_1^{fimz} = 0. \quad (17i)$$

Variables y_t^{fcozm}, y_t^{fcobm}, and y_t^{fcimz} are defined in the following example. If x_{ct}^{fcozm} does not equal $x_{c(t-1)}^{fcozm}$ for any c (i.e., pipeline ZM changes the type of crude forward transferring at the beginning of period t), then $y_t^{fcozm} \ge 1$:

$$y_t^{fcozm} \ge x_{ct}^{fcozm} - x_{c(t-1)}^{fcozm}, \quad c\in C,\ t>1, \quad (18a)$$
$$y_t^{fcozm} \ge x_{c(t-1)}^{fcozm} - x_{ct}^{fcozm}, \quad c\in C,\ t>1, \quad (18b)$$
$$y_1^{fcozm} = 0, \quad (18c)$$
$$y_t^{fcobm} \ge x_{ct}^{fcobm} - x_{c(t-1)}^{fcobm}, \quad c\in C,\ t>1, \quad (18d)$$
$$y_t^{fcobm} \ge x_{c(t-1)}^{fcobm} - x_{ct}^{fcobm}, \quad c\in C,\ t>1, \quad (18e)$$

Crude	SUD	XTJ	SUD_XTJ	IRH	SAM	SAM_IRH
SUD	0	0	0.7	0	0	0
XTJ	0	0	0.3	0	0	0
SUD_XTJ	0.7	0.3	0	0	0	0
IRH	0	0	0	0	0	0.5
SAM	0	0	0	0	0	0.5
SAM_IRH	0	0	0	0.5	0.5	0

Table A.1: The table shows an example of blending proportion $\tau_{c'c}$ for the pure and blend types of crude.

$$y_1^{fcobm} = 0, \tag{18f}$$

$$y_t^{fcimz} \geq x_{ct}^{fcimz} - x_{c(t-1)}^{fcimz}, \quad c \in C,\ t > 1, \tag{18g}$$

$$y_t^{fcimz} \geq x_{c(t-1)}^{fcimz} - x_{ct}^{fcimz}, \quad c \in C,\ t > 1, \tag{18h}$$

$$y_1^{fcimz} = 0. \tag{18i}$$

11. To ensure pipeline transportation stability, once a new type of crude starts to transfer in the pipeline, the transfer operation of this type of crude should last for at least N_{CT} periods:

$$\sum_{k=0}^{\min\{N_{CT},\, N_T - t\}} y^{fcozm}{}_{t+k} \leq 1, \quad t \in T, \tag{19a}$$

$$\sum_{k=0}^{\min\{N_{CT},\, N_T - t\}} y^{fcobm}{}_{t+k} \leq 1, \quad t \in T, \tag{19b}$$

$$\sum_{k=0}^{\min\{N_{CT},\, N_T - t\}} y^{fcimz}{}_{t+k} \leq 1, \quad t \in T. \tag{19c}$$

12. Pipeline BM can transfer at most one type of crude during period t, and the total amount of crude transferred during period t must be within the transfer limits:

$$\sum_{c \in C} x_{ct}^{fcobm} \leq 1, \quad t \in T, \tag{20a}$$

$$f_{ct}^{cobm} \leq \bar{F}_{BM} \cdot x_{ct}^{fcobm}, \quad c \in C,\ t \in T, \tag{20b}$$

$$f_t^{obm} = \sum_{c \in C} f_{ct}^{cobm}, \quad t \in T, \tag{20c}$$

$$\underline{F}_{BM} \cdot x_t^{bm} \leq f_t^{obm} \leq \bar{F}_{BM} \cdot x_t^{bm}, \quad t \in T. \tag{20d}$$

13. Pipeline ZM can forward transfer at most one type of crude, pure or blended, during period t, and the total amount of crude transferred during period t must be within the transfer limits:

$$\sum_{c \in C} x_{ct}^{fcozm} \leq 1, \quad t \in T, \tag{21a}$$

$$f_{ct}^{cozm} \leq \bar{F}_{ZM} \cdot x_{ct}^{fcozm}, \quad c \in C,\ t \in T, \tag{21b}$$

$$f_t^{ozm} = \sum_{c \in C} f_{ct}^{cozm}, \quad t \in T, \tag{21c}$$

$$\underline{F}_{ZM} \cdot x_t^{zm} \leq f_t^{ozm} \leq \bar{F}_{ZM} \cdot x_t^{zm}, \quad t \in T. \tag{21d}$$

