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Heuristic Rescheduling of Crude Oil Operations to Manage Abnormal Supply Chain Events

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Globalization and the resultant complexity of today's supply chains require that enterprises be agile and proactive. This communication looks at a refinery supply chain where disruptions such as crude arrival delay could make the current schedule infeasible and necessitate rescheduling of operations. Existing approaches for generating (near) optimal schedules for a real-world refinery typically require significantly large amounts of time. This is undesirable when rectification decisions need to be made in a short time. Further, when the problem data given to the existing scheduling approaches are changed, as is the case during a disruption, the optimizers follow different solution paths and result in substantially different schedules. A heuristic rescheduling strategy is proposed that overcomes both these shortcomings. The key insight exploited here is that any schedule can be broken into operation blocks. Rescheduling is performed by modifying these blocks in the original schedule using simple heuristics to generate a new schedule that is feasible for the new problem data. Our strategy avoids major operational changes by preserving—as far as possible—the blocks in the original schedule. The major advantages of the proposed method are its real-time computational performance and the minimal changes to the operations as compared to total rescheduling. Further, the proposed strategy can also identify many feasible schedules and allow refinery personnel to select one by considering other factors that cannot be adequately modeled in a scheduler. Our method is illustrated using five types of disruptions occurring in a refinery. The various factors that affect the robustness of a supply chain in the face of disruptions are also discussed. © 2007 American Institute of Chemical Engineers *AIChE J,* 53: 397–422, 2007
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Introduction

Supply chain management becomes increasingly important as companies adapt to today's competitive business climate by adopting various new strategies to reduce costs and maintain efficient operations. Common trends such as single sourcing, outsourcing, just-in-time logistics, and centralized distribution lead to complex supply chains, which are vulnerable to disruptions. Blockage in any material, information, or finance flow among supply chain constituents would engender undesirable outcomes such as process shutdown, financial loss, and under- or oversupply. Furthermore, uncertainties in supply, demand, transportation, market conditions, and many other factors can interrupt supply chain operations, causing significant adverse effects.

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In this communication, we define *disruption* as any event or situation that causes deviation from normal or planned supply chain operations. Disruption could be unexpected deviations in the input data (such as supply and demand) or changes in the supply chain structure (such as nonavailability of production facilities). Although a deviation between plan and actual realization is always to be expected, depending on the magnitude of the deviation, the response may have to differ qualitatively. Small deviations can usually be dealt with without modifying the previously generated solution. Robust scheduling would improve the extent of deviations that can be tolerated, but at the cost of quality. Large deviations, called disruptions, usually result in infeasibility of the original solution, and thus rescheduling becomes necessary.[1] In contrast to the proactive robust scheduling strategy, here we use a reactive optimal strategy. The proactive and the reactive strategies thus differ in the way they deal with the solution flexibility vs. quality trade-off. In contrast to the former, the latter weighs quality over flexibility. It also is able to make amends for uncertainty as necessary as and when it is actually realized.

Among the possible causes of disruption are operational difficulties, emergency shutdown, natural disasters, terrorist incidents, industrial actions (such as strikes or protests), and accidents (in-plant or during transportation). Root causes for disruptions are often human error, wrong information, and poor planning or forecasting. Disruptions bring about adverse effects such as blockage of material flow, loss of ability to deliver the right quantity of the right product at the right place and at the right time, inability to meet quality requirements, loss of cost efficiency, under- or oversupply, and process shutdown. All of these translate into financial losses—directly or indirectly—and motivate the development of simulation models and decision support systems for managing disruptions in the supply chain.

A disruption management system should be capable of detecting disruptions in a timely fashion before they occur so that there is enough time to take corrective actions.[2] It should also be capable of diagnosing the root cause(s) of the disruptions and help to identify the necessary corrective actions to prevent and minimize losses.

One such corrective action that is often needed is *rescheduling*, which is the focus of this report. We look at a refinery supply chain and present a strategy for managing disruptions by rescheduling. Some common disruptions in a refinery supply chain include delays in crude oil arrivals, crude oil being out-of-spec, unexpected changes in product distribution, unavailable or constrained plant units, and demand fluctuations. Such disruptions are not infrequent. For example, every month there are four to five occasions on average when crude oil transportation by sea to the refinery is delayed. Similarly, use of crude oil from storage is constrained four to five times each month arising from entrained rainwater.[3]

The concept of disruption management has received attention in various areas such as airline flight and crew scheduling, production planning, and batch plant (job shop and flow shop) scheduling. However, to our knowledge, there has not been any reported work on rescheduling of refinery operations in response to supply chain disruptions.

In general, there are two approaches to disruption management: predictive and reactive.

(1) *Predictive scheduling* seeks to accommodate possible disruptions while planning or scheduling. In other words, the predictive approach aims to produce inherently robust plans or schedules. This could be done, say, by allowing some buffer time or capacity in the plan or schedule. The predictive approach includes robust optimization, stochastic programming, and scheduling under uncertainty.[4,5] The reader is referred to Aytug et al.[6] for a review of predictive scheduling literature. Predictive scheduling, performed before the disruptions actually occur, is largely based on probabilistic approaches. It involves a trade-off because providing for uncertainties in the schedule would mean allowing for a loss in optimality. Also, because not all disruptions can be preenumerated, predictive scheduling is almost always coupled with reactive strategies.

(2) *Reactive scheduling* is used during the actual execution of the plan or schedule, when a disruption has occurred. For reactive scheduling, the time required for rescheduling is a critical issue because rescheduling has to be performed in the actual course of the operation execution and any delay in responding to the disruptions could have significant financial impact. Herein, we propose a reactive scheduling strategy that uses an optimal deterministic schedule as the basis. The initial schedule is not suboptimal, as in the case of predictive approaches that allow for uncertainty and stochasticity. Thus, in our approach, the optimal schedule is used; any disruption will be managed quickly, if and when it occurs, by heuristic rescheduling.

The remainder of this article is organized as follows. A literature survey of supply chain management with uncertainties and disruptions is presented next. In the next major section, we present the problem statement for refinery rescheduling and a motivating example. The following section describes the proposed heuristic rescheduling methodology, which is illustrated by examples in a subsequent section. In the final section, we identify and evaluate the factors that determine a supply chain's robustness to disruptions.

Uncertainties and Disruptions in Supply Chain Management: A Literature Survey

Disruption management in supply chain

Sheffi et al.[7] describe mechanisms that companies follow to assess terrorism-related risks, protect the supply chain from those risks, and attain resilience. Because it is difficult to identify all possible sources of risks, they emphasize that the type of disruption matters more than its source. They classify disruptions into those arising in supply, transport, facility, communication, and demand. They identify two basic principles to achieve resilience: (1) Redundancy—duplicating resources to ensure the availability of a backup solution in case of a disruption and (2) Flexibility—that is, the ability to accommodate sudden fluctuations in the availability of resources. The latter is in general more cost effective. The approach presented herein falls into this category.

Gaonkar and Viswanadham[8] propose a conceptual framework to approach supply chain risk problems. They classify supply chain risks into three forms—deviation, disruption, and disaster—and note that supply chains need to be robust in three levels: strategic, tactical, and operational. A supply chain deviation occurs when one or more parameters (such as cost, demand, etc.) deviate from their expected values without any changes to the supply chain structure. A disruption occurs when there is a radical change in structure of the supply chain, such as because an unexpected event impedes production, warehousing, or distribution. A disaster is defined as a temporary, irrecoverable shutdown of the supply chain network arising from unforeseen catastrophic, systemwide disruptions. They developed mathematical models for strategic-level deviation as well as disruption management. One model addresses the problem of selecting an optimal group of suppliers based on each supplier's expected costs and variability. Given the expected probabilities for various supplier disruptions, the second model is used to select a set of suppliers that minimize the expected supply shortfall. Similarly, Xu et al.[9] consider demand disruptions in a one-supplier–one-retailer model. They used nonlinear demand functions in their mathematical model, whose objective is to identify the supplier policy that maximizes the total supply chain profit.

Airline rescheduling

Disruptions are common in the airline industry, and thus airline rescheduling has received much attention in the literature. Airline rescheduling is a complex task that has to consider many resources such as aircraft, crew, passengers, slots, cargo, gates, and so forth, which have to be replanned. Mathaisel[10] suggests that there is no one algorithm or model that will solve all of the problems associated with irregular airline operations because it is very difficult to describe mathematically the complete operation. Therefore, most work addresses specific subproblems. Filar et al.[11] review the different problems in the area of airline schedule recovery. Although some of these subproblems can be solved using mathematical models, for others heuristics are commonly used, either because exact algorithms do not suffice or require unacceptable solution time. Illustrative examples include the aircraft selection heuristic of Rosenberger et al.[12] to select a subset of aircraft to be included in the optimization and the reactive scheduling agent of Jo et al.[13] for aircraft parking.

Shop rescheduling

Batch-plant rescheduling has drawn much attention in the literature. In general, the shop scheduling problem can be described as assigning jobs, consisting of a number of operations, for processing in a number of machines to produce certain products and meet orders with different priorities under some technological precedence (sequence) and resource constraints. The source of shop disruptions could be internal or external. Examples of internal disruptions are machine breakdown, process time variation, and manpower unavailability. Examples of external disruptions are unavailability of raw material, arrival of urgent jobs, and cancellation of order. Aytug et al.[6] and Herroelen and Leus[14] review the vast literature on production scheduling under uncertainties, robust scheduling, and reactive scheduling procedures. Because a dynamic shop-scheduling problem is nondeterministic polynomial time (NP)–complete, various heuristic methods are commonly used to solve this problem.

Akturk and Gorgulu[15] propose a rescheduling strategy that reschedules part of the initial schedule in response to a machine breakdown. Kunnathur et al.[16] developed a rescheduling heuristic that reschedules operations when there is any variation from the expected value of flow time. The above methods do not specifically consider the propagation of the effect of disruptions, which is significant in continuous systems such as a refinery. The affected operations rescheduling (AOR) heuristics of Abumaizar and Svestka[17] account for propagation of disruptions in systems where operations are distinctly separated. Henseler[18] proposes an algorithm for reactive scheduling that efficiently repairs broken constraints by iteratively revising the schedule until there are no more violated constraints. Rules and heuristics are used to guide the rescheduling.

