Transportation Research Part E 123 (2019) 142–164

Contents lists available at ScienceDirect

Transportation Research Part E

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

An MILP formulation for optimizing detailed schedules of a multiproduct pipeline network

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ARTICLE INFO

Keywords:
Multiproduct pipeline network
Batch schedule
Optimization
Mixed integer linear programming (MILP)

ABSTRACT

This paper addresses how to optimize detailed schedules of a multiproduct pipeline network. A continuous-time mixed integer linear programming (MILP) formulation is developed to seek the minimum makespan of transportation tasks. Operation constraints about sequence of products, size of single-product batches, flow rate of delivery and injection operations, pumping rate of pipeline segments, batch tracking, conditions of implementing injection or delivery operations, inventory management of stations and consumer markets' demand are all satisfied. The MILP formulation is illustrated by three pipeline networks. Results show the proposed MILP model has a better performance than previous works.

1. Introduction

With the rapid development of world economy, demand for refined oil products grows at a rate of 2% per year (Zhang et al., 2017). At present, pipelines are the major way for delivering refined products from refineries to consumer markets over a long distance. In China, the multiproduct pipeline network owned by China National Petroleum Corporation (CNPC) consists of five trunk pipelines, by which diesel and gasoline can be conveyed from fourteen refineries to fifty tank farms. How to promote the management level of scheduling for such a complex multiproduct pipeline network is a challenging problem and needs to be addressed urgently. Detailed schedules of a multiproduct pipeline network involve product allocation, delivery times and volumes of products, guarantee of product quality, management of station tanks, etc. Reasonable detailed schedules are vital to guarantee safe, stable and economic operations of multiproduct pipeline networks. Different from other transportation ways, such as railway (Corman et al., 2017; Jiang et al., 2018), shipping (Lin and Chang, 2018; Reinhardt et al., 2016) and road (Kazemi and Szmerekovsky, 2015), the most prominent feature of pipeline scheduling is that different refined oils can be simultaneously pumped through pipelines in a back-to-back way over a long distance. By comparing with the liquefied natural gas (LNG) supply chain using ships as the means of transportation (Al-Haidous et al, 2016; Goel et al, 2012; Koza et al, 2017; Rakke et al, 2011; Shao et al, 2015), the characteristics of the refined oil supply chain based on pipelines are illustrated. There are some similarities and differences between the two supply chains. From a macro perspective, the two supply chains transport products from plants to consumer markets over a long distance. However, different transportation ways determine that the two supply chains are completely different. The comparison between the two supply chains in terms of the facilities, constraints and operations is given in Table B1. Besides, differences between optimization models for the two supply chains can be found in Table B2. For optimizing the scheduling of a single multiproduct pipeline or pipeline network,

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https://doi.org/10.1016/j.tre.2019.01.012
Received 13 April 2018; Received in revised form 25 January 2019; Accepted 26 January 2019
1366-5545/

Nomenclature

Indexes and sets

$i, i', ii \in I_n$ set of batches transported by pipeline n during a scheduling horizon, $I_n = \{1, 2, \ldots, IM_n\}$, $IM_n = IOM_n + INM_n$. IM_n is the number of all batches, IOM_n is the number of old batches and INM_n is the number of new batches

IN_n set of new batches injected into pipeline n during a scheduling horizon. New batches are numbered staring from $IOM_n + 1$ by inputting time order, $IN_n = \{IOM_n + 1, IOM_n + 2, \ldots, IOM_n + INM_n\}$

IO_n set of old batches in pipeline n at the starting moment of a scheduling horizon. Old batches are numbered starting from '1' by the distance to the initial station from far to near, $IO_n = \{1, 2, \ldots, IOM_n\}$

$j \in J_n$ set of stations or pipeline segments along pipelines, $J_n = \{1, 2, \ldots, JM_n\}$. If $j = 1$, station j is an input station. JM_n is the number of stations along pipeline n. If $j = JM_n$, station j is a terminal station. Pipeline segment j is between stations j and $j + 1$

$k \in K$ set of time nodes or time intervals, $K = \{1, 2, \ldots, KM\}$. KM indicates the total number of time nodes

$m \in M$ set of transfer stations, $M = \{1, 2, \ldots, MM\}$. MM indicates the total number of transfer stations

$n \in N$ set of pipelines, $N = \{1, 2, \ldots, NM\}$. NM indicates the total number of pipelines

$p, p' \in P$ set of products, $P = \{1, 2, \ldots, PM\}$. PM indicates the total number of products

Non-binary parameters

$F_{n,j}$ volumetric coordinate of station j from the origin of pipeline n

$QCA_{n,j,p}$ maximum flow rate by which intermediate delivery station j along pipeline n supplies product p to its consumer market

$QIA_{n,j}$, $QII_{n,j}$ upper and lower flow rates by which station j injects products into pipeline n or receives products from pipeline n

$QMCA_{m,p}$ maximum flow rate by which transfer station m supplies product p to its market

$QR_{m,p}$ production rate by which the refinery supplies product p to transfer station m

$QSA_{n,j}$, $QSI_{n,j}$ upper and lower pumping rates of pipeline segment j along pipeline n

TL length of the scheduling horizon

$VBPA_{n,p}$, $VBPI_{n,p}$ maximum and minimum sizes of product p pumped into pipeline n

VMI_n minimum volume by which a station along pipeline n downloads a batch

$VMTA_{m,p}$, $VMTI_{m,p}$ maximum and minimum allowed inventory levels for product p at transfer station m

$VMTO_{m,p}$ initial inventory of product p in transfer station m

$VMPD_{m,p}$ overall demand for product p at the consumer market located at transfer station m

$VPD_{n,j,p}$ overall demand for product p at the consumer market located at intermediate station j along pipeline n

$VTA_{n,j,p}$, $VTI_{n,j,p}$, maximum and minimum allowed inventory levels for product p at intermediate station j along pipeline n

$VTO_{n,j,p}$ initial inventory of product p in intermediate station j along pipeline n

$WO_{n,i}$ initial volume of old batch i in pipeline n

τ minimum length of a discrete time interval

Binary parameters

$AS_{m,n}$ 1 if transfer station m is located at the origin of pipeline n and can inject products into pipeline n

$AE_{m,n}$ 1 if transfer station m is located at the ending of pipeline n and can receive products from pipeline n

$FB_{p,p'}$ 1 if product p and product p' are allowed to be adjacently transported in pipelines

$YO_{n,i,p}$ 1 if old batch i in pipeline n consists of product p

Continuous variables

$h_{n,i,k}$ upper volumetric coordinate of batch i in pipeline n at moment t_k

l_k length of time interval (t_k, t_{k+1}), $l_k = t_{k+1}$-t_k

t_k time for time node k

$v_{n,j,i,k}$ volume of batch i that station j along pipeline n injects into pipeline n or receives from pipeline n in time interval (t_k, t_{k+1})

$vcp_{n,j,p,k}$ volume of product p that intermediate delivery station j along pipeline n supplies to its local market in time interval (t_k, t_{k+1})

$vmcp_{m,p,k}$ volume of product p that transfer station m supplies to its local market in time interval (t_k, t_{k+1})

$vmt_{m,p,k}$ inventory of product p in transfer station m at moment t_k

$vp_{n,j,i,p,k}$ volume of product p that station j along pipeline n injects into batch i or receives from batch i over time interval (t_k, t_{k+1})

$vs_{n,j,k}$ pumping volume in pipeline segment j along pipeline n in time interval (t_k, t_{k+1})

$vt_{n,j,p,k}$ inventory of product p in intermediate delivery station j along pipeline n at moment t_k

$w_{n,i,k}$ volume of batch i in pipeline n at moment t_k

Binary variables

$sp_{n,j,k}$ 1 if pipeline segment j along pipeline n is active in time interval (t_k, t_{k+1})

$u_{n,i,k}$ 1 if the volume of batch i in pipeline n is greater than zero at moment t_k

$x_{n,j,i,k}$ 1 if station j along pipeline n receives product from batch i in pipeline n or injects product into batch i in pipeline n over time interval (t_k, t_{k+1})

$y_{n,i,p}$ 1 if batch i in pipeline n contains product p

many mathematical models and solving algorithms have been developed.

1.1. Mathematical models based on different representations

The key point of establishing a rigorous mathematical model for the scheduling optimization of multiproduct pipelines is how to track the transportation of batches in pipelines. Three key elements are time representation, volume representation and batch/product tracking representation in pipelines, which need to be considered.

1.1.1. Time representation

Time representation is used to record delivery and injection operations performed by stations along pipelines. The first step of establishing a rigorous mathematical model is choosing a time representation. Rejowski and Pinto (2003) firstly adopted the discrete-time representation to establish optimization models, whereas Cafaro and Cerdá (2004) firstly used the continuous-time representation. The similarity of the two kinds of time representation is that scheduling period should be prior divided into several small time slots. However, the difference is that the starting and ending times of every discrete time slot are parameters and prior given to discrete-time models, whereas those are variables in continuous-time models. Obviously, the discrete-time representation can be seen as a special case of the continuous-time representation. Continuous-time models show better performance than discrete-time model in terms of the computational scale and time (Cafaro and Cerdá, 2004).

1.1.2. Volume representation

Volume representation determines whether dividing pipeline segments, including the discrete-volume representation (Herrán et al., 2010; MirHassani and Ghorbanalizadeh, 2008; Rejowski and Pinto, 2003, 2004, 2008) and the continuous-volume representation (Cafaro and Cerdá, 2004; Relvas et al., 2006). In discrete-volume models, pipeline segments are segregated into single-product packs for monitoring transportation of batches in pipelines. Any pack contains one product and the product is updated with time. For meeting this rule, the volume by which products enter into or flow out of a pipeline segment is designated to be the discrete volumetric step. Different from the discrete-volume representation, the continuous-volume representation does not need to divide pipeline segments. Compared with discrete-volume models, continuous-volume models use less variables. Cafaro and Cerdá (2004) demonstrated that continuous-volume models show better performance than discrete-volume models in terms of the computational scale and time.

1.1.3. Batch/Product tracking representation

After adopting the time and volume representations, the next step is to describe the transportation of products/batches inside a pipeline and delivery-injection operations carried out by stations. For implementing this step, previous works proposed two kinds of formulations that are the batch-centric formulation and the product-centric formulation (Castro, 2017; Castro and Mostafaei, 2017; Mostafaei and Castro, 2017). Batch-centric formulations needs to preset the number of batches and describe the transportation of batches in pipelines, whereas product-centric formulations just track the movement of products in pipeline segments. In batch-centric formulations: (a) Products are assigned to batches and every batch contains at most one product. (b) During any time interval, every input station can inject at most one batch. (c) The number of new batches injected into a pipeline must be prior given. (d) A pipeline segment can contain multiple batches of a same product. In product-centric formulations: (a) Every input station can inject at most one product. (b) At any time, there cannot be two batches of product inside a segment. Feature b may make product-centric formulations unable to describe initial contents in pipeline segments. Currently, each type of approach has advantages and disadvantages, and the comparison will be discussed in this article.

1.2. Optimization objective

From different perspectives, different objective functions have been proposed.

(1) Minimize the cost for pumping products by pipelines and storing products in station tanks (Rejowski and Pinto, 2003; Cafaro and Cerdá, 2004).
(2) Minimize the cost for activating pipeline segments (Cafaro et al., 2011, 2012).
(3) Minimize the number of interfaces between consecutive products (MirHassani and Ghorbanalizadeh, 2008).
(4) Minimize the makespan of transportation tasks. (Castro, 2017)
(5) Minimize the fluctuations of pumping rates in pipeline segments (Chen et al., 2016, Chen et al., 2017a, Chen et al., 2017b).
(6) Minimize the total deviation of the actual time-windows of delivering operation from due time-windows of each product at each delivery station (Liang et al., 2012).
(7) Minimize the unsatisfied demand volume at the ending of a scheduling horizon (Zhang et al., 2016).

1.3. Operation constraints

At the beginning of the study, many models just aimed to find feasible schedules. However, sometimes these batch schedules do not follow the real operating rules. As research progresses, optimization models become more practical.

Table B1
Facilities, constraints and operations of the refined oil supply chain and the LNG supply chain.