14. Pipeline ZM can reverse transfer at most one type of light crude during period t, and the total amount of crude transferred during period t must be within the transfer limits:

$$\sum_{c \in C_L} x_{ct}^{fcimz} \leq 1, \quad t \in T, \tag{22a}$$

$$\sum_{c \in C \setminus C_L} x_{ct}^{fcimz} = 0, \quad t \in T, \tag{22b}$$

$$f_{ct}^{cimz} \leq \bar{F}_{MZ} \cdot x_{ct}^{fcimz}, \quad c \in C,\ t \in T, \tag{22c}$$

$$f_t^{imz} = \sum_{c \in C_L} f_{ct}^{cimz}, \quad t \in T, \tag{22d}$$

$$\underline{F}_{MZ} \cdot x_t^{mz} \leq f_t^{imz} \leq \bar{F}_{MZ} \cdot x_t^{mz}, \quad t \in T. \tag{22e}$$

15. Continuity constraints to ensure the safe transportation of pipelines: When pipeline ZM (BM) transfers continuously, the total amount of crude transferred during each period should be the same. That is, if both x_t^{zm} and x_{t-1}^{zm} equal 1, then f_t^{ozm} equals f_{t-1}^{ozm}:

$$f_t^{ozm} - f_{t-1}^{ozm} \leq \bar{F}_{ZM} \cdot (2 - x_t^{zm} - x_{t-1}^{zm}), \quad t > 1, \tag{23a}$$

$$f_{t-1}^{ozm} - f_t^{ozm} \leq \bar{F}_{ZM} \cdot (2 - x_t^{zm} - x_{t-1}^{zm}), \quad t > 1, \tag{23b}$$

$$f_t^{obm} - f_{t-1}^{obm} \leq \bar{F}_{BM} \cdot (2 - x_t^{bm} - x_{t-1}^{bm}), \quad t > 1, \tag{23c}$$

$$f_{t-1}^{obm} - f_t^{obm} \leq \bar{F}_{BM} \cdot (2 - x_t^{bm} - x_{t-1}^{bm}), \quad t > 1, \tag{23d}$$

$$f_t^{imz} - f_{t-1}^{imz} \leq \bar{F}_{MZ} \cdot (2 - x_t^{mz} - x_{t-1}^{mz}), \quad t > 1, \tag{23e}$$

$$f_{t-1}^{imz} - f_t^{imz} \leq \bar{F}_{MZ} \cdot (2 - x_t^{mz} - x_{t-1}^{mz}), \quad t > 1. \tag{23f}$$

16. If refinery M is feeding pipeline ZM during period t, then refinery M cannot receive any crude from terminal Z via pipeline ZM during periods $t+1, t+2, \ldots$, and $t + S_{MZ} + S_{ZM}$. This constraint is used to approximate the bidirectional feature of pipeline ZM, instead of directly modeling the movement of flows inside it:

$$(S_{MZ} + S_{ZM}) \cdot x_t^{mz} + \sum_{k=0}^{\min\{S_{MZ}+S_{ZM},\, N_T - t\}} x_{(t+k)}^{zm} \leq S_{MZ} + S_{ZM}, \quad t \in T. \tag{24}$$

17. Equation (25) imposes the constraint that pipeline ZM can reverse transfer at most once during the scheduling horizon, where $x_1^{mz} = 1$ represents the constraint that the initial state of pipeline ZM is reverse:

$$\sum_{t \in T} y_t^{fimz} \leq 1 + (1 - x_1^{mz}). \tag{25}$$

18. If pipeline ZM has just switched the transfer state from stoppage (i.e., stop after forward transfer) to forward transfer, then the crude first ejected from pipeline ZM must be light crude. Equation (26) holds trivially, except when $x_{t+k}^{zm} = 0$ (i.e., pipeline ZM is not forward transferring during period $t+k$) and $y_{t+1}^{fozm} = 1$. The changeover of transfer state from stoppage to forward transfer of pipeline ZM takes place at the beginning of period $t+1$, that is, when the transfer state of pipeline ZM is reverse-stoppage-forward instead of forward-stoppage-forward, as modeled in item (16) via Equation (24). Equation (27) holds trivially, except when $x_{t+k}^{zm} = 1$ (i.e., pipeline ZM is forward transferring during period $t+k$) and $y_{t+1}^{fozm} = 1$. The change of transfer state from stoppage to forward transfer of pipeline ZM takes place at the beginning of period $t+1$ and $x_t^{roizm} = 1$. The latest period of transfer operations before period t is forward transfer (i.e.,