Roslöf et al.[19] present a mixed-integer linear programming (MILP)–based algorithm to efficiently improve an existing feasible, but nonoptimal, production schedule or to reschedule jobs in the case of changed operational parameters. Mendez and Cerdá[20] develop an MILP-reactive scheduling algorithm to revise the short-term schedule of resource-constrained multistage batch facilities arising from unexpected disruptions. The size of the problem formulation remains reasonable because a large part of the scheduling decisions are unchanged and rescheduling actions are applied gradually by first reassigning resource items to tasks yet to be processed and then reordering tasks.

Knowledge-based and artificial intelligence approaches have also been proposed for rescheduling, including case-based reasoning,[21,22] constraint-based scheduling,[23,24] fuzzy logic,[25,26] and neural networks.[27,28,29] The relative advantages and disadvantages of these methods are summarized by Subramaniam and Raheja.[30]

Shop rescheduling methods cannot be directly applied to continuous systems such as a refinery. The decisions to be made in batch scheduling involve allocation of resources, whereas in the continuous case we need to additionally specify throughputs. The typical objective in batch scheduling is minimum makespan, as opposed to maximum profit or minimum cost in continuous processes. A continuous process runs continuously, whereas a batch process runs per order. A plant shutdown as a result of a disruption would therefore have different operational impacts in a continuous plant in contrast to the batch case, given that *additional* shutdown and start-up–related operations would be necessary for the former. Thus, a different method is needed to reschedule refinery operations.

Refinery scheduling and rescheduling

Because today's refineries face extremely competitive business climates and uncertain oil markets, it is crucial for them to be able to respond effectively and promptly to market forces while maintaining reliable operations. Because of the complexity of refinery operations, the literature on the refinery scheduling problem has addressed three smaller subproblems: (1) crude oil operations from unloading up to charging into a crude distillation unit (CDU), (2) blending of intermediate products from the CDU into finished products, and (3) lifting or delivery of the finished products. Kelly and Mann[31] report that crude oil costs account for 80% of refinery turnover and optimal scheduling could make a difference of some million of dollars every year. Consequently, most of the literature in refinery scheduling addresses the crude oil operations subproblem. This article focuses on disruptions in crude oil scheduling. Given crude arrival data, production targets, and operational constraints, an optimal crude operation schedule can be determined. However, most of the research so far has been deterministic[32–36] and has not considered uncertainties.

The typical scheduling horizon in a refinery is 1 to 2 weeks, and it is not uncommon for unexpected events to occur and disrupt the schedule at hand. These disruptions could be such concerns as a delay in tanker arrival time, unavailability of processing equipment, and changes in product demands. In some cases, disruptions could lead to the current schedule becoming infeasible; for example, a ship arrival delay could lead to an out-of-crude situation. The crude oil scheduling problem is typically stated as an MINLP (mixed-integer nonlinear programming) problem. At the present time, no algorithms can find the global optimal solution of an MINLP problem in a tractable run time. Most research work[32–35] approximates the nonlinearity to simplify the problem to an MILP (mixed-integer linear programming) problem. However, it still takes a significant amount of time to solve the MILP problem and generate an optimal schedule for a real-world refinery. It is therefore not desirable to run the whole optimization again every time a disruption occurs because the time required for rescheduling is a critical issue, as previously discussed. Further, a small change in data could lead to large changes from the original schedule because the MILP solver in general would pursue a very different path. Such large changes are undesirable during operation. This provides the motivation for the heuristic rescheduling strategy proposed here.

Problem Statement and Motivating Example

This work is based on the discrete-time formulation of crude oil scheduling by Reddy et al.,[32] which considered the unloading of crude oil from crude carrier vessels up to the charging of crude oil to CDUs. Figure 1 shows the configuration of a typical marine access refinery including crude offloading facilities such as a single-buoy mooring (SBM) station and/or one or more jetties; storage facilities such as storage tanks and/or charging tanks; and processing facilities such as crude distillation units (CDUs). The supply chain operation involves unloading crudes into multiple storage tanks from the ships/tankers arriving at various times and feeding the CDUs from these tanks at various rates over time. Crudes arrive in either large multiparcel tankers or small single-parcel vessels. A very large crude carrier (VLCC) has multiple compartments to carry several large parcels of different crudes. However, because of its huge size, a VLCC must dock offshore at an SBM, which connects to the crude tanks in the refinery by one SBM pipeline. However, from time to time, a refinery may also receive small parcels of single crudes by small ships that dock at an onshore jetty. A refinery may have multiple such jetties. When there are multiple jetties, multiple ships can dock at the same time and simultaneously transfer crude parcels.

The operating rules followed in this report are:[32]

(1) A tank receiving crude from a ship, tanker, or another tank cannot feed a CDU at the same time.
(2) Each tank needs some time (8 h) for brine settling and removal after receiving crude.

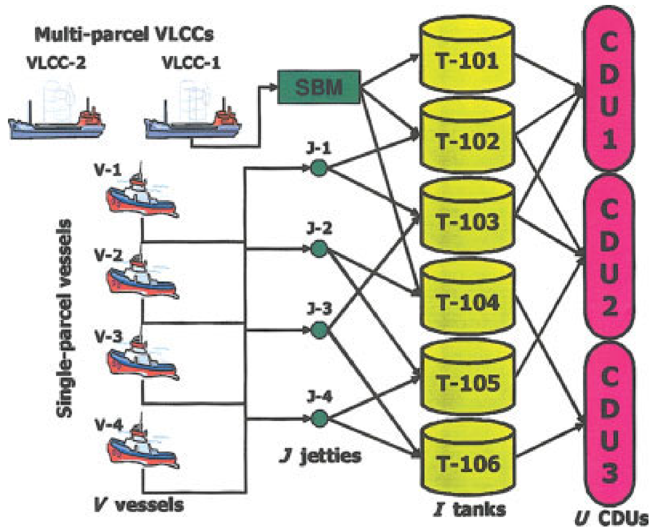

Figure 1. Refinery configuration.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

(3) Multiple tanks can feed a single CDU. Most refiners allow at most two tanks to feed a CDU because the operating complexity increases and controllability becomes a problem for more than two tanks.
(4) A tank may feed multiple CDUs. Again, a tank normally does not feed more than two CDUs.

The assumptions made regarding the refinery operations are:[32]

(1) Only one VLCC can unload at any moment. This is reasonable because there is only one SBM.
(2) The sequence in which a VLCC unloads its parcels is known a priori.
(3) A parcel can unload to only one storage tank at any moment.
(4) The SBM pipeline holds only one type of crude at any time and crude flow is plug flow. This is valid because parcel volumes in a VLCC are much larger than the SBM pipeline holdup.
(5) Crude mixing is perfect in each tank and time to change over tanks between processing units is negligible.
(6) For simplicity, one or more key components are used to decide the quality of a crude feed to CDU.

We assume that the refinery operations have been a priori scheduled but have been disrupted. The proposed method is effect based and not root-cause based because ultimately any source of disruption will imfluence the refinery by disrupting either the crude unloading operations, the CDU-charging operations, or both. This study considers five types of refinery supply chain disruptions: (1) delays in crude arrival, (2) unavailability of offloading facilities (SBM or jetty), (3) unavailability of storage tanks, (4) unavailability of CDUs, and (5) changes in demand. These disruptions are either detected by an automated disruption management system (see, for example, Mishra et al.[2,37] and Bansal et al.[38]) or by operations personnel. Other types of disruptions can be handled using the same heuristic approach by observing their effects on the operations. The rescheduling problem is then stated as follows. Given:

(1) Refinery specifications: configuration details, information about modes of crude segregation in storage and processing, quantity limits (flow rates from the SBM station and jetties to tanks and from tanks to CDUs, CDU processing rates, holdup in the SBM pipeline, storage tank capacities), and quality limits (key component concentration limits during storage and processing).
(2) Production demands during the scheduling horizon.
(3) Initial refinery state (initial crude type in the SBM pipeline, initial inventory levels, and initial volume fractions of crudes in each tank).
(4) Original operation schedule.
(5) Disruption specifications (detection time, disrupted object, disruption duration, etc.).
(6) Economic data such as sea-waiting costs, pumping costs, and crude changeover costs. Within an acceptable solution time, generate one or more new schedules that are:
   - feasible after accommodating the disruption.
   - efficient, that is, having profit close to the initial schedule (within 5–10% is reasonable).

Motivating example

We consider an example to demonstrate the necessity of rescheduling in response to supply chain disruptions. Consider the refinery with specifications summarized in Table 1, which follows the original schedule shown in Table 2. Discrete time representation is used in the schedule and each period is of 8-h duration, in accordance with the fact that most refiners prefer to begin their major operations at the start of a shift, typically 8 h long. The rows correspond to different tanks; the columns, to different periods. Period 1 is the period between Time 0 and 1. There are two types of operation: crude unloading from a vessel to a tank by SBM/jetty (termed *parcel-unloading* operation) and charging a CDU from tank(s) (termed *CDU-charging* operation). In the schedule, a parcel unloading is depicted by the name of the parcel source and a positive volume because it increases the crude volume in a tank, whereas a CDU charging decreases the crude volume in a tank and is depicted by a negative amount and the name of the destination CDU. For example, in the schedule shown in Table 2, Tank 1 is charging 20 kbbl to CDU 3 at Periods 1 and 2 and Tank 6 is receiving 100 kbbl from Parcel 7 at Period 7.