	Refined oil supply chain			LNG supply chain		
	Facility	Operation	Constraint	Facility	Operation	Constraint
Source	Tanks	a) Receiving oils from refineries b) Outputting oils to pipelines	a) Storage capacity of tanks b) Inventory balance	Tanks	a) Receiving LNG from nature gas liquefaction plants b) Outputting LNG to ships	a) Storage capacity of tanks b) Inventory balance
Terminal	Tanks	a) Receiving oils from pipelines b) Outputting oils to markets	a) Storage capacity of tanks b) Inventory balance c) Market demand	Tanks	a) Receiving LNG from ships b) Outputting LNG to markets	a) Storage capacity of tanks b) Inventory balance c) Market demand
Transportation	Pipelines	a) Receiving oils from sources b) Outputting oils to terminals	a) Sequence of batches b) Volume of batches c) Batch tracking d) Pumping rate of pipeline segments e) Flow rate of receiving and outputting operations f) Execution conditions for splitting and injecting operations	Ships	a) Receiving LNG from sources b) Outputting LNG to terminals	a) Network-flow conservation b) The upper number of berths at terminals

Table B2
Differences between optimization models for optimizing the refined oil and LNG supply chains.

Supply chain	Optimization object	Difficulty of establishing optimization model
Refined oil	a) Injection and delivery plans of pipelines b) Inventory management of tanks	a) Batch tracking in pipelines b) Execution conditions for injecting and delivering operations performed by stations c) Influence of injecting and delivering operations on batch movements in pipelines d) Compliance with operation procedures e) Constructing linear models using the continuous-time representation
LNG	a) Transportation route of ships b) Inventory management of tanks	Description and classification of transportation routes of ships

(1) Cafaro et al. (2011) assumed that at most one depot can receive products from the pipeline at every injection. Later works (Cafaro et al., 2012; Mostafaei et al., 2014, Mostafaei et al., 2015a, Mostafaei et al., 2015b, Mostafaei et al., 2015c, Mostafaei et al., 2016) allow several depots to simultaneously perform delivery operations at every injection.
(2) Relvas et al. (2006) and Cafaro and Cerdá (2008b) considered settling requirements for products held in station tanks and every product has a uniform settling duration. Then, the work by Relvas et al. (2007) allows variable settling periods with products in station tanks.
(3) Relvas et al. (2006) firstly considered pre-arranged stoppages of a pipeline.
(4) Cafaro and Cerdá (2009) assumed that at most one source can inject products into the pipeline at any time interval, which does not accord to the reality. Later, this shortage was successfully overcome by Cafaro and Cerdá (2010).
(5) Castro (2017) considered that pipelines can be operated with reverse flow and reported that reverse flow can improve the quality of optimal solutions. However, since reverse flow can increase the volume of contaminations and additional pumps need to be constructed, reverse flow in a pipeline is forbidden in the reality.
(6) Due to unexpected events that involve variation on client demand, imposition on product sequence, unpredicted pipeline stoppages, batch volume modifications, flow-rate adjustments and variation on maximum storage capacity, Relvas et al. (2007) developed a rescheduling framework to modify original operational plans.

1.4. Solving strategies

Generally, most optimization models in literature can be solved using commercial optimizers, such as *CPLEX*, *GUROBI* and *MATLAB*. However, limited by computational time, commercial optimizers are not suitable to optimize the long-term scheduling of complex pipeline systems. Thus, some heuristic and meta-heuristic algorithms, decomposition strategies and pretreatments are developed to improve the efficiency of solving optimization models. Besides, some special constraints are also introduced to improve the computational efficiency. For instance, Rejowski and Pinto (2004) introduced a set of integer cuts that depend on the initial state of pipeline segments and market demands. The improved model was tested on a Brazil pipeline and results showed that integer cuts could help save the computational time almost 70%.

1.4.1. Heuristic algorithms

Given aggregate batch schedules of a single multiproduct pipeline with a unique source and multiple depots, Cafaro et al. (2011) proposed three heuristic rules that are the nearest-first rule, the farthest-first rule and the nearest-to-the-current-terminal (NC) rule to generate detailed delivery schedules. Test results reported that the NC rule can find near-optimal schedules. Later, MirHassani and BeheshtiAsl (2013) developed a heuristic approach to optimize the scheduling of a single-source and single-depot pipeline as well. Tested on real-life cases, results showed that commercial optimizers fail at finding feasible solutions, but the heuristic approach succeeds. Although heuristic approaches can find solutions in a short time, many heuristic approaches are tailor-made and case-dependent. Sometimes heuristic approaches are even unable to find feasible solutions.

1.4.2. Meta-heuristic algorithms

Compared with commercial optimizers, meta-heuristic algorithms can generate good solutions in reasonable times. In many works, heuristic approaches are used to generate initial solutions for meta-heuristic algorithms. Herrán et al. (2012) developed three heuristic methods of constructing an initial solution and four heuristic methods of generating a neighborhood of solutions to search meta-heuristic procedures for the scheduling optimization of a multi-pipeline system. Meta-heuristic methods are Multi-Start Search, Variable Neighborhood Search, Taboo Search and Simulated Annealing (SA), respectively. Results of numerical examples indicated that SA algorithm can achieve best solutions due to the fact that SA algorithm can accept worse solutions. Chen et al. (2017a) presented a space recursion method to generate an initial solution for detailed schedules of a multi-source and multi-depot multi-product pipeline, which is further refined using SA algorithm. The approach by Chen et al. (2017a) was validated on two real-world pipelines. Results showed that compared with *CPLEX*, the SA algorithm can find better solutions for long-term scheduling of a complex pipeline.

1.4.3. Decomposition strategies

Magatão (2004) proposed a decomposition framework composed of three sub-models for the scheduling optimization of a single-source and single-depot multiproduct pipeline. The first sub-model is to optimize schedules of tanks in stations. In turn, time nodes can be determined using the second sub-model. Finally, schedules of the pipeline are optimized by the third sub-model. Cafaro and Cerdá (2008a) proposed a two-level approach to optimize batch schedules of a multiproduct pipeline. The first level generates aggregate schedules, including sequence of products, size of batches and volume allocation of batches to distribution centers. Provided aggregate schedules, the second level optimizes detailed schedules that include the times, volumes and flow rates of delivery operations. However, no work reports how to ensure that feasible solutions exist in the second level based on aggregate schedules. Moreover, for a long-term scheduling horizon, Cafaro and Cerdá (2008a) implemented a cyclic scheduling approach which divides the scheduling horizon into several periods to fulfill market demands at period ends. Although decomposition strategies can save computational time, the quality of optimization results cannot be guaranteed.

1.4.4. Pretreatment of optimization model

For improving computational efficiency, heuristic and meta-heuristic algorithms are often implemented to determine a part of binary variables from MILP formulations in advance. The most difficult procedure of optimizing batch schedules of pipelines is determining product sequences. If product sequences can be preset, the difficultly of optimizing batch schedules will be significantly cut down. Based on this, Relvas et al. (2009) and Zhang et al. (2017) developed sequencing heuristics to optimization model preprocessing, which are validated on real world pipelines.

1.5. Contributions of this work

Most mathematical models and solving algorithms in literature mainly optimized the scheduling of a multi-pipeline system, in which every pipeline connects a single source and a single depot (Fabro et al., 2014; Lopes et al., 2010, Lopes et al., 2012; Magatão et al., 2012, Magatão et al., 2015; Ribas et al., 2013; Stebel et al., 2012). A few works addressed the scheduling optimization of a pipeline network in which every pipeline connects several depots. Cafaro and Cerdá (2012) introduced a continuous MILP formulation based on the batch-centric representation to optimize aggregate schedules for a mesh multiproduct pipeline network, in which every pipeline can convey products from a unique input station to several depots. However, the MILP formulation by Cafaro and Cerdá (2012) cannot generate detailed schedules. For the same pipeline system, Castro (2017) established a monolithic product-centric MILP formulation to optimize detailed schedules. Since the model by Cafaro and Cerdá (2012) cannot determine detailed schedules of a pipeline network and the optimization results given by Castro (2017) can be improved, this work proposes a monolithic MILP formulation for optimizing detailed schedules of a pipeline network, including (a) sequence of products to be pumped in every pipeline, their injection times, volumes and flow rates, and (b) times, volumes and flow rates of delivery operations that are performed by delivery stations along every pipeline at batch injections.

(1) The proposed model is applicable to multiproduct pipeline networks of tree-like and mesh structures.
(2) Castro (2017) reported that the forbidden product sequence caused by full-stream delivery operations is difficult to be satisfied in the batch-centric model. In this work, this constraint is successfully represented using mathematical formulations.
(3) The model by Cafaro and Cerdá (2012) can generate just aggregate schedules, whereas the model proposed in this work can optimize detailed schedules. In the work by Cafaro and Cerdá (2012), the scheduling period is divided by the injection times of new batches at the pipeline origin. The injection of a new batch occupies at most one time slot. Since a delivery station may perform several delivery operations at the injection of a new batch, the injection duration of a new batch is so long that detailed delivery schedules are unable to be described. However, in this work, for describing detailed delivery schedules, the injection of a new batch can occupy several time slots.
(4) This work verifies that batch-centric formulations can generate better solutions than product-centric formulations.

2. Motivating example

The multiproduct pipeline network addressed in this work is composed of pipelines, transfer stations and intermediate delivery stations for delivering products from refineries to consumer markets. Stations located at both extremes of a pipeline are called transfer stations, which can receive products from pipelines/refineries and deliver products to pipelines/consumer markets. If a transfer station connects to the origin of a pipeline, the transfer station functions as an input station. If a transfer station links to the end of a pipeline, the transfer station functions as a receiving station. Intermediate stations are located at the middle positions of pipelines, which divide a pipeline into several pipeline segments. For example, five intermediate stations divide a pipeline into six pipeline segments. Any intermediate station along a pipeline downloads products from the pipeline and supply products to its local consumer market. Every pipeline conveys products from a unique transfer station located at the origin of the pipeline to several intermediate delivery stations and a terminal transfer station along the pipeline. The multiproduct pipeline network can be tree-like or mesh. Fig. A1 shows an example for a tree-like pipeline network with three pipelines LA-LB-LC and four transfer stations N1-N2-N3-N4. Transfer station N2 is a key station which receives products from pipeline LA and delivers products to pipelines LB-LC and its consumer market. Fig. A2 depicts an example for a mesh network composed of three pipelines XA-XB-XC, three transfer stations D1-D2-D4 and one intermediate delivery station D3. Station D4 can simultaneously supply products to pipeline XC and its consumer market, and download products from pipeline XB. Station D1 can receive products from the refinery and inject products into pipelines XA-XB. An example for illustrating detailed schedules of the mesh pipeline network is shown in Fig. A3. At 0 h, pipeline XA are filled with four batches that are ($B1_{XA}$-P1-30,000 m^3), ($B2_{XA}$-P2-30,000 m^3), ($B3_{XA}$-P3-30,000 m^3) and ($B4_{XA}$-P2-30,000 m^3). ($B1_{XA}$-P1-

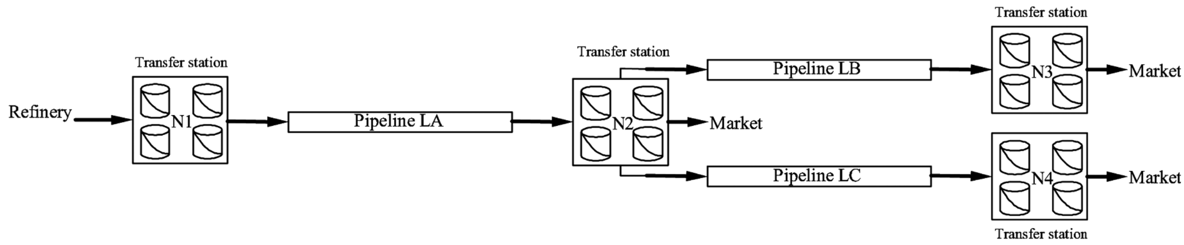

Fig. A1. An example for a tree-structure multiproduct pipeline network.