the transfer state of pipeline ZM is forward-stoppage-forward instead of reverse-stoppage-forward):

$$\sum_{c\in C_L} f_{c(t+k)}^{cozm} \le F_{ZM}^{CL} \cdot (x_{t+k}^{zm} - y_{t+1}^{fozm} + 1),$$

$$t < N_T,\ k = 1, 2, \ldots, \min\{S_{ZM}^{CL}, N_T - t\}, \qquad (26)$$

$$\sum_{c\in C_L} f_{c(t+k)}^{cozm} \ge F_{ZM}^{CL} \cdot (x_{t+k}^{zm} + y_{t+1}^{fozm} - 2 + x_t^{roizm}),$$

$$t < N_T,\ k = 1, 2, \ldots, \min\{S_{ZM}^{CL}, N_T - t\}. \qquad (27)$$

If pipeline ZM is forward transferring during the latest period of transfer operations before period t (including t), then the binary variable x_t^{roizm} equals 1, otherwise 0:

$$N_T \cdot x_t^{roizm} \ge r_t^{tozm} - r_t^{timz}, \quad t \in T, \qquad (28a)$$

$$N_T \cdot (1 - x_t^{roizm}) \ge r_t^{timz} - r_t^{tozm}, \quad t \in T, \qquad (28b)$$

$$r_1^{timz} = x_1^{mz}, \qquad (29a)$$

$$r_t^{timz} \ge r_{t-1}^{timz}, \quad t > 1, \qquad (29b)$$

$$r_t^{timz} \le r_{t-1}^{timz} + t \cdot x_t^{mz}, \quad t > 1, \qquad (29c)$$

$$r_t^{timz} \ge t \cdot x_t^{fimz}, \quad t > 1, \qquad (29d)$$

$$r_t^{timz} \le t, \quad t > 1, \qquad (29e)$$

$$r_1^{tozm} = x_1^{zm}, \qquad (30a)$$

$$r_t^{tozm} \ge r_{t-1}^{tozm}, \quad t > 1, \qquad (30b)$$

$$r_t^{tozm} \le r_{t-1}^{tozm} + t \cdot x_t^{zm}, \quad t > 1, \qquad (30c)$$

$$r_t^{tozm} \ge t \cdot x_t^{zm}, \quad t > 1, \qquad (30d)$$

$$r_t^{tozm} \le t, \quad t > 1. \qquad (30e)$$

19. To take into account the initial holdup inside the long-distance pipelines, we impose a constraint that during the first $S_{ZM}(S_{BM})$ periods of the scheduling horizon, refinery plant M cannot receive any crude that terminal Z (B) feeds during the scheduling horizon:

$$x_t^{zm} = 0, \quad t \le S_{ZM}, \qquad (31a)$$

$$x_t^{bm} = 0, \quad t \le S_{BM}. \qquad (31b)$$

To summarize, the upper-level model consists of Equations (1)–(31).

Acknowledgments

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Verification Letter

A. Li, Sinopec Group Maoming Petroleum Chemical Company, Changqian East Road, Maonan, Maoming, Guangdong, China, writes:

"This letter is written to verify that the short-term crude oil scheduling problem presented in the INFORMS *Interfaces* article is the real-life plant problem, known as the "ten-day plan," of the SINOPEC (China Petroleum & Chemical Corporation) Maoming Company, Guangdong Province, China.

"The hierarchical decomposition approach was developed under one of the projects of the Tsinghua-Maoming Petrochem Production Simulation and Optimization Research Center,[1] co-founded by the SINOPEC Maoming Company together with Professor Li Zheng and the Industrial Engineering Department of Tsinghua University in October 2009. The ten-day plan was made by the experienced scheduler with the Aspen ORION system. The generation of a schedule took several hours. The obtained schedules are not systematically optimized and are difficult to modify. Therefore, the goal of the project is to develop models and algorithms to automatically generate optimized schedules efficiently. Because of confidentiality issues, precise economic benefits cannot be released. The decomposition methodology was adopted in the refinery, providing satisfactory and practically implementable results in minutes. Crude demands of crude distillation units were all satisfied. No demurrage cost is incurred because of the timely unloading of marine vessels. Changeovers of tanks, pipelines and crude distillation units are reduced up to 20 percent."

[1] http://www.tsinghua.edu.cn/publish/ie/5262/index.html (in Chinese).

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