Now suppose, as the result of bad weather at sea, Parcel 7, which is originally scheduled to arrive at Time 6 (see Table 1), is delayed by 16 h (two periods). Under this disruption, the unloading of Parcel 7 to Tank 6 can be performed at Period 9 at the earliest because the parcel arrives only at Time 8. At Period 9, however, Tank 6 is scheduled to charge to CDU 3. Because the first operating rule dictates that a tank cannot receive crude and charge at the same time, Parcel 7 cannot be unloaded into Tank 6, which will then run out of crude at Time 11, rendering the existing schedule infeasible. Rescheduling is thus imperative. Rescheduling is different from scheduling, in that a schedule is already available at hand and this initial schedule should form the basis of rescheduling. A totally different schedule is generally not desirable because operational steps might already have been taken in line with the initial schedule. One feature of MILP

Table 1. Detailed Problem Data for Motivating Example

Flow Rate Limits (kbbl/period)	Min	Max	Tank	(Max Vol) Capacity (kbbl)	(Min Vol) Heel (kbbl)	Initial Inventory (kbbl)	Initial Crude Composition (kbbl) C1	C2	C3	C4	C5	C6
Parcel-Tank	10	250	T1	400	50	250	100	100	50	0	0	0
Tank-CDU	0	50	T2	400	50	250	0	0	0	50	100	100
CDU throughput	20	50	T3	400	50	300	0	0	0	100	100	100
			T4	400	50	350	0	0	0	100	150	100
			T5	400	50	250	0	0	0	100	75	75
Demurrage Cost (k$/period)		15	T6	400	50	100	25	25	50	0	0	0
Changeover Loss (k$/instance)		5	T7	400	50	100	50	25	25	0	0	0
Safety Stock Penalty ($/bbl/period)		0.2	T8	400	50	250	75	75	100	0	0	0

Crude	Sulfur	Wax Content	Viscosity	Margin ($/bbl)	Tanker	Arrival Time	Parcel No: (Crude, Parcel Size kbbl)
C1	0.0135	0.005	8.32	1.5	VLCC-1	2	1: (C2, 10), 2: (C6, 100), 3: (C1, 100), 4: (C4, 90)
C2	0.0115	0.008	7.5	1.75	V1-V2	4	5: (C2, 125), 6: (C5, 125)
C3	0.015	0.004	9.22	1.85	V3	6	7: (C3, 100)
C4	0.007	0.015	4.23	1.25			
C5	0.0065	0.01	4.11	1.45			
C6	0.005	0.02	4.2	1.65			

CDU	Key Component Limits			Demand (kbbl)
CDU1 (Min–Max)	0.0053–0.0067	0.0125–0.0185	4.12–4.21	400
CDU2 (Min–Max)	0.0053–0.0068	0.0125–0.0175	4.10–4.21	400
CDU3 (Min–Max)	0.012–0.014	0.0040–0.0070	7.7–9.1	400

Table 2. Initial Optimal Schedule for the Examples (Profit = 1849)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5																		
2	250					90	2	10	2			−20	2	−20	2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3	300									80	4	20	6																		
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
		−20	2	−20	2	−20	2	−20	2	−20	2																				
5	250									10	4	105	6			−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6	100											105	5	100	7			−50	3	−50	3	−50	3	−30	3	−20	3	−20	3	−20	3
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3														
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3														

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	340	340	340	340	340	340	340
2	250	250	250	340	350	350	330	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	300	300	300	380	400	400	400	400	400	400	400	400	400	400
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	260	365	365	340	315	290	265	240	215	190	165
6	100	100	100	100	100	100	205	305	305	255	205	155	125	105	85	65
7	100	100	100	80	76.8	73.6	70.4	67.2	64	64	64	64	64	64	64	64
8	250	250	250	250	233.2	216.4	199.6	182.8	166	166	166	166	166	166	166	166

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

Table 3. Computation Time of Crude Oil Scheduling Examples in Reddy et al. (2004a)

Reddy et al.'s Example	Horizon [Periods]	Relative MILP Gaps	CPU time (s)*
2	5 days [15]	3%, 2%, 0.01%	1068 (597)
3	5 days [15]	1%, 0.5%	2615 (774)
4	7 days [20]	5%, 3.5%, 2%, 0%	1364 (408)
5	14 days [42]	7%, 4%, 2%, 0%	11,963 (1958)

*CPLEX 7.0 solver within GAMS on Pentium II (IV) machine running Windows NT (XP)

is that a small difference in the problem could lead to very different solution paths being pursued by the solver. Total rescheduling or simply running the scheduler again disregards the initial schedule and results in a new schedule that is most likely very different from the initial. Further, as shown in Table3, the scheduling computation time varies from 20 min to 3 h to schedule this refinery according to the examples reported by Reddy et al.[32] It is therefore not desirable to run the whole optimization again every time a disruption occurs. In the next section, we propose a rescheduling methodology that quickly generates a new schedule that is feasible in the face of the disruption and has fewer changes in the operational steps.

Proposed Methodology

The framework for the proposed rescheduling methodology is schematically shown in Figure 2. The inputs to the rescheduler are the original schedule, the initial refinery state, and details of the disruption. The original schedule contains the crude (ship) arrival data, the production targets, and the transfer rates based on the crude arrivals and production targets. The plant hardware model represents the evolving refinery state (tank inventory, CDU throughput, unit availabilities) over the scheduling horizon. The disruption details include the source of the disruption, as well as the disruption magnitude, duration, and detection time. Using these, the rescheduler first determines the effect of the disruption on the original schedule and the infeasibilities if any. New schedules are then generated based on heuristics that take into account the constraints from the plant hardware model. The schedule evaluator calculates the profit of each new schedule. As described in detail below, rescheduling is performed by decomposing the original schedule into blocks.

Definition of block

A schedule can be considered as a time-ordered list of operations to be performed in the refinery. The execution of the schedule moves the refinery from one state to another. In

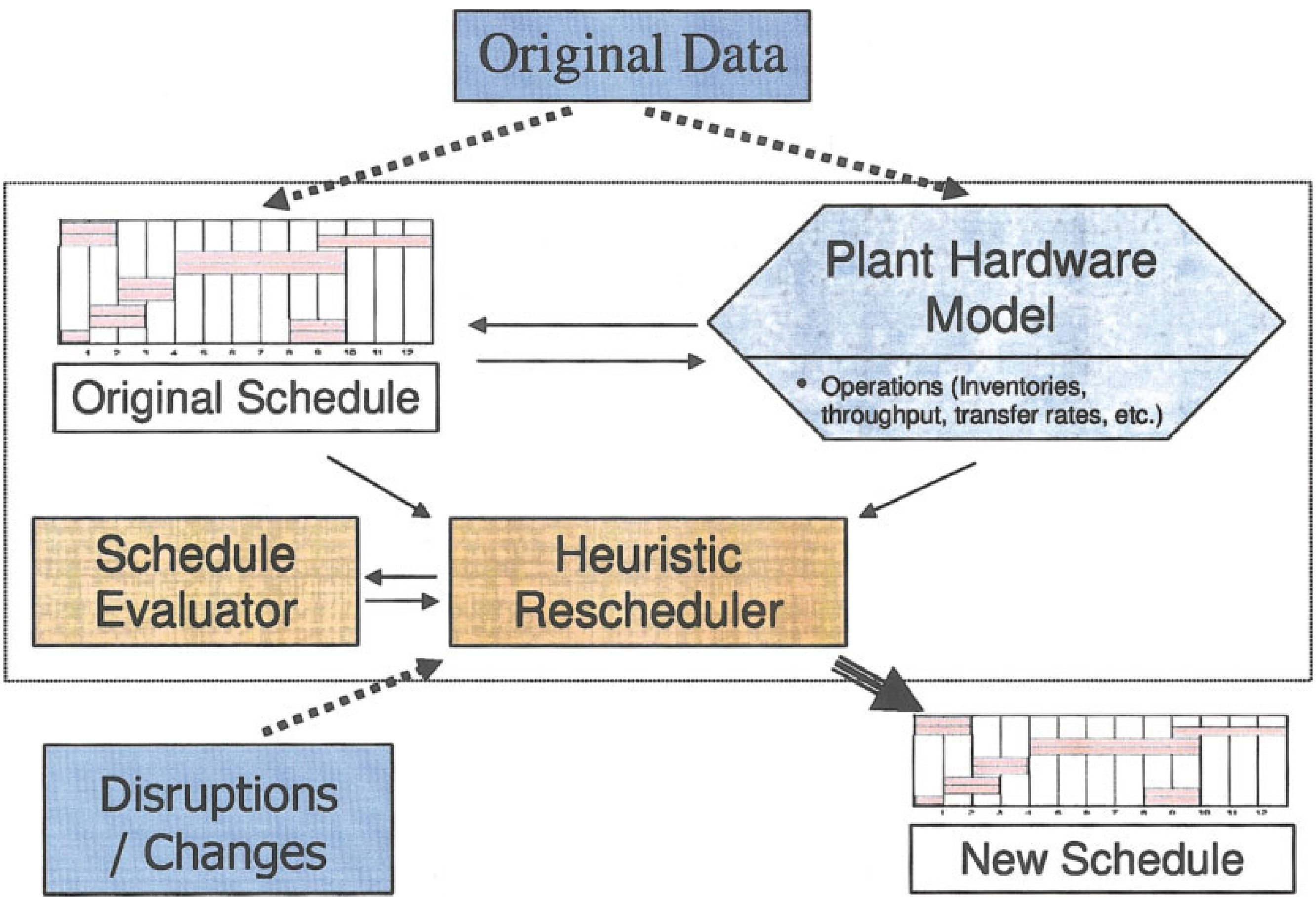

Figure 2. Proposed rescheduling framework.

[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com] general, the crude oil schedule in the refinery specifies the rates and timings of two kinds of operations: parcel unloading and CDU charging. The schedule also implicitly establishes the configuration—parcel-to-tank connections and tank-to-CDU connections—in the refinery at every period over the scheduling horizon. In this article, changes in configuration as well as any change in transfer rates within the same configuration are considered to be different operations. A schedule can be decomposed into blocks of operation. One or more operations spanning one or more periods is considered to be a *block* if it involves no intervening change in configuration. As a corollary, adjacent blocks are separated by a change in configuration. Also, multiple tanks simultaneously charging the same CDU are considered to be the same. In the schedule shown in Table 2, Tank 6 is charging CDU 3 in Periods 9–15. This is considered to be one block, which consists of three operations, with different transfer rates: 50 kbbl/period (Periods 9–11), 30 kbbl/period (Period 12), and 20 kbbl/period (Periods 13–15).