30,000 m^3) represents that batch $B1_{XA}$ in pipeline XA contains 30,000 m^3 of product P1. Batches $B1_{XA}$, $B2_{XA}$, $B3_{XA}$ and $B4_{XA}$ are called old batches. Pipelines XB and XC contain three old batches, respectively. When two batches are adjacently transported in a pipeline, an interface exists between the two batches. The upstream and downstream interfaces of a batch in a pipeline can be described using volumetric coordinate. The volumetric coordinate of the pipeline origin is zero and that of the pipeline end is the volumetric capacity of the pipeline. The volumetric coordinate of a batch in a pipeline can be calculated by volumes of batches in a pipeline. For instance, at 0 h, the coordinate of the upstream interface of batch $B2_{XA}$ is 60,000 m^3 and that of the downstream interface is 90,000 m^3. Given product demands at consumer markets, the receiving and outputting schedules of transfer and intermediate stations need to be determined, which must satisfy the process constraints of operating a multiproduct pipeline network. During first time interval (0–20 h), station D1 injects batch $B5_{XA}$ containing 20,000 m^3 of product P3 into pipeline XA at 1000 m^3/h. Batch $B5_{XA}$ is called a new batch. Since batch $B5_{XA}$ is injected into pipeline XA, batches $B1_{XA}$, $B2_{XA}$, $B3_{XA}$ and $B4_{XA}$ are pushed forward in pipeline XA and 20,000 m^3 of product P1 from batch $B1_{XA}$ is delivered to transfer station D2. Station D1 also injects 16,000 m^3 of product P3 into old batch $B3_{XB}$ at 800 m^3/h in (0–20 h). At the injection of old batch $B3_{XB}$, intermediate station D3 and transfer station D4 simultaneously perform delivery operations. In (0–20 h), 6000 m^3 of product P2 from in-transit batch $B2_{XB}$ is delivered to station D3 at 300 m^3/h and 10,000 m^3 of product P3 from in-transit batch $B1_{XB}$ is conveyed to station D4 at 500 m^3/h. Considering products P1 and P3 are forbidden to be adjacently transported, station D4 injects new batch $B4_{XC}$ of product P2 into pipeline XC at 1100 m^3/h during (0–20 h). In the second time interval (20–36 h), no product is injected into pipeline XA, new batch $B4_{XB}$ is delivered to pipeline XB at 750 m^3/h and new batch $B5_{XC}$ is transported by pipeline XC at 500 m^3/h.

3. Problem description

3.1. Assumptions

(1) Every pipeline can just deliver products from its origin to its end, which means the reverse flow is forbidden.
(2) Any mixed section between two consecutive transported products is regarded as an interface.
(3) All pipelines are always full of incompressible products.
(4) At every injection performed at the origin of a pipeline, several delivery stations along the pipeline can simultaneously receive products from in-transit batches.
(5) Any station has multiple tanks for holding products.
(6) Any two pipelines are connected by a transfer station.

3.2. Basic data of a multiproduct pipeline network

(1) Volumetric coordinate of stations along every pipeline.
(2) Forbidden sequences between pairs of products transported in pipelines.
(3) Flow rate limitations for stations injecting products into pipelines or receiving products from pipelines.
(4) Pumping rate limitations in pipeline segments along every pipeline.
(5) Maximum rates by which stations supply products to local consumer markets.
(6) Maximum and minimum volumes of products pumped into pipelines.
(7) Inventory limitations for products in every station.

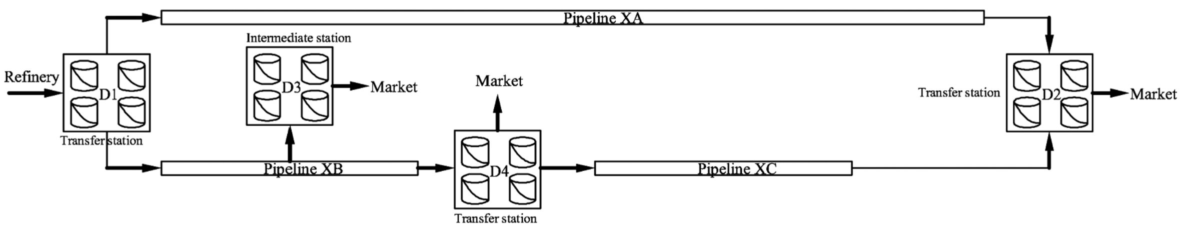

Fig. A2. An example for a mesh-structure multiproduct pipeline network.

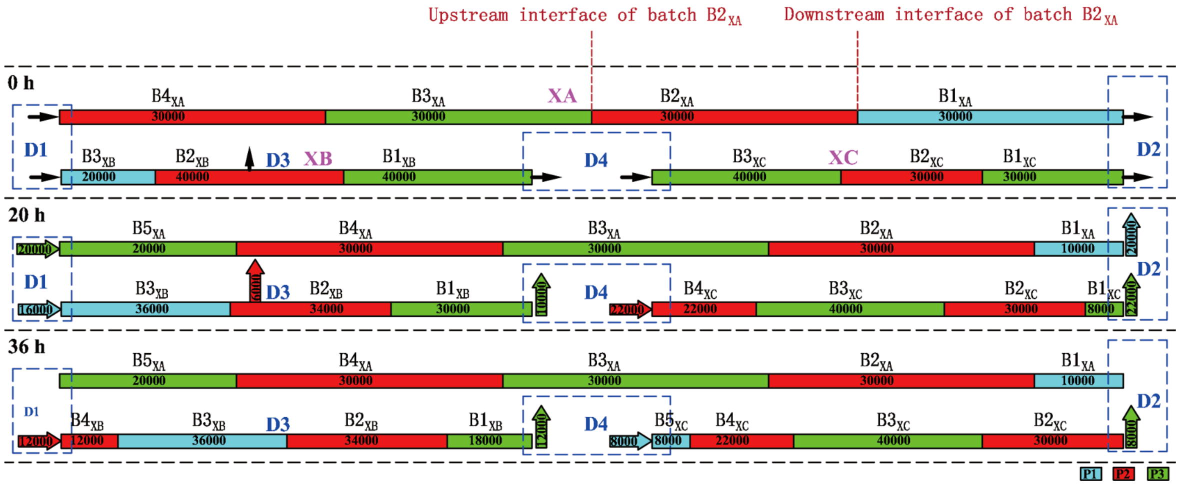

Fig. A3. An example for illustrating batch schedules of a multiproduct pipeline network.

3.3. Transportation tasks and initial conditions

(1) Starting and ending moments of the scheduling horizon.
(2) Overall demand volumes for products at every consumer market.
(3) Initial line-fill in every pipeline, including sequence and volume of products.
(4) Initial inventory of products that are stored in station tanks.
(5) Supplying rates by which refineries deliver products to stations during the scheduling horizon.
(6) The number of new batches that will be pumped into every pipeline during the scheduling horizon can be obtained from the historical data of operating a multiproduct pipeline network. This value is used to set the initial number of new batches. Then, the number of new batches is incremented by 1 until optimization results do not change and every pipeline transports at least one fictitious batch.

4. Mathematical model based on continuous-time representation

4.1. Operation constraints

4.1.1. Time constraints

In discrete-time formulations, the scheduling horizon is evenly divided into several time intervals by a specific time step in advance, which means that the starting and ending moments of every time intervals are known conditions. In continuous-time formulations, the scheduling horizon is also prior divided. However, the starting and ending moments of every time interval are variables, which are optimized by continuous-time formulations. As seen in Fig. A4, time nodes are preset in discrete-time formulations, while these are optimization variables in continuous-time formulations.

The first time node is 0 h. The last time node must not greater than the length of the scheduling period.

$$t_1 = 0 \tag{1}$$

$$t_{KM} \leqslant TL \tag{2}$$

Constraint (3) states the relation between two consecutive time nodes.

$$t_{k+1} = t_k + l_k \quad k < KM \tag{3}$$

Considering that an injection operation is started and intermitted over a too short period is uneconomic, a lower bound is imposed

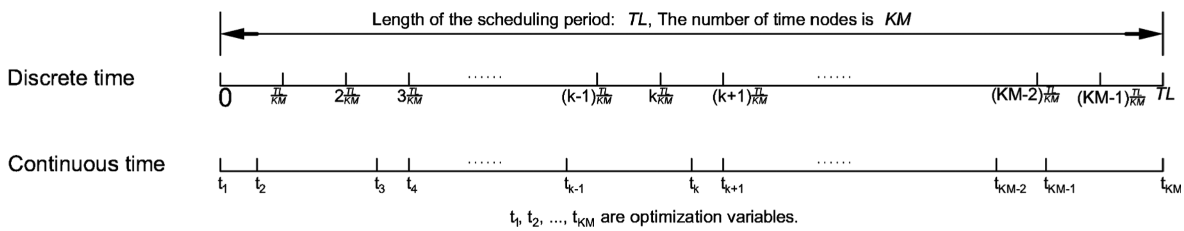

Fig. A4. Schematic diagram for explaining discrete-time and continuous-time representations.

on the length of any time interval.

$$l_k \geqslant \tau \quad k < KM \tag{4}$$

4.1.2. Product and volume allocations for batches pumped into pipelines

(1) Product allocation

The sequence of products in every pipeline at the starting moment of a scheduling horizon is known in advance.

$$y_{n,i,p} = YO_{n,i,p} \quad n \in N,\ i \in IO_n,\ p \in P \tag{5}$$

Any new batch injected into a pipeline during the scheduling horizon consists of at most one product. If batch i does not contain a product, batch i is a fictitious batch.

$$\sum_{p=1}^{PM} y_{n,i,p} \leqslant 1 \quad n \in N,\ i \in IN_n \tag{6}$$

All fictitious batches are arranged after nonempty batches.

$$\sum_{p=1}^{PM} y_{n,i,p} \geqslant \sum_{p=1}^{PM} y_{n,i+1,p} \quad n \in N,\ IOM_n + 1 \leqslant i < IM_n \tag{7}$$

If two products p and p' are forbidden to be adjacently pumped through pipeline n, constraint (8) is active.

$$y_{n,i,p} + y_{n,i+1,p'} \leqslant 1 + FB_{p,p'} \quad n \in N,\ IOM_n \leqslant i < IM_n,\ p \in P,\ p' \in P \tag{8}$$

(2) Forbidden product sequences caused by full-stream delivery operation

Considering that in-transit batches in a pipeline may be fully downloaded by intermediate delivery stations, the sequence of products given by constraint (8) may become infeasible. For example, a pipeline can convey three products P1-P2-P3, where products P1 and P3 are forbidden to be adjacently transported. As seen in Fig. A5, at moment t_k, the pipeline contains three batches (B1-P3-3000 m^3, B2-P2-2000 m^3, B3-P1-5000 m^3). Then, batch B2 is fully delivered to intermediate delivery station D1 at the injection of batch B4. As a result, at moment t_{k+1}, batch B1 of product P1 and batch B3 of product P3 become back to back, which is forbidden. To avoid forbidden sequence of products caused by full-stream delivery operations, constraint (9) is introduced into the problem formulation. Only if $u_{n,i,k=}u_{n,i',k} = 1$ that batches (i, p) and (i', p') are nonempty in pipeline n and $\sum_{ii=i+1}^{i'-1} u_{n,ii,k} = 0$ that all the batches between batches i and i' are empty, constraint (9) is active.

$$y_{n,i,p} + y_{n,i',p'} \leqslant 1 + FB_{p,p'} + \sum_{ii=i+1}^{i'-1} u_{n,ii,k} + (2 - u_{n,i,k} - u_{n,i',k}) \quad n \in N,\ p \in P,\ p' \in P,\ k \leqslant KM,\ i+2 \leqslant i' \leqslant IM \tag{9}$$

Constraint (10) is used to identify the value of binary variable $u_{n,i,k}$ which represents whether the volume of batch i in pipeline n at moment t_k is greater than zero. Since the minimum delivery rate is imposed on the delivery volume by which a station along pipeline n downloads a batch, the volume of the downloaded batch at the starting moment of the delivery operation should be not less than the minimum delivery volume VMI_n. If $u_{n,i,k} = 0$, the volume of batch i in pipeline n at moment t_k is equal to zero. If $u_{n,i,k} = 1$, then $W_{n,i,k}$ is greater than VMI_n In this article, $VMI_n = \min(QII_{n,1}, QII_{n,2}, \cdots, QII_{n,JM_n}) \cdot \tau$.

$$u_{n,i,k} \cdot VMI_n \leqslant W_{n,i,k} \leqslant u_{n,i,k} \cdot F_{n,JM_n} \quad n \in N,\ i \in I_n,\ k \leqslant KM \tag{10}$$

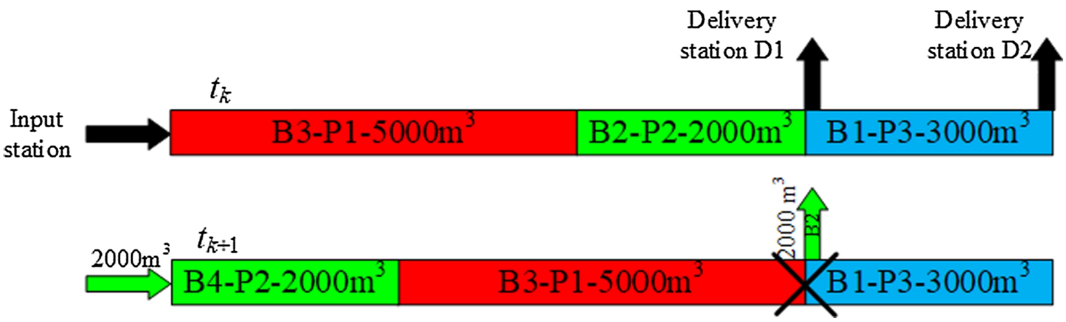

Fig. A5. Situation that forbidden product sequence appears when batches move in pipelines.