Rescheduling methodology

Our rescheduling methodology is based on the blocks in the original schedule. A configuration change is more significant than a volume change because the former would imfluence the compositions of the crude charges to the CDUs and thus product yields and qualities. Therefore, the rescheduler uses heuristics that seek to minimize changes to the sequence of blocks in the original schedule. Rescheduling is performed as follows: First, the feasibility of the original schedule after taking the disruption into account is verified. If the schedule is still feasible, rescheduling is not critical. However, infeasibilities can arise as the result of state violations, that is, the violations of limits on tank volume, CDU throughput, quality specification, or production target. Rescheduling is imperative when the schedule becomes infeasible. In such cases, disrupted blocks are removed from the schedule to a temporary space called the *D-space*. Rescheduling involves inserting variations of these blocks into the schedule, to correct the changes arising from the disruption. A block preservation heuristic strategy is used to identify the corrective blocks. The heuristics are described below in detail. Although the heuristics inherently take into account quantity limits and would not produce schedules with state violations, quality constraints are best imposed after all the operations have been scheduled. Thus, the method can deal with any number of key components. We simulate the resulting new schedules to ensure their overall feasibility and discard the infeasible ones. If there is a configuration change in the new schedule, the resulting compositions would be affected and could lead to quality violations. Therefore, this step is essential. Finally, the objective value of the new, feasible schedules is evaluated. Following Reddy et al.,[32] we measure the quality of a schedule based on gross profit, defined as the sum of crude margins (netbacks) minus the operating costs related to logistics, changeover, demurrage or sea-waiting cost, and safety-stock penalty. Next, we describe the principles used for rescheduling.

Rescheduling principles

In general, five types of disruption can affect the crude oil operations in a refinery: ship arrival delay, SBM/jetty unavailability, tank unavailability, CDU unavailability, and demand change. In all cases, the proposed heuristics seek to retain the blocks of operation from the original schedule as well as their relative positions. The key characteristics of the original schedule can be preserved even if the positions or volumes of the blocks are changed (such as in the face of ship arrival delay and demand changes) or alternate processing strategies enlisted (such as in case of equipment unavailability). Based on this insight, the following four principles are used to generate new schedules.

Principle 1: Reschedule Every Disruption Individually. In this methodology, multiple simultaneous disruptions are considered individually and sequentially, that is, the proposed schedule(s) after accounting for the first disruption is considered as the initial schedule(s) for the second disruption and so on. For completeness, all combinations of possible sequences are explored. If we have two disruptions A and B, the final proposed schedules will constitute all schedules from the two possible sequences: rescheduling for disruption A then B; and B then A.

Principle 2: Reschedule Every Disrupted Block Individually. A disruption may affect multiple operations and cause them to be removed to the D-space. Every disrupted block is rescheduled individually, one after the other. For example, a tank unavailability may disrupt a parcel-unloading block as well as a CDU-charging block scheduled for that tank. In our approach, the parcel-unloading block would be first rescheduled and subsequently the CDU-charging block.

Principle 3: Minimize Domino Effects. It is preferable either to not impact other blocks when reconfiguring a disrupted block or to affect only blocks with no subsequent operations during the scheduling horizon. If other blocks are affected, then the rescheduler has to make up for these induced *secondary disruptions*. For example, if a parcel unloading is rescheduled to a tank currently charging a CDU then the CDU-charging operation has to be reconfigured and any resulting difference in throughput compensated. Also, during rescheduling, loops of corrective actions should be avoided, that is, an operation that has been inserted in response to one disruption cannot be removed while rectifying another.

Principle 4: Minimize CDU Changeover. Changing the configuration of CDU charging has an associated cost reflecting the operational realities involved in a changeover. When faced with a choice, the rescheduler should select block variations that minimize changeovers. For example, such a choice would occur during a demand increase disruption and the rescheduler can either increase volumes of a previously scheduled CDU-charging block or create a new one. To minimize costs, the rescheduler should prefer to extend existing CDU-charging blocks rather than create new ones.

The above principles are incorporated in the following heuristics that modify the blocks in the original schedule to derive new ones.

Proposed heuristics for general block operations

We use heuristics to identify disrupted blocks and to generate variations that overcome the effect of the disruption. Because there are two kinds of operations (parcel unloading and CDU charging) and both can be removed or rescheduled, we need four heuristics.

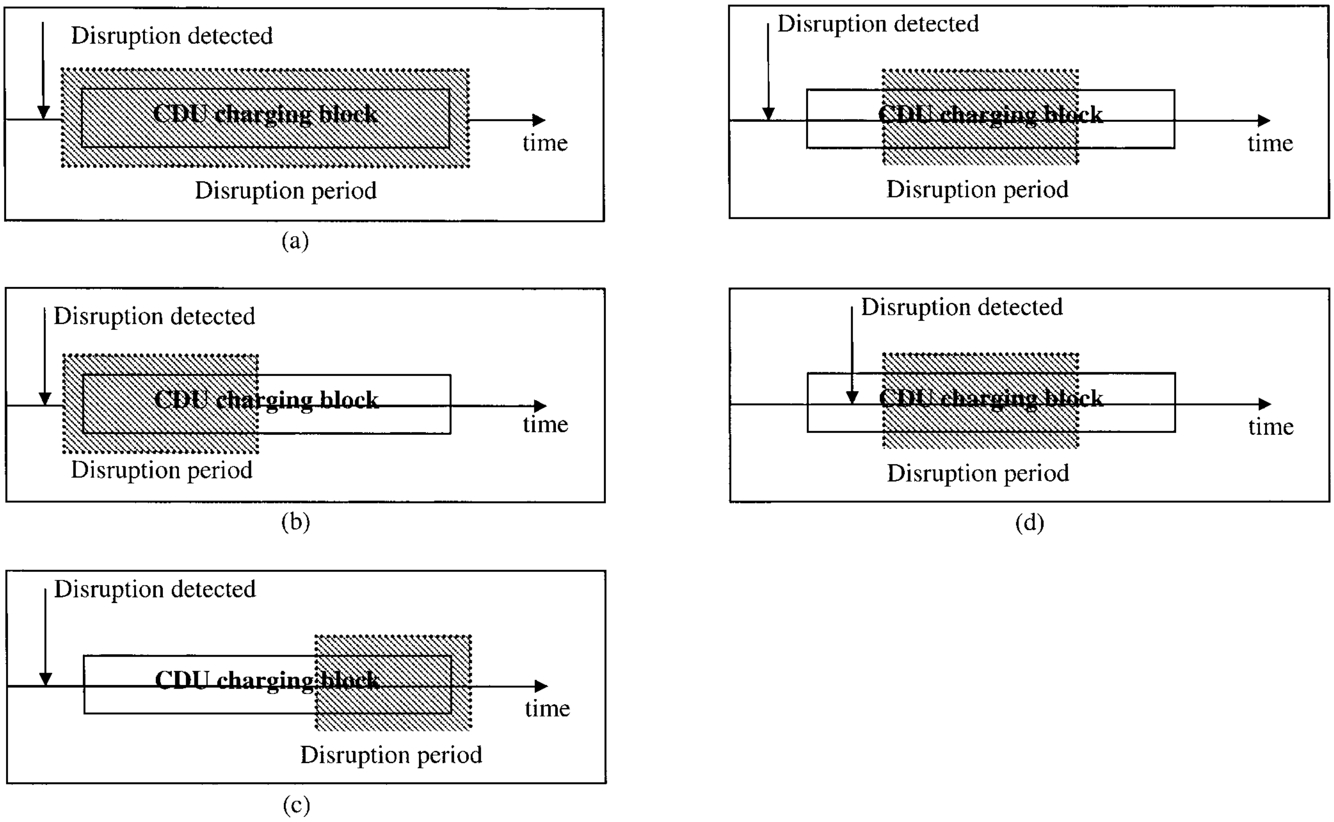

Figure 3. Disruption to CDU-charging block can affect it: (a) completely; (b) only at initial part; (c) only at final part; or (d) at an intermediate part.

Heuristic 1: Identifying Disrupted CDU-Charging Operations. A CDU-charging operation may be disrupted directly (such as tank unavailability, CDU unavailability) or because of secondary disruptions (such as inserting a parcel-unloading operation). A CDU-charging block typically spans a long period and can be disrupted in four possible ways as shown schematically in Figure 3.

(1) Disruption affects the whole CDU-charging block (Figure 3a). In this case, the rescheduler removes the whole block to the D-space.
(2) The initial part of the CDU-charging block is affected by the disruption (Figure 3b). The CDU-charging block is split into two parts—the affected part and the unaffected part. The former part is removed to the D-space and the latter is not modified. In essence, the CDU-charging block is shortened. This is because the initial schedule presumably identified the most profitable CDU charging possible; thus the rescheduler should retain it to the extent possible.
(3) The final part of the CDU-charging block is affected by disruption (Figure 3c). As in the previous case, the rescheduler removes the affected part to the D-space and retains the remaining unaffected part.
(4) The intermediate part of the CDU-charging block is affected by disruption. A simple removal of the affected part would lead to three CDU-charging blocks and therefore two changeovers. To obviate the extra changeover, we need to differentiate between two cases based on when the disruption is detected—before the CDU-charging block has started or after the start of the charging. In the former case, to minimize changeover cost the rescheduler removes the affected part as well as the shorter of the two unaffected parts to the D-space. In essence, only the longer unaffected CDU-charging block is retained. A new CDU-charging block will be introduced by Heuristic 3 for the affected period. In case the disruption is detected after the charging has started, the rescheduler would remove the portion of the block starting from the disruption time until the end of the block.

Heuristic 2: Identifying Disrupted Parcel-Unloading Operations. Similar to a CDU-charging operation, a parcel-unloading operation may be disrupted directly (such as parcel delay, offloading facility unavailability, tank unavailability) or indirectly (such as when a CDU-charging operation is inserted at the same period). Unlike the CDU-charging case, no changeover cost is associated with parcel-unloading operations. Therefore, we remove only the disrupted portion of the block and retain other portions in the schedule.

Heuristic 3: Rescheduling Disrupted CDU-Charging Operations. The main idea in rescheduling a CDU-charging operation is twofold: (1) to rectify any possible minimum throughput violation caused by the removal of the originally scheduled operation and (2) to maximize profit. This is performed by identifying all eligible tanks that can charge the CDU and calculating the charging volume based on the aforementioned criteria.