(3) Volume allocation

During the scheduling horizon, the input station of pipeline n can continue to inject old batch IOM_n that is closest to the origin of pipeline n. The size bounds on old batch IOM_n transported by pipeline n are imposed in constraint (11).

$$y_{n,i,p}\cdot VBPI_{n,p} \leqslant \sum_{k=1}^{KM-1} vp_{n,1,i,p,k} + y_{n,i,p}\cdot WO_{n,i} \leqslant y_{n,i,p}\cdot VBPA_{n,p} \quad n \in N,\ i = IOM_n,\ p \in P \tag{11}$$

Constraint (12) indicates the size limitations for new batches.

$$y_{n,i,p}\cdot VBPI_{n,p} \leqslant \sum_{k=1}^{KM-1} vp_{n,1,i,p,k} \leqslant y_{n,i,p}\cdot VBPA_{n,p} \quad n \in N,\ i \in IN_n,\ p \in P \tag{12}$$

4.1.3. Batch tracking in pipelines

The volume of batch i in pipeline n at moment t_{k+1} is equal to the summation of (a) the volume of batch i in pipeline n at t_k, (b) the overall volume by which the input station injects batch i over $(t_k,\ t_{k+1})$ and (c) subtracting the sum of the volume by which every delivery station along pipeline n receives batch i in $(t_k,\ t_{k+1})$.

$$w_{n,i,k+1} = w_{n,i,k} + v_{n,1,i,k} - \sum_{j=2}^{JM_n} v_{n,j,i,k} \quad n \in N,\ i \in I_n,\ k < KM \tag{13}$$

The initial volume of every old batch in every pipeline is known in advance.

$$w_{n,i,1} = WO_{n,i} \quad n \in N,\ i \in IO_n \tag{14}$$

The initial volume of every new batch in every pipeline is zero.

$$w_{n,i,1} = 0 \quad n \in N,\ i \in IN_n \tag{15}$$

At moment t_k, the upper coordinate of batch i in pipeline n is equal to the sum of the upper coordinate of batch $i + 1$ and the volume of batch i.

$$h_{n,i,k} = h_{n,i+1,k} + w_{n,i,k} \quad n \in N,\ i < IM_n,\ k \leqslant KM \tag{16}$$

For batch IM_n that is finally injected into pipeline n, its upstream interface must be always located at the origin of pipeline n. Namely, the lower coordinate of batch IM_n should be zero and the upper coordinate should be always equal to the volume of batch IM_n. Fig. A6 depicts lower-upper coordinates and upstream-downstream interfaces of a batch in pipeline.

$$h_{n,i,k} = w_{n,i,k} \quad n \in N,\ i = IM_n,\ k \leqslant KM \tag{17}$$

For old batch $i = 1$ that is farthest to the origin of pipeline n, its downstream interface must be always located at the end of pipeline n.

$$h_{n,1,k} = F_{n,JM_n} \quad n \in N,\ k \leqslant KM \tag{18}$$

The upper coordinate of any batch in pipeline n must be not greater than the coordinate of the end of pipeline n.

$$h_{n,i,k} \leqslant F_{n,JM_n} \quad n \in N,\ i = IM_n,\ k \leqslant KM \tag{19}$$

4.1.4. Injecting products into pipelines or downloading products from pipelines

(1) Volume of injection and delivery operations

If input station $j = 1$ of pipeline n does not inject batch i or delivery station $j \geq 2$ along pipeline n does not download batch i in $(t_k,\ t_{k+1})$, the injection or delivery volume must be zero.

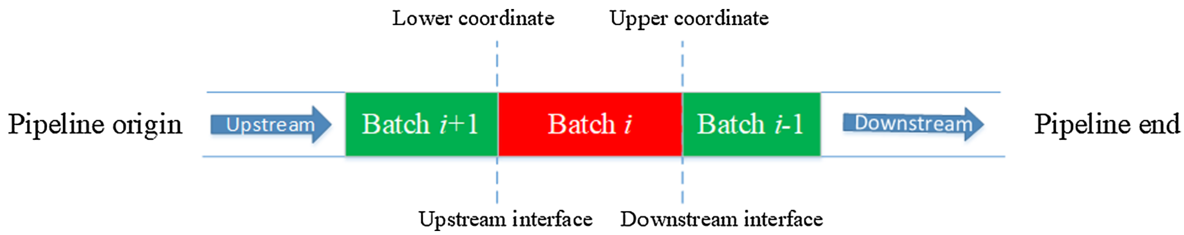

Fig. A6. Lower-upper coordinates and upstream–downstream interfaces of a batch.

$$x_{n,j,i,k}\cdot QII_{n,j}\cdot\tau \leqslant v_{n,j,i,k} \leqslant x_{n,j,i,k}\cdot QIA_{n,j}\cdot TL \quad n \in N,\, j \in J_n,\, i \in I_n,\, k < KM \tag{20}$$

If batch i transported by pipeline n does not contain product p, the volume by which product p is transferred from batch i to delivery station $j \geq 2$ or from input station $j = 1$ to batch i must be zero. If $y_{n,i,p} = 1$, the value of $v_{n,j,i,k}$ should be equal to the value of $vp_{n,j,i,p,k}$, because any batch contains only one product.

$$v_{n,j,i,k} = \sum_{p\in P} vp_{n,j,i,p,k} \quad n \in N,\, j \in J_n,\, i \in I_n,\, k < KM \tag{21}$$

$$\sum_{k=1}^{KM-1} vp_{n,j,i,p,k} \leqslant y_{n,i,p}\cdot QIA_{n,j}\cdot TL \quad n \in N,\, j \in J_n,\, i \in I_n,\, p \in P \tag{22}$$

(2) Flow rate of injection and delivery operations

The flow rate bounds on injection or delivery operations performed by station j along pipeline n in time interval $(t_k,\, t_{k+1})$ are imposed in constraint (23). If station j along pipeline n does not implement a delivery operation or an injection operation in $(t_k,\, t_{k+1})$, constraint (23) is redundant.

$$\frac{\sum_{i=1}^{IM_n} v_{n,j,i,k}}{QIA_{n,j}} \leqslant l_k \leqslant \frac{\sum_{i=1}^{IM_n} v_{n,j,i,k}}{QII_{n,j}} + TL\cdot\left(1 - \sum_{i=1}^{IM_n} x_{n,j,i,k}\right) \quad n \in N,\, j \in J_n,\, k < KM \tag{23}$$

(3) Conditions for a transfer station injecting products into a pipeline

When the transfer station located at the origin of pipeline n injects batch i into pipeline n in $(t_k,\, t_{k+1})$, all subsequent batches $i + 1 \sim IM_n$ following after batch i must have not been injected into pipeline n before t_k. If $x_{n,1,i,k} = 0$, constraint (24) is redundant.

$$x_{n,1,i,k} + \sum_{i'=i+1}^{IM_n} \sum_{k'=1}^{k-1} x_{n,1,i',k} \leqslant 1 + IM_n\cdot KM\cdot(1 - x_{n,1,i,k}) \quad n \in N,\, IOM_n \leqslant i < IM_n,\, 2 \leqslant k < KM \tag{24}$$

If the transfer station located at the origin of pipeline n injects batch i into pipeline n in $(t_k,\, t_{k+1})$, the lower coordinate of batch i must be equal to be zero at moments t_k and t_{k+1}.

$$\begin{cases} h_{n,i,k} - w_{n,i,k} \leqslant F_{n,JM_n}\cdot(1 - x_{n,1,i,k}) \\ h_{n,i,k+1} - w_{n,i,k+1} \leqslant F_{n,JM_n}\cdot(1 - x_{n,1,i,k}) \end{cases} \quad n \in N,\, i \geqslant IOM_n,\, k < KM \tag{25}$$

The transfer station located at the origin of pipeline n is unable to inject products into old batches, except the old batch that is closest to the origin of pipeline n.

$$\sum_{k=1}^{KM-1} x_{n,1,i,k} = 0 \quad n \in N,\, i \leqslant IOM_n - 1 \tag{26}$$

At any time interval, the transfer station located at the origin of pipeline n can inject at most one batch into the pipeline. Besides, if no batches are injected into pipeline n, the first pipeline segment along pipeline n must be idle.

$$\sum_{i=1}^{IM_n} x_{n,1,i,k} = sp_{n,1,k} \quad n \in N,\, k < KM \tag{27}$$

(4) Conditions for an intermediate delivery station receiving products from a pipeline

If station j along pipeline n downloads batch i in $(t_k,\, t_{k+1})$, the upper coordinate of batch i in pipeline n at moment t_k must be not less than the coordinate of station j and the lower coordinate of batch i in pipeline n at moment t_{k+1} must be not greater than the coordinate of station j. Otherwise, constraint (28) is redundant.

$$\begin{cases} h_{n,i,k} \geqslant F_{n,j} - F_{n,JM_n}\cdot(1 - x_{n,j,i,k}) \\ h_{n,i,k+1} - w_{n,i,k+1} \leqslant F_{n,j} + F_{n,JM_n}\cdot(1 - x_{n,j,i,k}) \end{cases} \quad n \in N,\, 2 \leqslant j < JM_n,\, i \in I_n,\, k < KM \tag{28}$$

At any time interval, at most one batch can be downloaded by any delivery station. Moreover, if pipeline segment j-1 along pipeline n which connects stations j-1 and j is idle, station j is unable to carry out delivery operations.

$$\sum_{i=1}^{IM_n} x_{n,j,i,k} \leqslant sp_{n,j-1,k} \quad n \in N,\, 2 \leqslant j < JM_n,\, k < KM \tag{29}$$

(5) Conditions for a transfer station receiving products from a pipeline

If the transfer station located at the end of pipeline n downloads batch i in time interval (t_k, t_{k+1}), the downstream interface of batch i at t_{k+1} must be located at the end of the pipeline. This limitation is satisfied by constraints (19) and (30).

$$h_{n,i,k+1} \geqslant F_{n,JM_n} \cdot x_{n,JM_n,i,k} \quad n \in N,\ i \in I_n,\ k < KM \tag{30}$$

If the last pipeline segment along pipeline n is idle, no product can be delivered from batches in pipeline n to the transfer station located at the end of pipeline n. Otherwise, the transfer station located at the end of pipeline n can download products from at most one batch.

$$\sum_{i=1}^{IM_n} x_{n,JM_n,i,k} \leqslant sp_{n,JM_n-1,k} \quad n \in N,\ k < KM \tag{31}$$

4.1.5. Pumping products by pipeline segments

In any time interval, the volume pumped by pipeline segment j along pipeline n must be equal to the total volume by which batches are injected into pipeline n, subtracting the sum of the overall volume by which upstream delivery stations $2 \sim j$ download products from batches. Fig. A7 depicts an example about how to calculate the volume pumped by a pipeline segment over a time interval.

$$vs_{n,j,k} = \sum_{i=1}^{IM_n} v_{n,1,i,k} - \sum_{j'=2}^{j} \sum_{i=1}^{IM_n} v_{n,j',i,k} \quad n \in N,\ j < JM_n,\ k < KM \tag{32}$$

The pumping rate bounds on pipeline segments are imposed in constraint (33). If pipeline segment j along pipeline n is idle in time interval (t_k, t_{k+1}), constraint (33) is redundant.

$$\frac{vs_{n,j,k}}{QSA_{n,j}} \leqslant l_k \leqslant \frac{vs_{n,j,k}}{QSI_{n,j}} + TL\cdot(1 - sp_{n,j,k}) \quad n \in N,\ j < JM_n,\ k < KM \tag{33}$$

If pipeline segment j along pipeline n is idle in a time interval, downstream pipeline segment $j + 1$ along pipeline n must be also idle.

$$sp_{n,j,k} \geqslant sp_{n,j+1,k} \quad n \in N,\ j \leqslant JM_n - 2,\ k < KM \tag{34}$$

4.1.6. Demand constraints of consumer markets

When the scheduling horizon is terminated, the planned overall demand by which every intermediate delivery station or transfer station supplies every product to its local consumer market must have been satisfied.

$$VPD_{n,j,p} = \sum_{k=1}^{KM-1} vcp_{n,j,p,k} \quad n \in N,\ 2 \leqslant j < JM_n,\ p \in P \tag{35}$$

$$VMPD_{m,p} = \sum_{k=1}^{KM-1} vmcp_{m,p,k} \quad m \in M,\ p \in P \tag{36}$$

At any time interval, the supplying rate by which every station delivers every product to its local consumer market must be not greater than the maximum allowable supplying rate.

$$vcp_{n,j,p,k} \leqslant QCA_{n,j,p} \cdot l_k \quad n \in N,\ 2 \leqslant j < JM_n,\ p \in P,\ k < KM \tag{37}$$

$$vmcp_{m,p,k} \leqslant QMCA_{m,p} \cdot l_k \quad m \in M,\ p \in P,\ k < KM \tag{38}$$

4.1.7. Inventory of intermediate stations

(1) Intermediate stations

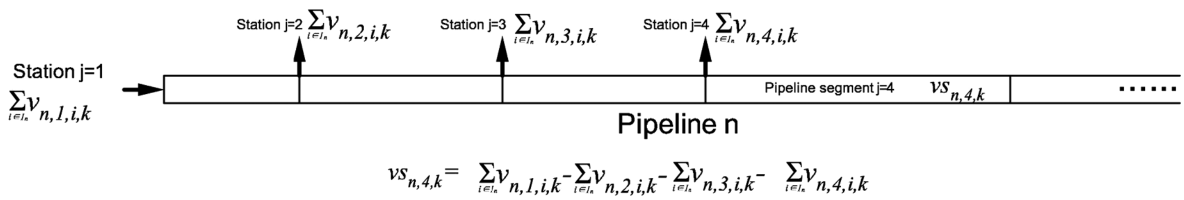

Fig. A7. An example for calculating the volume pumped by a pipeline segment over a time interval.

Fig. A8 depicts where products come from and where products go in an intermediate station. The inventory of product p in intermediate station j along pipeline n at moment t_{k+1} is equal to the sum of (a) that at t_k and (b) the total volume by which station j along pipeline n downloads product p from in-transit batches in (t_k, t_{k+1}) less (c) the supplying volume by which station j along pipeline n supplies product p to its local market over (t_k, t_{k+1}).

$$vt_{n,j,p,k+1} = vt_{n,j,p,k} + \sum_{i=1}^{IM_n} vp_{n,j,i,p,k} - vcp_{n,j,p,k} \quad n \in N,\ 2 \leqslant j < JM_n,\ p \in P,\ k < KM \tag{39}$$

The initial inventory of every product in every intermediate delivery station is known in advance.

$$vt_{n,j,p,1} = VTO_{n,j,p} \quad n \in N,\ 2 \leqslant j < JM_n,\ p \in P \tag{40}$$

The inventory of every product in every intermediate delivery station must be always kept within the allowable range.

$$VTI_{n,j,p} \leqslant vt_{n,j,p,k} \leqslant VTA_{n,j,p} \quad n \in N,\ 2 \leqslant j < JM_n,\ p \in P,\ k \leqslant KM \tag{41}$$

(2) Transfer stations

Fig. A9 depicts where products come from and where products go in a transfer station. The inventory of product p in transfer station m at t_{k+1} is equal to the sum of (a) that at t_k less (b) the total volume by which station m conveys product p to every pipeline in (t_k, t_{k+1}) and (c) the overall volume by which station m receives product p from every pipeline in (t_k, t_{k+1}) and (d) the receiving volume by which the refinery supplies product p to station m less (e) the supplying volume by which product p is delivered from station m to its local market over (t_k, t_{k+1}).

$$vmt_{m,p,k+1} = vmt_{m,p,k} - \sum_{n \in N} \sum_{i \in I_n} AS_{m,n} \cdot vp_{n,1,i,p,k} + \sum_{n \in N} \sum_{i \in I_n} AE_{m,n} \cdot vp_{n,JM_n,i,p,k} + QR_{m,p} \cdot l_k - vmcp_{m,p,k} \quad m \in M,\ p \in P,\ k < KM \tag{42}$$

The initial inventory of every product in every transfer station m is prior given.

$$vmt_{m,p,1} = VMTO_{m,p} \quad m \in M,\ p \in P \tag{43}$$

The inventory of every product in every transfer station must be always kept within the permissible range.

$$VMTI_{m,p} \leqslant vmt_{m,p,k} \leqslant VMTA_{m,p} \quad m \in M,\ p \in P,\ k \leqslant KM \tag{44}$$

4.2. Objective function

The optimization objective is to finish the transportation task as early as possible.

$$Min\ t_{KM} \tag{45}$$

5. Case study

In this section, the developed continuous-time MILP formulation is tested on three multiproduct pipeline networks using *CPLEX* 12.6.3 as the solver. The computer configuration is Intel Core i7-4600 M CPU @2.90 GHz with 4 parallel threads. Cases 1 and 2 optimize detailed schedules of a tree-like network called TPN (see Fig. A1) and a mesh network called MPN (see Fig. A2), that are owned by CNPC. The planning horizons for Case 1 and Case 2 are (0–168 h). Case 3 illustrates the good performance of the proposed MILP model on a mesh pipeline network named PNC, which was used by Cafaro and Cerda (2012) and Castro (2017). The minimum and maximum inventories of products in stations for pipeline networks TPN and MPN can be found in Table B3. Table B4 represents the product demands at consumer markets and the initial inventories in stations for Cases 1 and 2. The production rates by which refineries supply products to stations N1 and D1 are given in Table B5. The length of any discrete time interval should be not shorter than 5 h to avoid high changeover cost of injection operations. According to historical data on operating pipeline networks TPN and MPN, every pipeline usually pumps at least four new batches for a seven-day scheduling horizon. In the three cases, products P1, P2, P3, P4, P5 and P6 are depicted in orange, purple, yellow, blue, green and red, respectively.

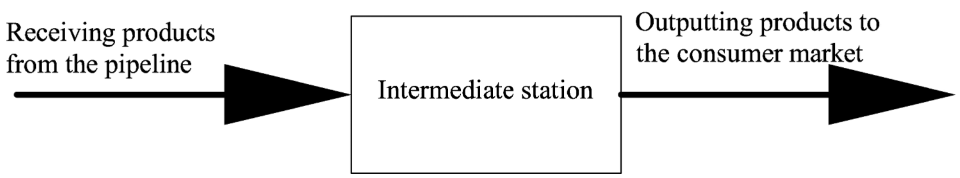

Fig. A8. Schematic diagram for an intermediate station receiving and outputting products.

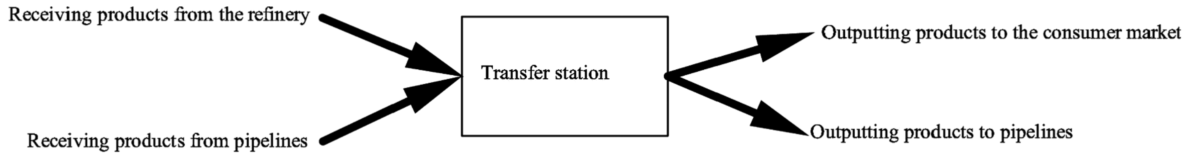

Fig. A9. Schematic diagram for a transfer station receiving and outputting products.

Table B3
Minimum and maximum inventories of products in stations for TPN and MPN (10^3 m^3).

Pipeline network	Station	P1		P2		P3		P4		P5		P6	
		Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
TPN	N1	30	1	30	1	30	1	30	1	–	–	–	–
	N2	40	1	40	1	40	1	40	1	–	–	–	–
	N3	30	1	30	1	30	1	30	1	–	–	–	–
	N4	30	1	30	1	30	1	30	1	–	–	–	–
MPN	D1	50	1	50	1	50	1	50	1	50	1	50	1
	D2	50	1	50	1	50	1	50	1	50	1	50	1
	D3	20	1	–	–	20	1	0	0	0	–	0	–
	D4	50	1	50	1	50	1	50	1	50	1	50	1

Table B4
Product demands at consumer markets and initial inventories in stations (10^3 m^3).

Pipeline network	Station	P1		P2		P3		P4		P5		P6	
		Demand	Initial	Demand	Initial	Demand	Initial	Demand	Initial	Demand	Initial	Demand	Initial
TPN	N1	–	6	–	10.5	–	6	–	6	–	–	–	–
	N2	3	29.6	3	34	10	32	10	30	–	–	–	–
	N3	40	15	44	12	39	24	25	18	–	–	–	–
	N4	37.5	15	30	18	55	21	33.6	15.6	–	–	–	–
MPN	D1	–	25	–	27	–	30	–	5	–	5	–	16
	D2	30	8	6.5	10	56	5	15	4	25	5	50	2
	D3	7.5	1	–	–	7.5	1	–	–	–	–	–	–
	D4	0	28	15	7	0	28	12	2	0	28	30	31

Table B5
Production rates of products in refineries (m^3/h).

Pipeline network	Refinery	P1	P2	P3	P4	P5	P6
TPN	N1	180	280	280	200	–	–
MPN	D1	200	200	200	200	200	200

Table B6
Model sizes and results for optimizing schedules of pipeline network TPN using *CPLEX* as solver.

INM	*KM*	A	Constraints	Binary variables	Continuous variables	CPU time (s)	Makespan (h)	Optimality gap (%)
6	9	Infeasible						
6	10	NO	5727	819	4310	84	165	0
6	11	NO	6285	894	4779	211	137.5	0
6	12	NO	6813	969	5248	622	137.5	0
7	10	NO	6216	885	4640	109	165	0
7	11	NO	6783	966	5145	440	137.5	0
7	12	NO	7350	1047	5656	443	137.5	0
8	10	YES	6675	951	4970	112	165	0
8	11	YES	7281	1038	5511	129	137.5	0
8	12	YES	7887	1125	6052	6773	137.5	0

"A" indicates whether every pipeline transports at least one fictitious batch.

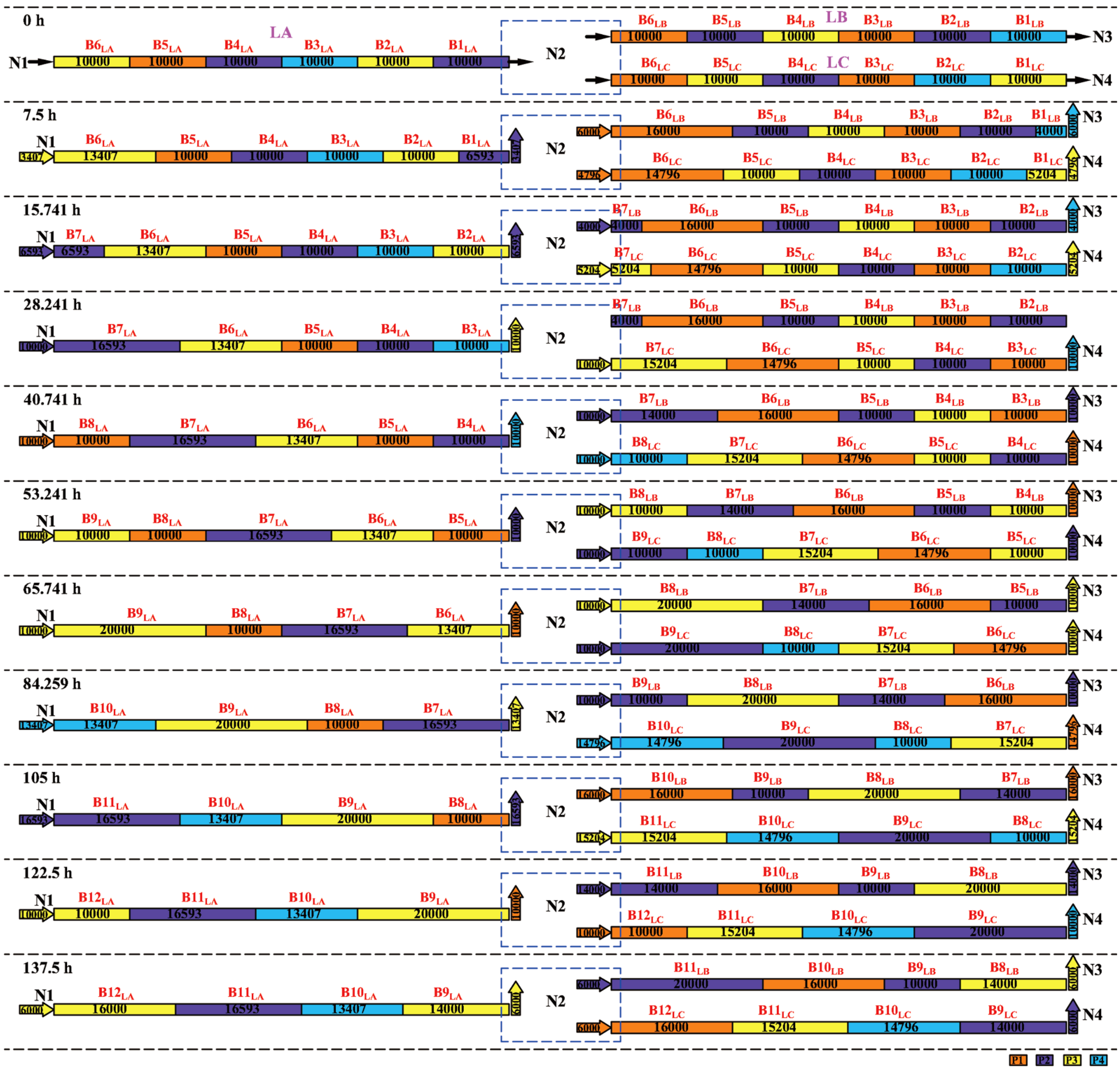

Fig. A10. Optimal detailed schedules for pipeline network TPN.