Overall, there are two distinct procedures involved in rescheduling a CDU-charging operation: reconfiguring, which

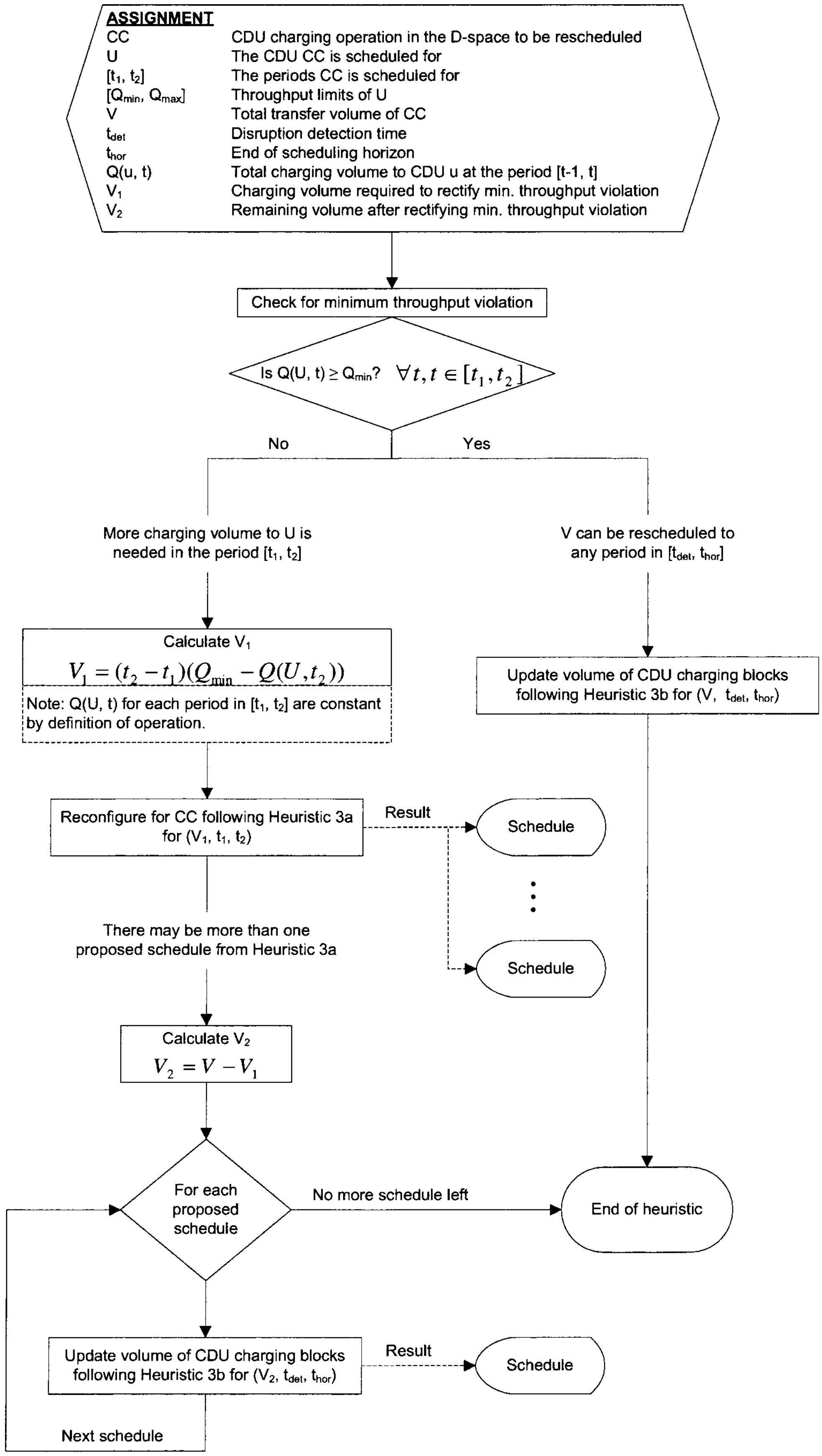

Figure 4. Flowchart for Heuristic 3—rescheduling disrupted CDU-charging operations.

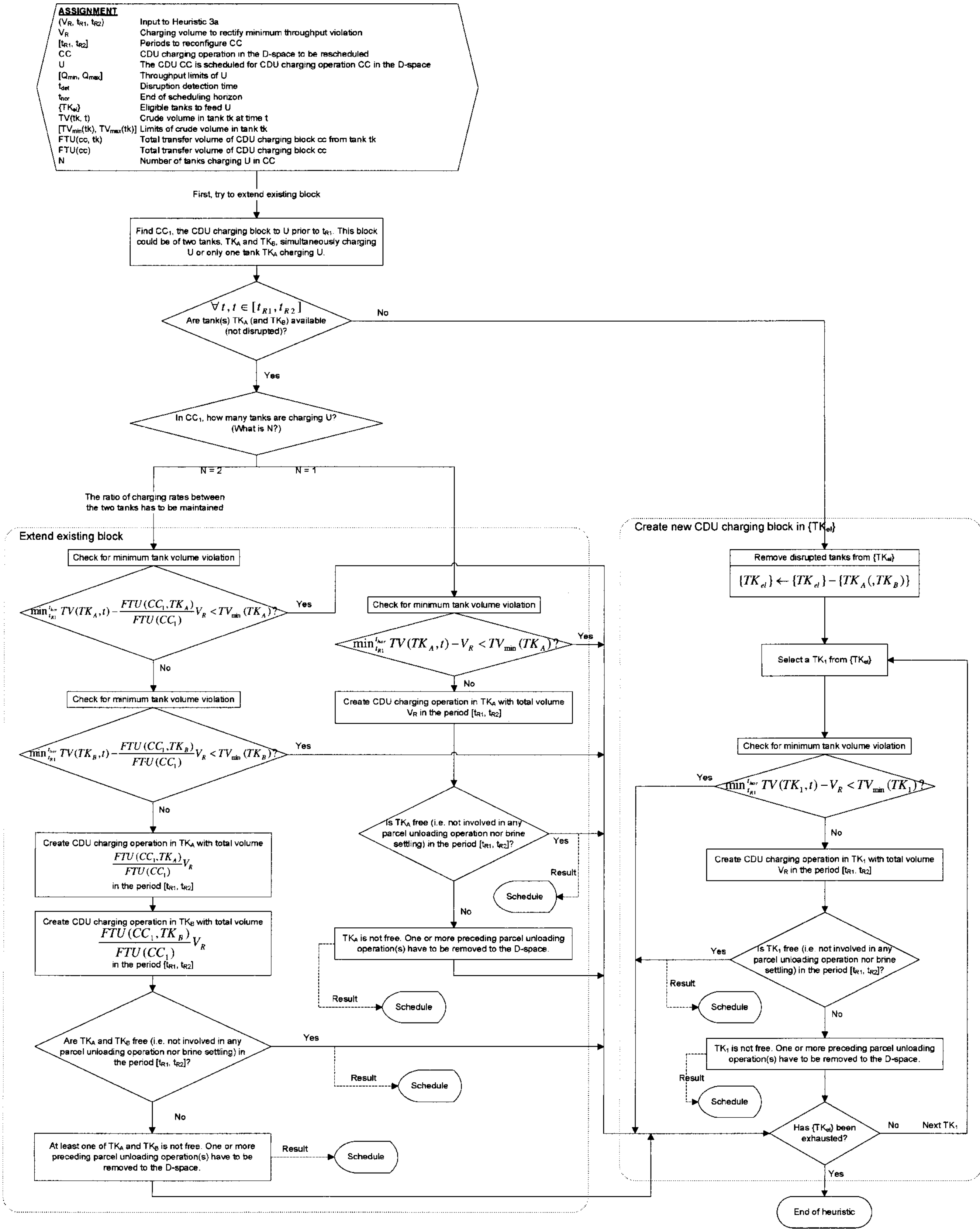

Figure 5. Flowchart for Heuristic 3a—reconfiguring CDU-charging operations.

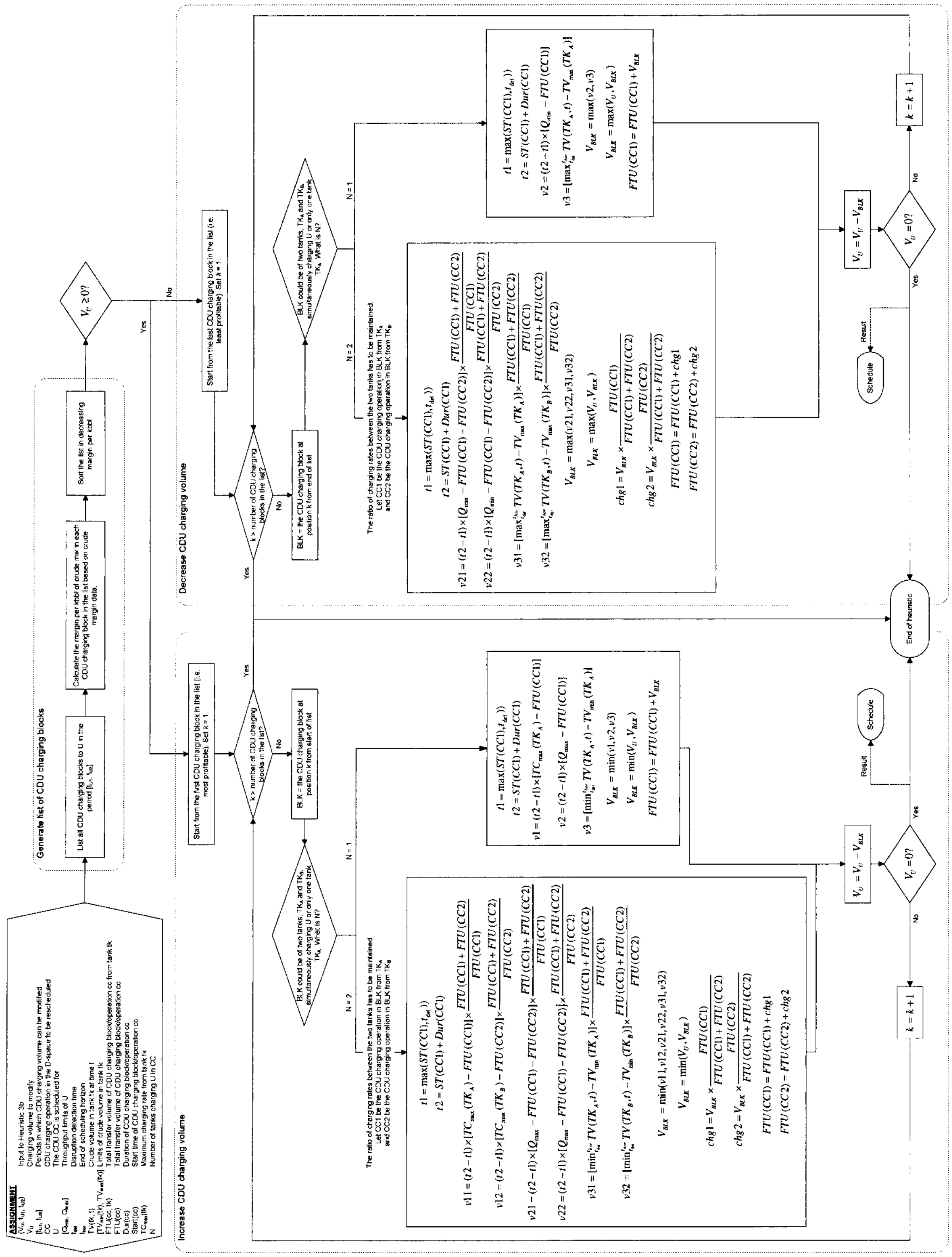

Figure 6. Flowchart for Heuristic 3b—updating volumes of CDU-charging blocks.