5.1. Case 1 for pipeline network TPN

5.1.1. Basic data

In pipeline network TPN, four products P1, P2, P3 and P4 can be simultaneously transported in every pipeline at a flow rate ranging from 400 to 800 m^3/h. Products P1 and P4 are forbidden to be adjacently conveyed. Every pipeline can operate at the full volume capacity of 60,000 m^3. Transfer stations N2, N3 and N4 can supply products to consumer markets at a maximum rate of 400 m^3/h. The size of every product pumped into every pipeline ranges from 8000 to 20,000 m^3. The initial sequence of products in pipelines are (LA: $B1_{LA}$-P2, $B2_{LA}$-P3, $B3_{LA}$-P4, $B4_{LA}$-P2, $B5_{LA}$-P1, $B6_{LA}$-P3), (LB: $B1_{LB}$-P4, $B2_{LB}$-P2, $B3_{LB}$-P1, $B4_{LB}$-P3, $B5_{LB}$-P2, $B6_{LB}$-P1) and (LC: $B1_{LC}$-P3, $B2_{LC}$-P4, $B3_{LC}$-P1, $B4_{LC}$-P2, $B5_{LC}$-P3, $B6_{LC}$-P1). The volume of every old batch is 10,000 m^3.

5.1.2. Optimizing schedules using CPLEX

Setting different numbers of time nodes and new batches, the results for optimizing batch schedules of pipeline network TPN using *CPLEX* are given in Table B6. When the number of new batches $INM = 6$ and the number of time nodes $KM = 9$, KM is so low that no feasible solution can be found. Increasing KM from 10 to 11, optimal solutions are successfully obtained and the quality is improved. When $KM = 12$, the quality of the optimal solution does not change. Then, setting $INM = 7$, the optimal makespan is 137.5 h. Finally, adopting $INM = 8$, the best final objective function is also 137.5 h. In particular, when $INM = 8$, fictitious batches occurs in the optimization results, which means that the optimal value of INM is 8.

By adopting $INM = 8$ and $KM = 11$, *CPLEX* successfully finds the optimal batch schedule for pipeline network TPN in 129 s (see

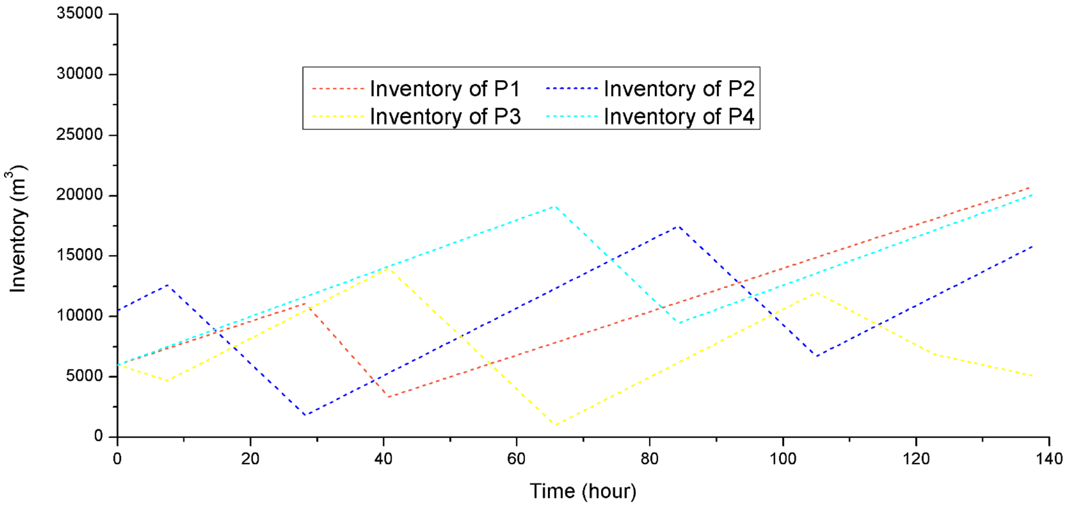

Fig. A11. Evolutions on inventories of products in station N1 of pipeline network TPN.

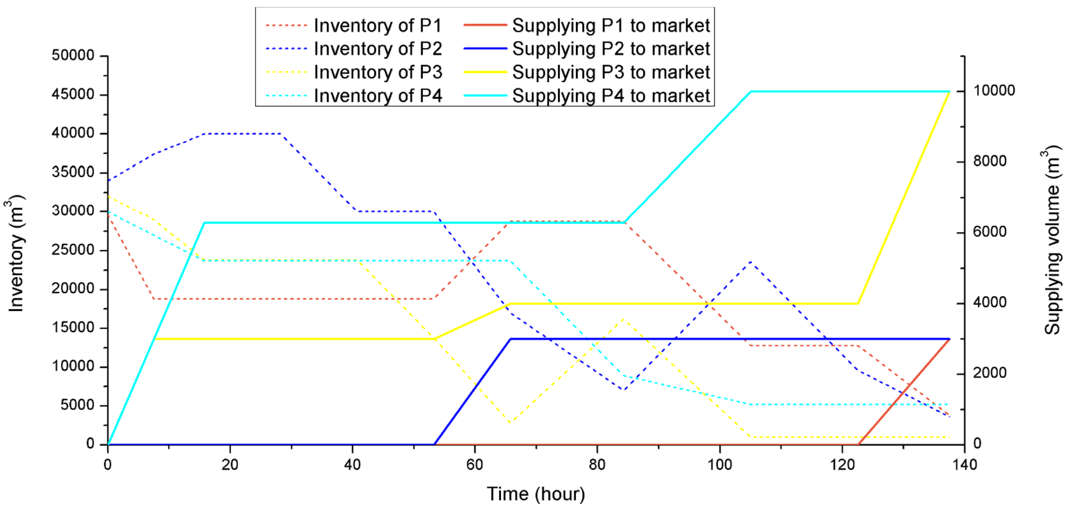

Fig. A12. Evolutions on inventories and supplying volumes in station N2 of pipeline network TPN.

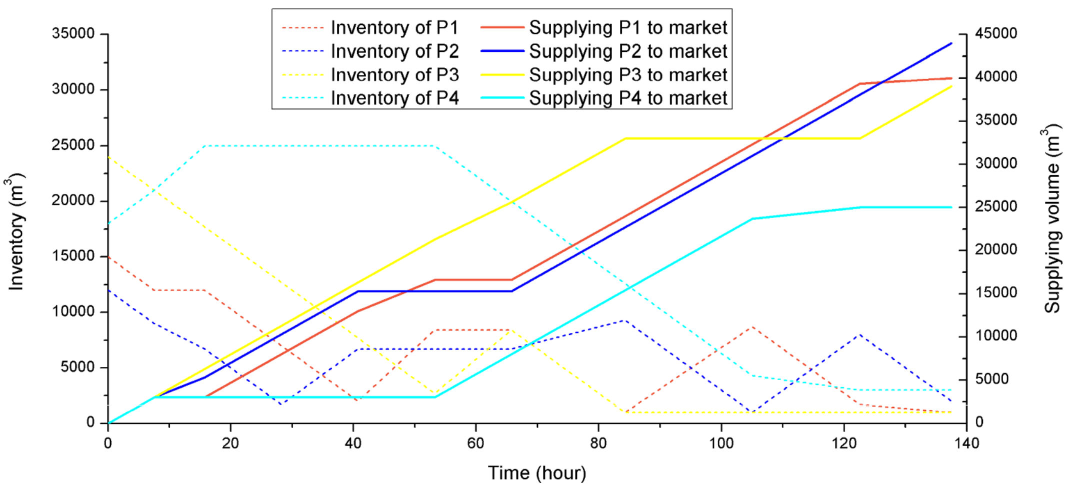

Fig. A13. Evolutions on inventories and supplying volumes in station N3 of pipeline network TPN.

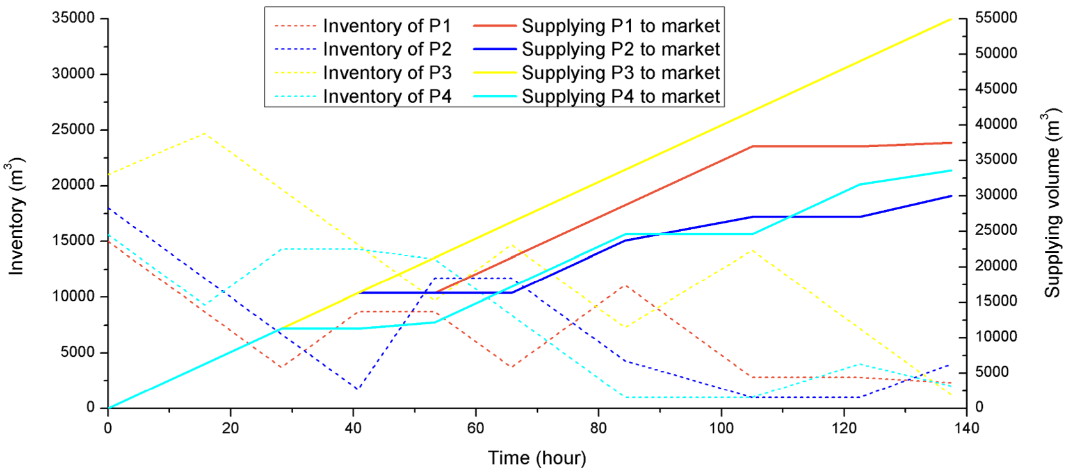

Fig. A14. Evolutions on inventories and supplying volumes in station N4 of pipeline network TPN.

Table B7
Model sizes and results for optimizing schedules of pipeline network MPN using *CPLEX* as solver.

INM	*KM*	A	Constraints	Binary variables	Continuous variables	CPU time (s)	Makespan (h)	Optimality gap (%)
4	4	Infeasible						
4	5	NO	3116	398	2115	1.22	132.33	0
4	6	NO	3590	460	2625	3.75	110	0
4	7	NO	4064	522	3135	11.02	104.44	0
4	8	NO	4538	584	3645	21.56	104.44	0
5	5	YES	3490	444	2341	2.03	132.33	0
5	6	YES	4008	513	2906	3.28	110	0
5	7	NO	4526	582	3471	11.25	104.44	0
5	8	NO	5044	651	4036	51.25	104.44	0
6	5	YES	3864	490	2567	1.46	132.33	0
6	6	YES	4426	566	3187	3.44	110	0
6	7	YES	4988	642	3807	13.58	104.44	0
6	8	YES	5550	718	4427	28.75	104.44	0

"A" indicates whether every pipeline transports at least one fictitious batch.

Fig. A10). The transportation task is finished at 137.5 h and the scheduling period is divided by 7.5, 15.741, 28.741, 40.741, 53.241, 65.741, 84.259, 105 and 122.5 h. Although *INM* = 8, pipelines LA, LB and LC inject just six, five and six new batches, respectively, that are (LA: $B7_{LA}$-P2, $B8_{LA}$-P1, $B9_{LA}$-P3, $B10_{LA}$-P4, $B11_{LA}$-P2, $B12_{LA}$-P3), (LB: $B7_{LB}$-P2, $B8_{LB}$-P3, $B9_{LB}$-P2, $B10_{LB}$-P1, $B11_{LB}$-P2) and (LC: $B7_{LC}$-P3, $B8_{LC}$-P4, $B9_{LC}$-P2, $B10_{LC}$-P4, $B11_{LC}$-P3, $B12_{LC}$-P1). The forbidden sequence (P1-P3) does not appear in all the pipelines during (0–137.5 h). During the first time interval (0–7.5 h), the three pipelines continue to inject products into old batches $B6_{LA}$, $B6_{LB}$ and $B6_{LC}$, respectively. In the next pumping run (7.5–15.741 h), the injected products are switched in all the three pipelines. In turn, pipeline LB is idle in (15.741–28.241 h). All pipelines operate at the maximum pumping rate of 800 m^3/h over (28.241–40.741 h). During (0–137.5 h), the total volumes of batches transported by pipelines are kept with 10,000–20,000 m^3. Any new batch injected into pipelines occupied at most two time intervals. For example, batch $B12_{LA}$ is injected into pipeline LA at (105–122.5 h) and (122.5–137.5 h). Evolutions on inventories and supplying volumes of products in transfer stations are shown in Figs. A11–A14. In the first pumping run (0–7.5 h), the inventory of product P3 in station N1 reduces from 6000 m^3 to 4693 m^3 due to receiving 2100 m^3 from the refinery and outputting 3407 m^3 to pipeline LA. The inventory of product P2 in transfer station N2 rises from 34,000 m^3 to 37,407 m^3 due to receiving 3407 m^3 of product P2 from pipeline LA. The inventory of product P1 in station N2 reduces from 29,600 m^3 to 18,804 m^3 because of outputting 6000 m^3 to pipeline LB and 4796 m^3 to pipeline LC. The inventory of product P4 in station N3 reduces from 15,600 m^3 to 12,600 m^3, because 3000 m^3 of product P4 is delivered to the consumer market at the rate of 400 m^3/h. During (0–137.5 h), the inventory of every product in every station is always kept within the feasible range. Meanwhile, when the scheduling horizon ends, the demand of every product in every consumer market is fulfilled.

5.2. Case 2 for pipeline network MPN

5.2.1. Basic data

In mesh pipeline network MPN, pipelines XA-XB-XC can transport six products P1-P2-P3-P4-P5-P6. The size of every product pumped into every pipeline ranges from 10,000 to 30,000 m^3. The coordinates of delivery stations along pipelines are (XA: D1-0 m^3, D2-120,000 m^3), (XB: D1-0 m^3, D3-40,000 m^3, D4-100,000 m^3) and (XC: D4-0 m^3, D2-100,000 m^3), respectively. Every input station

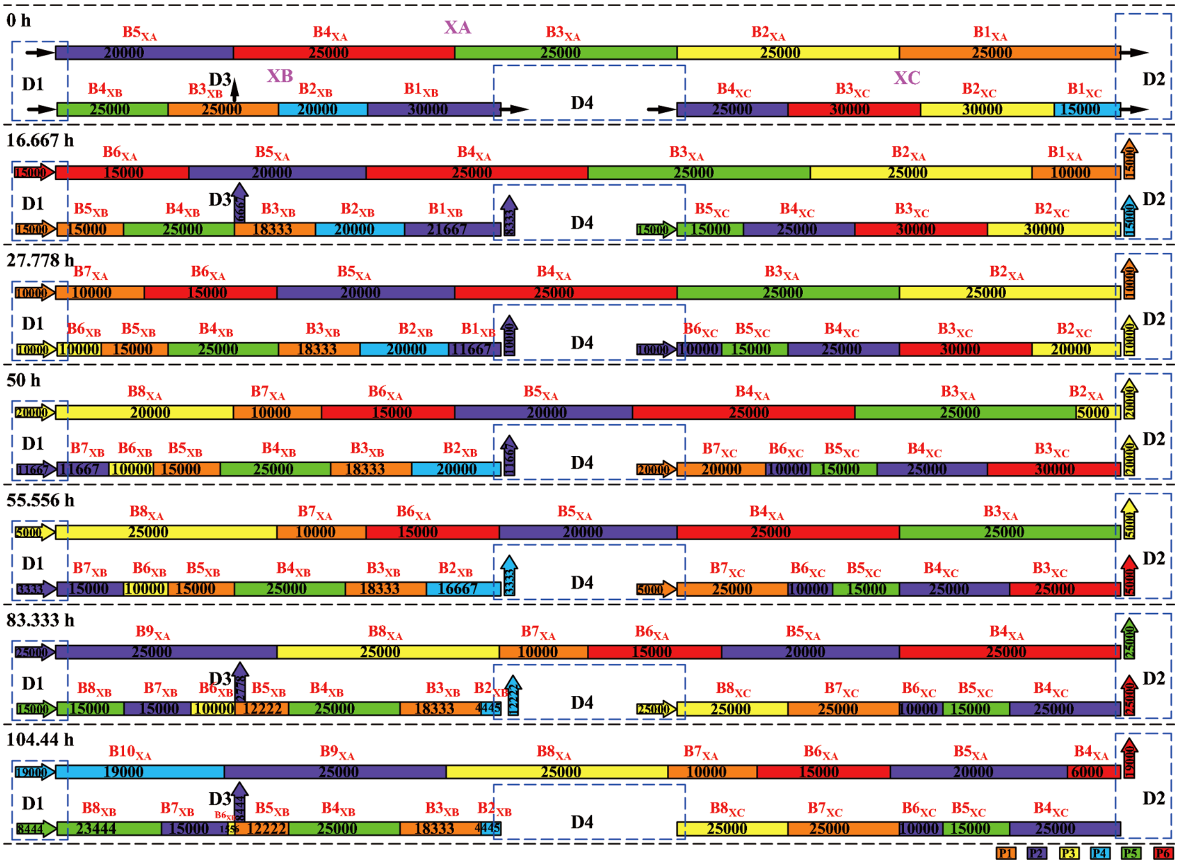

Fig. A15. Optimal detailed schedules for pipeline network MPN.

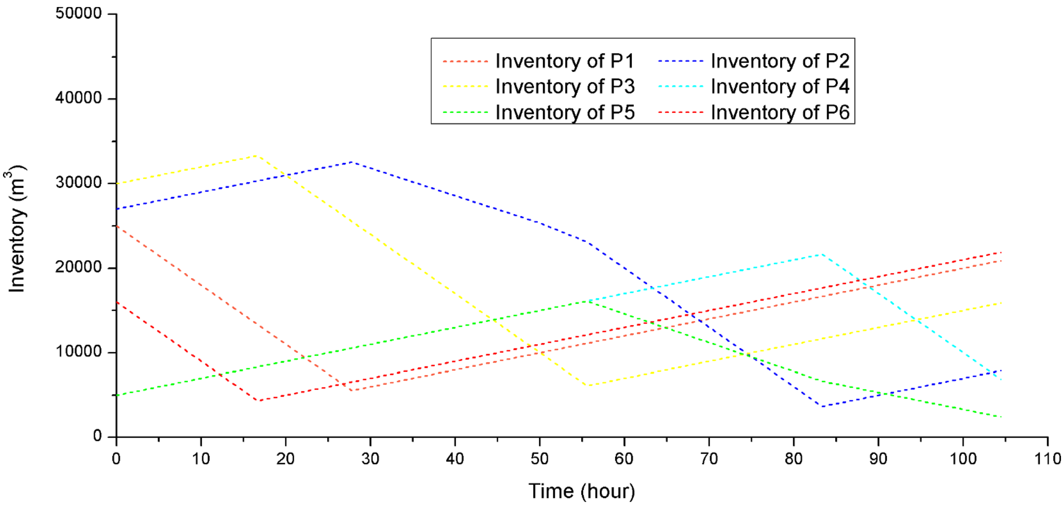

Fig. A16. Evolutions on inventories in station D1 of pipeline network MPN.

can inject products into every pipeline at a flow rate ranging from 400 to 900 m^3/h. Besides, the flow rate by which intermediate station D3 receives products from in-transit batches ranges from 100 to 400 m^3/h. Any transfer or intermediate station can supply products to its consumer market at a maximum rate of 1000 m^3/h. The initial line-fills in pipelines are (XA: $B1_{XA}$-P1, $B2_{XA}$-P3, $B3_{XA}$-P5, $B4_{XA}$-P6, $B5_{XA}$-P2), (XB: $B1_{XB}$-P2, $B2_{XB}$-P4, $B3_{XB}$-P1, $B4_{XB}$-P5) and (XC: $B1_{XC}$-P4, $B2_{XC}$-P3, $B3_{XC}$-P6, $B4_{XC}$-P2).

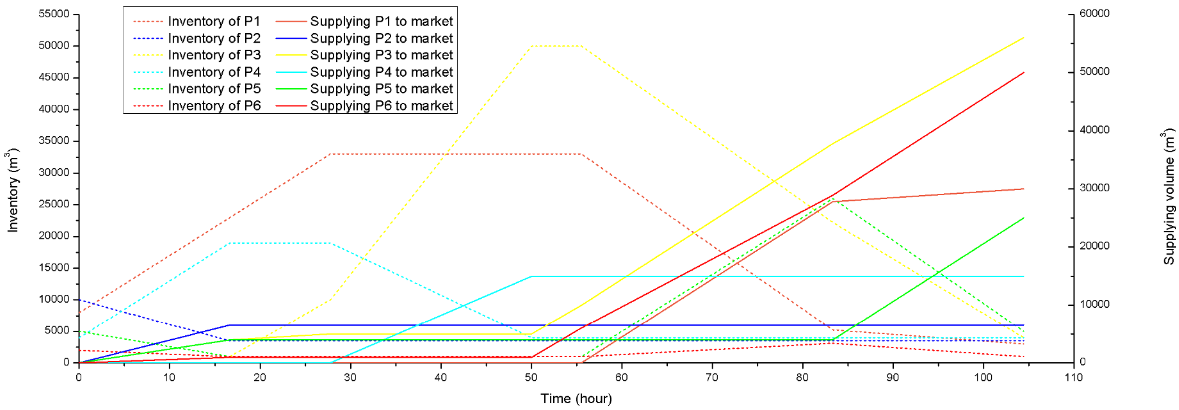

Fig. A17. Evolutions on inventories and supplying volumes in station D2 of pipeline network MPN.

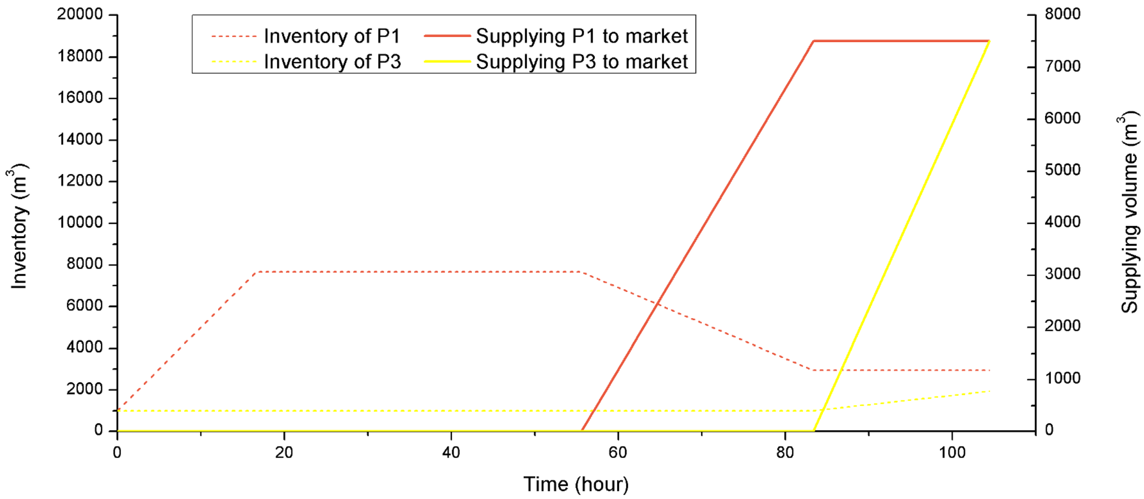

Fig. A18. Evolutions on inventories and supplying volumes in station D3 of pipeline network MPN.