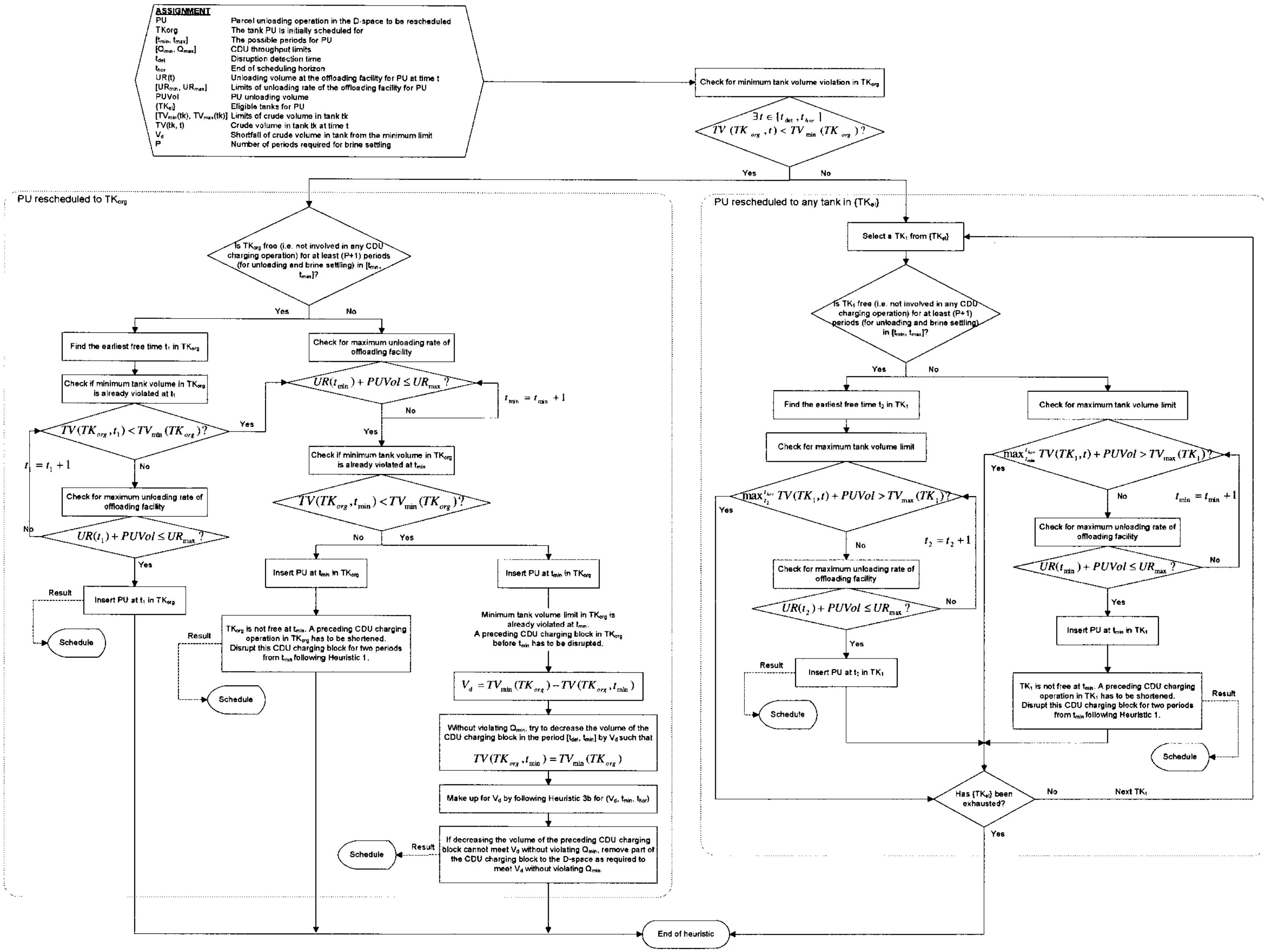

Figure 7. Flowchart for Heuristic 4—rescheduling disrupted parcel-unloading operations.

involves changes in configuration, and updating volume, which involves only changes to transfer rates. Reconfiguring could result in new CDU-charging block(s), whereas updating volume would not (see Figure 4 for the detailed flowchart). The heuristic for reconfiguring CDU-charging operations (Heuristic 3a as shown in Figure 5) may result in one or more proposed schedules as corresponding to a different configuration. If no configuration changes are necessary, only the charging rates can be varied following the procedure in Figure 6 (Heuristic 3b).

Heuristic 4: Rescheduling Disrupted Parcel-Unloading Operations. The main idea in inserting a parcel-unloading operation to the schedule is to first rectify the possible violation caused by removal of the parcel-unloading operation, that is, minimum tank volume violation, and then consider all possible places for the parcel-unloading operation to be rescheduled. The considerations for this heuristic are summarized in Figure 7 and can also result in more than one possible rectification.

Strategy for managing disruptions using the heuristics

The above heuristics are applied to the five types of disruptions as summarized in Table4. A crude arrival delay involves removal of the respective parcel-unloading operation to the D-space (Heuristic 2) and rescheduling the affected parcel-unloading operation (Heuristic 4). In the case of unavailable offloading facilities, any parcel-unloading operation by a disrupted facility is removed to the D-space (Heuristic 2) and rescheduled (Heuristic 4). For tank unavailability, any CDU-charging and parcel-unloading operations involving the disrupted tank are removed to the D-space (Heuristics 1 and 2). The affected parcel-unloading operations are then rescheduled using Heuristic 4 and the affected CDU-charging operations rescheduled using Heuristic 3. In the case of unavailable CDU, any CDU-charging operation to the disrupted CDU during the disruption period is removed to the D-space (Heuristic 1). The affected CDU-charging operations are rescheduled using Heuristic 3. In the case of demand change, we update the volume of CDU-charging blocks for a volume equal to the demand change and of the corresponding CDU using Heuristic 3b. Disruptions other than the five considered here can be similarly handled using a combination of Heuristics 1–4, depending on which type of operation they disrupt.

For both parcel-unloading and CDU-charging operations, tank allocation is one of the important decision variables. In the former, the parcel is fixed and the scheduler has to decide the destination tank. For the latter, a target throughput is specified for each CDU and the scheduler has to assign the source tank(s). Most refineries practice crude segregation whereby crude with similar characteristics (processability, yields, impurities, key component concentrations, etc.) are segregated in both storage and processing. Thus, tanks and CDUs usually store or process only specific classes of crudes. As a result of this crude segregation practice, based on the crude type involved, only a subset of tanks is "eligible" for each block. This constrains the search space because the disrupted block can be rescheduled only to the eligible tanks.

Table 4. Heuristics Used for Managing Each Type of Disruption

Disruption	Heuristics 1	2	3	3a	3b	4
Crude arrival delay		✓				✓
Unavailability of offloading facility		✓				✓
Unavailability of tank	✓	✓	✓	✓	✓	✓
Unavailability of CDU	✓		✓	✓	✓	
Demand change					✓	

It should be noted that, although the heuristics are designed to be consistent with the operating rules of the refinery practices, they are not handicapped by them. The overall methodology, framework, and even heuristics remain the same even for other operating practices; only some of their details change. For example, in the case where the refinery allows only a single tank to charge a CDU, the threads for $N = 2$ in Heuristics 3a and 3b will be unnecessary. Similarly, if brine settling is unnecessary, P can be set to 0 in Heuristic 4.

The above heuristic rescheduling strategy has been implemented as a decision support system using Gensym's G2 expert system shell. In the next section, we illustrate the application of the strategy using examples.

Case Studies

Consider the refinery configuration shown in Figure 1 operating in accordance with the data given in Table 1. The crude oil operations were previously scheduled using the scheduling algorithm of Reddy et al.,[32] which results in an expected profit of 1849, as shown in Table 2. During the operation of this schedule, the refinery supply chain could be disrupted as a consequence of any of the following cases:

Example 1 (motivating example): Crude arrival delay

The refinery is informed at Time 5 that because of bad weather at sea, the ship carrying Parcel 7 will arrive 16 h (two periods) later at Time 8. This will lead to a disruption in the refinery operations, which will require rescheduling. Heuristic rescheduling is performed as follows: the original parcel-unloading operation (Parcel 7 to Tank 6 at Period 7) is removed to the D-space and rescheduled according to Heuristic 4 for inserting parcel-unloading operations.

Only one variation of the parcel-unloading operation (Parcel 7 to Tank 6 at Period 9) is possible and is inserted. This leads to a secondary disruption to a CDU-charging block (CDU 3 charged from Tank 6 at Periods 9–15) and this has to be corrected (see Table 2). This block is thus removed to the D-space (Heuristic 1) and a variation (such as CDU 3 charged from Tanks 7 and 8 at Periods 9 and 10) identified using Heuristic 3. This heuristic results in three proposed schedules with different tanks charging CDU 3 at Periods 9 and 10, as shown in Tables5a–5c. CDU 3 is fed by Tanks 7 and 8 together (Table 5a), or Tank 8 (Table 5b), or Tank 1 (Table 5c).