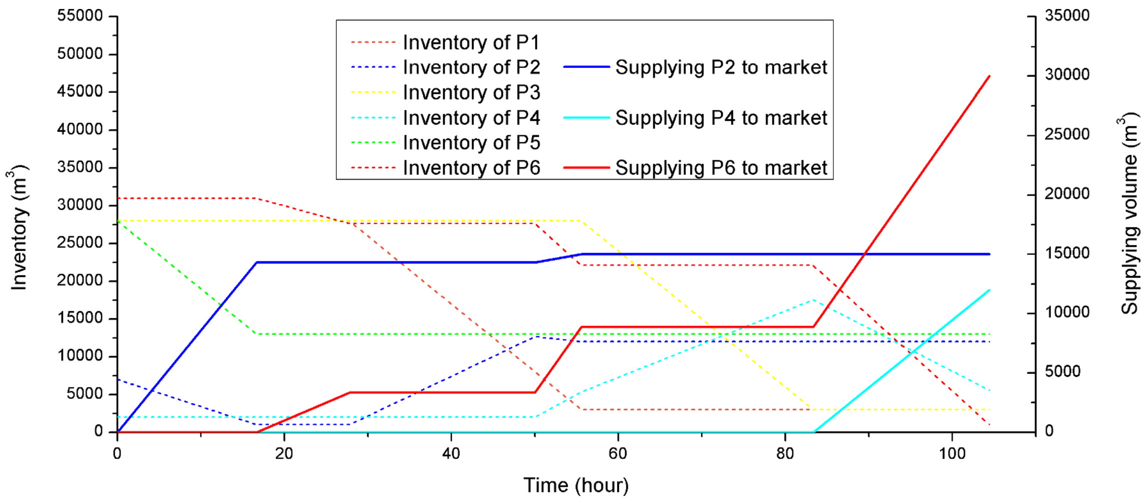

Fig. A19. Evolutions on inventories and supplying volumes in station D4 of pipeline network MPN.

5.2.2. Optimizing schedules using CPLEX

By adopting the number of new batches *INM* and the number of time intervals *KM*, the model size and optimization results for pipeline network MPN provided by *CPLEX* are shown in Table B7. Obviously, when $INM = 6$ and $KM = 7$, the final solution found in

Table B8
Optimization results for pipeline network PNC provided by different works.

Optimization model	Constraints	Binary variables	Continuous variables	Makespan (h)	Optimality gap (%)
This work	6027	744	4207	172.20	0
Cafaro (2012)	3464	330	1785	179.00	0
Castro (2017)	6252	1329	2680	194.29	0

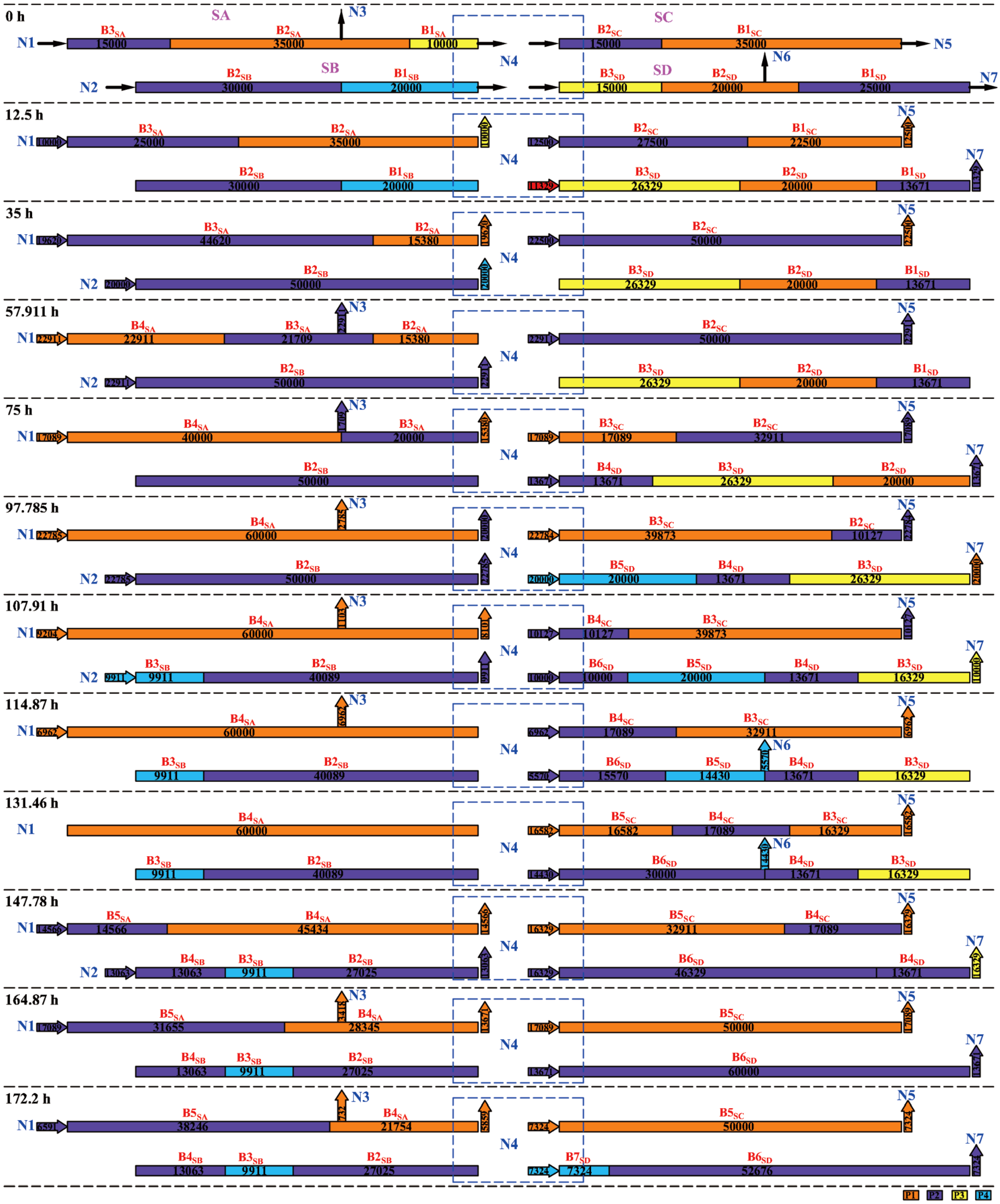

Fig. A20. Optimal detailed schedules for pipeline network PNC.

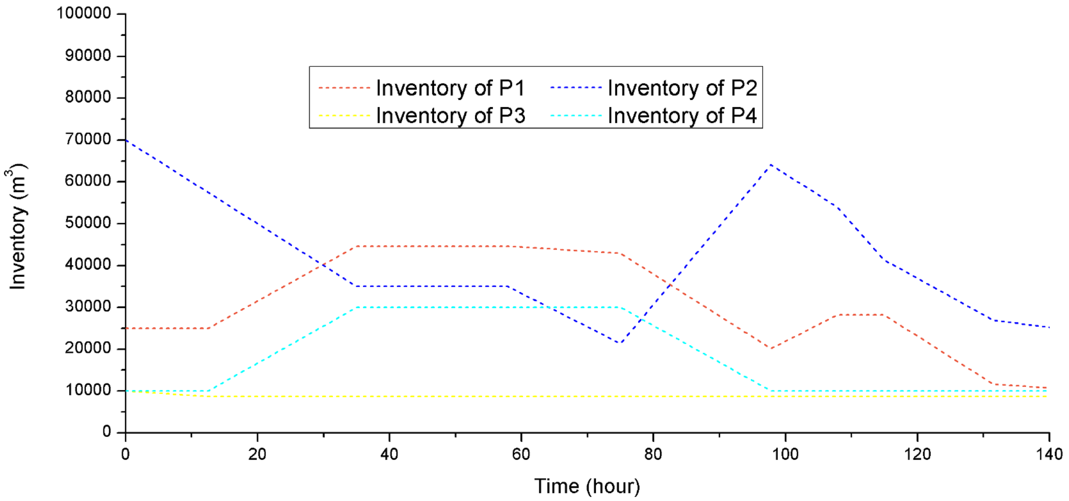

Fig. A21. Evolutions on inventories in station N4 of pipeline network PNC.

13.58 s by *CPLEX* is the best and the optimal detailed schedule is depicted in Fig. A15. The transportation task is finished at 104.44 h and the scheduling period is divided by 16.667, 27.778, 50, 55.556 and 83.333 h. The sequence of products injected into pipelines during the scheduling horizon are (XA: $B6_{XA}$-P3, $B7_{XA}$-P2, $B8_{XA}$-P6, $B9_{XA}$-P1, $B10_{XA}$-P5), (XB: $B5_{XB}$-P1, $B6_{XB}$-P3, $B7_{XB}$-P2, $B8_{XB}$-P5) and (XC: $B5_{XC}$-P5, $B6_{XC}$-P2, $B7_{XC}$-P1, $B8_{XC}$-P3), respectively. During the first pumping run (0–16.667 h), every pipeline pumps a new batch at the maximum rate of 900 m^3/h. During the last pumping run (83.333–104.44 h), pipeline XC becomes idle. Product inventory and supplying volume profiles in stations are shown in Figs. A16–A19. The inventory of every product in every station is always within the allowable range. When the scheduling period ends, the demand for every product in every station is satisfied.

5.3. Case 3 for pipeline network PNC

Cafaro and Cerda (2012) published a continuous MILP model based on the batch-centric representation for the scheduling optimization of a mesh multiproduct pipeline network named PNC. Castro(2017) proposed an MILP model using the product-centric representation. Different from the model published by Castro (2017), the MILP model proposed in this article adopts the batch-centric representation. For illustrating the good performance of our work, pipeline network PNC used by Castro (2017) and Cafaro and Cerda (2012) is tested. Pipeline network PNC can send four products P1, P2, P3 and P4 from transfer stations N1-N2 to transfer stations N4-N5-N7 and intermediate stations N3-N6 through pipelines SA, SB, SC and SD at the pumping rate of 800–1000 m^3/h. Before solving the model proposed in this work, set $INM_1 = 2$, $INM_2 = 2$, $INM_3 = 3$ and $INM_4 = 4$. Based on the MILP model proposed in this article, *CPLEX* successfully finds the optimal solution for pipeline network in 2400 s. The optimization results provided by different works can be found in Table B8. The model proposed in this article shows a better performance than the works published by Cafaro and Cerda (2012) and Castro (2017). The optimal makespan given by this work is 172.20 h, which is 3.80% and 11.37% lower than that reported by Cafaro and Cerda (2012) and Castro (2017), respectively. Fig. A20 depicts the optimal schedule for pipeline network PNC obtained by this work. The inventory of key station N4 is shown in Fig. A21. Compared with the work by Cafaro and Cerda (2012), Cafaro and Cerda just obtain optimal aggregate schedules and this article finds optimal detailed schedules. In the model by Castro (2017), any two batches in a pipeline segment cannot contain a same product at any discrete time node, which does not accord to the reality and reduces the quality of optimal solutions.

6. Summary

An MILP formulation is developed to optimize detailed schedules of multiproduct pipeline networks, which can be tree-like or mesh. Transfer stations are the links between pipelines. Every pipeline can convey products from a unique station to several delivery stations. Delivery stations along a pipeline can simultaneously perform delivery operations. Operation constraints about sequence of products, size of batches, flow rate of delivery/injection operations, pumping rate of pipeline segments, batch tracking, conditions of implementing injection/delivery operations, inventory management of stations and consumer markets' demand are all satisfied in the proposed MILP formulation. Especially, sequence constraints of products are satisfied not only when products are pumped into a pipeline, but also when batches move in a pipeline. For seeking the minimum makespan, optimal detailed schedules of a tree-like network comprising three pipelines and four transfer stations and supplying four products from one refinery to three consumer markets are successfully obtained. In turn, a second case deals with a mesh network delivering six products from one refinery to three consumer markets through three pipelines, three transfer stations and one intermediate station. The optimal schedules of the mesh network are successfully found. Finally, a case tested on a mesh pipeline network used by Cafaro and Cerda (2012) and Castro (2017) successfully illustrates the good performance of our work. The three cases for different pipeline networks fully demonstrate the practicality of the proposed MILP formulation.

On future works, the proposed model will be extended to address the scheduling of a multiproduct pipeline network with reversible pipelines where batches can be transported in two directions. Moreover, considering the large size of the MILP formulation for more complex pipeline networks, a tailored strategy for solving the formulation is required, instead of the direct use of a commercially optimization solver.

Acknowledgments

This study was supported by the National Science and Technology Major Project of China (No. 2016ZX05028004) and the Beijing Oil and Gas Pipeline Control Center of CNPC.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.tre.2019.01.012.

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