Upon simulating these schedules, none violates the quality (key component) limits, so all three are found to be feasible. Next the rescheduler evaluates the profit of each schedule and identifies the schedule in Table 5a to be the best. It should be noted that all three schedules are similar to the ini-

Table 5a. Proposed Schedule for Motivating Example (Profit = 1846)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5																		
2	250					90	2	10	2			−20	2	−20	2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3	300									80	4	20	6																		
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
		−20	2	−20	2	−20	2	−20	2	−20	2																				
5	250									10	4	105	6			−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6	100											105	5					100	7			−50	3	−50	3	−33.3	3	−33.3	3	−33.3	3
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3										
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3										

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	340	340	340	340	340	340	340
2	250	250	250	340	350	350	330	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	300	300	300	380	400	400	400	400	400	400	400	400	400	400
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	260	365	365	340	315	290	265	240	215	190	165
6	100	100	100	100	100	100	205	205	205	305	305	255	205	171.7	138.4	105.1
7	100	100	100	80	76.8	73.6	70.4	67.2	64	60.8	57.6	57.6	57.6	57.6	57.6	57.6
8	250	250	250	250	233.2	216.4	199.6	182.8	166	149.2	132.4	132.4	132.4	132.4	132.4	132.4

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

Table 5b. Proposed Schedule for Motivating Example (Profit = 1841)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5		
2	250					90	2	10	2			−20	2	−20	2
3	300									80	4	20	6		
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1
		−20	2	−20	2	−20	2	−20	2	−20	2				
5	250									10	4	105	6		
6	100											105	5		
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3

	8		9		10		11		12		13		14		15	
Tank	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1																
2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3																
4	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
5	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6			100	7			−50	3	−50	3	−33.3	3	−33.3	3	−33.3	3
7	−3.2	3														
8	−16.8	3	−20	3	−20	3										

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	340	340	340	340	340	340	340
2	250	250	250	340	350	350	330	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	300	300	300	380	400	400	400	400	400	400	400	400	400	400
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	260	365	365	340	315	290	265	240	215	190	165
6	100	100	100	100	100	100	205	205	205	305	305	255	205	171.7	138.4	105.1
7	100	100	100	80	76.8	73.6	70.4	67.2	64	64	64	64	64	64	64	64
8	250	250	250	250	233.2	216.4	199.6	182.8	166	146	126	126	126	126	126	126

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

Table 5c. Another Feasible Schedule for Motivating Example (Profit = 1838)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5		
2	250					90	2	10	2			−20	2	−20	2
3	300									80	4	20	6		
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1
		−20	2	−20	2	−20	2	−20	2	−20	2				
5	250									10	4	105	6		
6	100											105	5		
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3

	8		9		10		11		12		13		14		15	
Tank	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1			−20	3	−20	3										
2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3																
4	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
5	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6			100	7			−50	3	−50	3	−33.3	3	−33.3	3	−33.3	3
7	−3.2	3														
8	−16.8	3														

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	320	300	300	300	300	300	300
2	250	250	250	340	350	350	330	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	300	300	300	380	400	400	400	400	400	400	400	400	400	400
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	260	365	365	340	315	290	265	240	215	190	165
6	100	100	100	100	100	100	205	205	205	305	305	255	205	171.7	138.4	105.1
7	100	100	100	80	76.8	73.6	70.4	67.2	64	64	64	64	64	64	64	64
8	250	250	250	250	233.2	216.4	199.6	182.8	166	166	166	166	166	166	166	166

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

Table 6. Proposed Schedule for Example 2—Tank 4 Unavailable in Periods 2–4, Detected at Time 1 (Profit = 1837)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5																		
2	250					90	2	10	2			−20	2	−20	2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3	300			−20	1	−20	1	−20	1	−20	1	−20	1	−20	1																
				−20	2	−20	2	−20	2	−20	2																				
4	350	−20	1							80	4					−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
		−20	2																												
5	250									10	4	125	6			−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6	100											105	5	100	7			−50	3	−50	3	−50	3	−30	3	−20	3	−20	3	−20	3
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3														
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3														

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	340	340	340	340	340	340	340
2	250	250	250	340	350	350	330	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	260	220	180	140	120	100	100	100	100	100	100	100	100	100
4	350	310	310	310	310	390	390	390	382.5	375	367.5	360	352.5	345	337.5	330
5	250	250	250	250	250	260	385	385	360	335	310	285	260	235	210	185
6	100	100	100	100	100	100	205	305	305	255	205	155	125	105	85	65
7	100	100	100	80	76.8	73.6	70.4	67.2	64	64	64	64	64	64	64	64
8	250	250	250	250	233.2	216.4	199.6	182.8	166	166	166	166	166	166	166	166

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

Table 7. Proposed Schedule for Example 3—CDU 3 Demand Increases from 400 to 450, Detected at Time 4 (Profit = 1935)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5																		
2	250					90	2	10	2			−20	2	−20	2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3	300									80	4	20	6																		
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
		−20	2	−20	2	−20	2	−20	2	−20	2																				
5	250									10	4	105	6			−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6	100											105	5	100	7			−50	3	−50	3	−50	3	−45	3	−20	3	−20	3	−20	3
7	100					−20	3	−3.2	3	−4.6	3	−4.6	3	−4.6	3	−4.6	3														
8	250							−16.8	3	−24.2	3	−24.2	3	−24.2	3	−24.2	3														

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	340	340	340	340	340	340	340
2	250	250	250	340	350	350	330	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	300	300	300	380	400	400	400	400	400	400	400	400	400	400
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	260	365	365	340	315	290	265	240	215	190	165
6	100	100	100	100	100	100	205	305	305	255	205	155	110	90	70	50
7	100	100	100	80	76.8	72.2	67.6	63	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4
8	250	250	250	250	233.2	209.05	184.9	160.75	136.6	136.6	136.6	136.6	136.6	136.6	136.6	136.6

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	450	20	50	450

tial schedule, except for the two operations for which rescheduling is necessary—this is one key advantage of the proposed approach. Furthermore, these schedules are generated by the system within 1 s—a computational performance that is suited for real-time decision support.

Example 2: Tank unavailability

In this example, we consider the case where heavy overnight rainfall leads to water entrainment in Tank 4 at Time 1. As a result, Tank 4 has to immediately stop charging CDU and undergo dewatering for 24 h (three periods). At Time 1, Tank 4 holds 28% of the total inventory of Group 2 type crude (C4, C5, and C6). If no action is taken, CDUs 1 and 2 will be down in Periods 2–4 when Tank 4 is dewatered. Consequently, 120 kbbl of throughput would be lost and shutdown/start-up costs incurred, so rescheduling is critical.

The proposed strategy works as follows: Here, two CDU-charging blocks are disrupted (Tank 4 to CDU 1 and Tank 4 to CDU 2). Tanks 2, 3, and 5 contain Group 2 type crude that could replace Tank 4 in charging CDUs 1 and 2. Following the heuristics, the rescheduler proposes nine feasible schedules. The one with the highest profit is shown in Table6. Tank 3 takes over the CDU charging previously scheduled from Tank 4 (CDU 1 in Periods 2–7; CDU 2 in Periods 2–5). This operation continues even after Tank 4 has finished dewatering at Time 4 to avoid CDU changeover costs. The parcel-unloading operations previously scheduled to Tank 3 in Periods 5 and 6 were rescheduled to Tanks 4 and 5. Because there is no subsequent CDU-charging operation scheduled for Tank 3, inserting the parcel-unloading operations in Tank 3 has no further effect. Overall, there is minimum change from the initial schedule and the decrease in profit is 13 units compared to that of the undisrupted base case.

Example 3: Demand change

In this example, we consider the case where an important customer has placed an urgent order for jet fuel, one of the products downstream of CDU. At Time 4, after yield analysis calculations, the planner decides that CDU 3 needs to deliver 50 kbbl more than the initial 400 kbbl target for the scheduling horizon under consideration. The CDU 3 throughput has to be increased and rescheduling becomes necessary.

The crux in this scenario is to decide the CDU-charging block(s) to be increased. The rescheduler handles this easily by following Heuristic 3b and proposes the schedule shown in Table 7. First the CDU charging from Tank 6 (with starting Time 8), which has the highest margin per kbbl, is increased until the minimum tank volume limit of Tank 6 is met, that is, it is increased by 15 kbbl. The remaining 35 kbbl is accommodated by increasing the CDU-charging block from Tanks 7 and 8 starting at Period 5. The ratio of charging rates of the two tanks is kept constant so there is no change in the product quality from the CDU.

Other disruption types

Next we consider two examples from other types of disruptions.

Example 4. Parcel transfer from a VLCC is delayed by three periods because of SBM unavailability, which is detected at Time 1. Multiple parcel-unloading operations are affected in this case. The proposed heuristic strategy identifies the schedule shown in Table8 as the best.

Example 5. Tank 2 becomes unavailable in Periods 4–6 and concurrently CDU 2 demand increases from 400 to 440 kbbl. Both are detected at Time 2. Four possible schedules were generated and the schedule with the highest profit is shown in Table9.

These two cases demonstrate that the approach is capable of handling multiple disruptions by considering one disruption at a time.

The proposed approach can handle disruptions of different magnitudes because it is effect driven and not root-cause driven. For example, if a tank is unavailable for five periods instead of one period, then it simply means that more disrupted operations move to the D-space and get rescheduled. Table10 shows the impact of the magnitude of disruptions on the solutions for Examples 1 and 2.

To evaluate the efficacy of the approach, total rescheduling based on the method of Reddy et al.[32] is performed for the above examples and the schedules compared with the best one identified by the heuristic strategy (Table11). The optimal schedule for the motivating example obtained by total rescheduling is given in Table12. Schedules were compared using three factors: (1) the objective values in terms of difference from the profit of initial schedules, (2) number of rescheduled operations, and (3) computation time. The number of rescheduled operations is defined as the number of operation blocks that were in the initial schedule but not in the new schedule, that is, changes in configuration (parcel to tank and tank to CDU connections). The same configuration with different start time or duration is also counted as a rescheduled operation; however, an identical configuration with a difference in transfer rates is not. This is because changes in configuration, especially in the immediate future, are undesirable because they might not be easy to perform operationally. As shown in Table 11, the proposed heuristic approach results in 75% fewer changes in operation configurations on average and requires 99% less computation time, whereas the difference in profit is not significant. The new schedules identified by total rescheduling are very different from the initial schedule, as is evident from the large number of rescheduled operations. This is expected because one feature of MILP solvers is that a small difference in the problem could lead to very different solution paths being pursued. The significantly large computation time for total rescheduling would make it untenable for disruption decision support.

Two counterintuitive results in Table 11 require further discussion. In Example 1, total rescheduling for crude arrival delay gives increased profit (+2) from the initial schedule, which implies that the delay is actually beneficial to the refinery. This can be explained by the fact that the delayed crude is less profitable than the crude mix that is being processed during the delay period. Although delaying the parcel unloading to allow the current crude mix to run longer would have been possible in the initial schedule, this option is not taken because it will incur a demurrage cost of 30. In Example 3, the solution obtained by total rescheduling has a lower profit than that of the solution obtained by the heuristic strategy. This is because the algorithm

Table 8. Proposed Schedule for Example 4—VLCC Delayed by 3 Periods, New Arrival Time for Parcels 1–4 Is Time 5, Detected at Time 1 (Profit = 1847)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3					20	5	10	1	100	3																
2	250											100	2			−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3	300											−20	2	−20	2	90	4														
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
		−20	2	−20	2	−20	2	−20	2	−20	2																				
5	250											125	6			−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6	100											105	5	100	7			−50	3	−50	3	−50	3	−30	3	−20	3	−20	3	−20	3
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3														
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3														

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	210	210	230	240	340	340	340	340	340	340	340	340	340
2	250	250	250	250	250	250	350	350	317.5	285	252.5	220	187.5	155	122.5	90
3	300	300	300	300	300	300	280	260	350	350	350	350	350	350	350	350
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	250	375	375	350	325	300	275	250	225	200	175
6	100	100	100	100	100	100	205	305	305	255	205	155	125	105	85	65
7	100	100	100	80	76.8	73.6	70.4	67.2	64	64	64	64	64	64	64	64
8	250	250	250	250	233.2	216.4	199.6	182.8	166	166	166	166	166	166	166	166

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

Table 9. Proposed Schedule for Example 5—Tank 2 Unavailable in Periods 4–6, CDU 2 Demand Increases from 400 to 440 kbbl, Detected at Time 4 (Profit = 1895)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5	10	5																		
2	250					90	2							−30	2	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1	−32.5	1
3	300							10	2			−50	2																		
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2	−7.5	2
		−20	2	−20	2	−20	2	−20	2	−20	2																				
5	250									90	4	125	6			−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2	−25	2
6	100											105	5	100	7			−50	3	−50	3	−50	3	−30	3	−20	3	−20	3	−20	3
7	100					−20	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3	−3.2	3														
8	250							−16.8	3	−16.8	3	−16.8	3	−16.8	3	−16.8	3														

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	340	340	340	340	340	340	340	340	340	340
2	250	250	250	340	340	340	340	310	277.5	245	212.5	180	147.5	115	82.5	50
3	300	300	300	300	310	310	260	260	260	260	260	260	260	260	260	260
4	350	310	270	230	190	150	130	110	102.5	95	87.5	80	72.5	65	57.5	50
5	250	250	250	250	250	340	465	465	440	415	390	365	340	315	290	265
6	100	100	100	100	100	100	205	305	305	255	205	155	125	105	85	65
7	100	100	100	80	76.8	73.6	70.4	67.2	64	64	64	64	64	64	64	64
8	250	250	250	250	233.2	216.4	199.6	182.8	166	166	166	166	166	166	166	166

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	440
3	400	20	50	400

Table 10. Solution Sensitivity of Motivating Example and Example 2

	Duration of Delay (Period)							
Motivating Example	1	2	3	4	5	6	7	8
Profit	1848	1846	1836	1835	1833	1828	1828	1833
# Resch. operations	4	4	2	2	2	2	2	2
# Proposed schedule	3	3	2	2	2	2	2	2
	Duration of Tank Unavailability (Period)							
Example 2	1	2	3	4	5	6	7	8
Profit	1837	1837	1837	1837	1837	1837	1828	1828
# Resch. operations	4	4	4	4	4	4	5	5
# Proposed schedule	9	9	9	9	9	9	9	9

of Reddy et al.[32] does not guarantee global optimality; in fact, to our knowledge, no existing algorithm guarantees global optimality for the crude scheduling problem. Furthermore, even existing general-purpose global optimization tools such as BARON (Branch-And-Reduce Optimization Navigator, developed and maintained by N. Sahinidis and M. Tawarmalani) are unable to solve problems of the size reported here.

Limitations of the heuristics

As with any heuristic approach, the proposed method does not guarantee completeness. It may fail to find a feasible solution even when one exists, if it lies outside the heuristic search space. In this work, although there are three instances where the proposed heuristics fail, all three can be easily obviated by suitable revision of the heuristics:

(1) A long CDU-charging block has to be rescheduled from the D-space, but no eligible tank holds enough crude to sustain the whole CDU-charging block. This can be overcome by extending Heuristic 3a.
(2) Existing CDU-charging blocks are near the maximum limit such that they cannot accommodate any further increase in the CDU demand. This can be overcome by extending Heuristic 3 to include creation of new CDU-charging blocks.
(3) Removal of a parcel-unloading block causes the crude mix in the original destination tank to fall outside the allowable key component range during subsequent CDU-charging blocks. This can be overcome by modifying Heuristic 1 to check CDU-charging blocks for key component limits.

In our computational experiments we encounter these instances in less than 20% of the cases.

Factors Affecting Schedule Resilience

In this section, we report the effect of various parameters on the resilience of the refinery supply chain. We look at parameters related to the refinery hardware, schedule, and supply chain configuration. The studies were performed through numerous computational runs similar to those reported above; in the interest of space, only our observations from these experiments and illustrative examples are presented.

Inventory, hardware redundancy, and flexibility

Observation 1. The current trend of lower inventories for cost efficiency has made supply chains more susceptible to disruptions. Smaller inventory implies that lesser transportation delay can be accommodated and the impact of the disruption becomes more immediate.

- Illustration: Consider the motivating example. If Parcel 7 is delayed up to Time 11, the proposed schedules discussed there still hold because there is still enough inventory in Tank 6 for charging CDU 3 starting at Time 8. If the delay is beyond Time 11, given that there is no further inventory of Group 2 crude, the CDU will have to be shut down. A larger safety stock is essential for handling larger disruptions and would involve a trade-off against higher inventory cost.

Observation 2. As a corollary, hardware redundancy such as more tanks, pumps, and offloading facilities would improve disruption management capability. This involves a trade-off against higher capital costs.

Observation 3. The wider the operating range of equipment (such as CDU), the higher the resilience. Wider CDU

Table 11. Block Preservation vs. Total Rescheduling

		Block Preservation			Total Rescheduling*		
Example	Disruption	ΔProfit	# Resch. Op.	CPU Time	ΔProfit	# Resch. Op.	CPU Time
1	Parcel 7 delayed from 6 to 8. Detected at Time 5.	−3	4	~1 s	+2	9	182 s
2	Tank 4 unavailable in Periods 2–4. Detected at Time 1.	−13	4	~1 s	−4	18	132,646 s
3	CDU 3 demand increases from 400 to 450 kbbl. Detected at Time 4.	+86	0	~1 s	+96	7	1274 s
4	VLCC delayed by 3 periods. New arrival time for Parcels 1, 2, 3, 4 is Time 5. Detected at Time 1.	−2	8	~1 s	−8	16	38,720 s
5	Tank 2 unavailable in Periods 4–6. CDU 2 demand increases from 400 to 440 kbbl. Detected at Time 2.	+50	4	~1 s	+57	12	6593 s

*CPLEX 9.0.2 solver within GAMS on Intel Xeon 3.60GHz, 3GB RAM running Windows XP.

Table 12. Optimal Schedule for the Motivating Example by Total Rescheduling (Profit = 1851)

Parcel Unloading (positive volume) and CDU Charging (negative volume) (u: CDU index, p: parcel index)

	0	1		2		3		4		5		6		7	
Tank	Vol	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1	250	−20	3	−20	3	10	1	100	3	10	5				
2	250					90	2	10	2			−20	2	−50	2
3	300									80	4				
4	350	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1	−20	1
		−20	2	−20	2	−20	2	−20	2	−20	2				
5	250									10	4	125	6		
6	100											115	5		
7	100					−20	3	−3.2	3	−3.2	3	−1.93	3	−1.93	3
8	250							−16.8	3	−16.8	3	−19.7	3	−19.7	3

	8		9		10		11		12		13		14		15	
Tank	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p	Vol	u/p
1																
2	−20	2	−50	2	−50	2	−30	2	−20	2	−20	2	−20	2	−20	2
3																
4	−7.5	1	−7.5	1	−7.5	1	−7.5	1	−7.5	1	−7.5	1	−7.5	1	−7.5	1
5	−25	1	−25	1	−25	1	−25	1	−25	1	−25	1	−25	1	−25	1
6			100	7			−50	3	−50	3	−22	3	−20	3	−50	3
7	−1.93	3	−1.93	3	−1.93	3										
8	−19.7	3	−19.7	3	−19.7	3										

Tank Volume (min = 50, max = 400)

	0	1	2	3	4	5	6	7
Tank	Vol	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	250	230	210	220	320	330	330	330
2	250	250	250	340	350	350	330	280
3	300	300	300	300	300	380	380	380
4	350	310	270	230	190	150	130	110
5	250	250	250	250	250	260	385	385
6	100	100	100	100	100	100	215	215
7	100	100	100	80	76.8	73.6	71.673	69.746
8	250	250	250	250	233.2	216.4	196.727	177.054

	8	9	10	11	12	13	14	15
Tank	Volume	Volume	Volume	Volume	Volume	Volume	Volume	Volume
1	330	330	330	330	330	330	330	330
2	260	210	160	130	110	90	70	50
3	380	380	380	380	380	380	380	380
4	102.5	95	87.5	80	72.5	65	57.5	50
5	360	335	310	285	260	235	210	185
6	215	315	315	265	215	193	173	123
7	67.819	65.892	63.965	63.965	63.965	63.965	63.965	63.965
8	157.381	137.708	118.035	118.035	118.035	118.035	118.035	118.035

CDU Throughput

CDU	Demand	Min/period	Max/period	Total Throughput
1	400	20	50	400
2	400	20	50	400
3	400	20	50	400

throughput operating limits increase the disruption management capability because there is more room to adjust the rates when required. The same can be said for parcel-unloading rates, CDU-charging rates, crude tank volume, and product tank volume. However, more capital costs could be incurred to provide higher equipment flexibility.

- Illustration: To cope with a delay until Time 12 in the above scenario, the CDU-charging rate should be reduced such that Tank 6 does not run out of crude before Parcel 7 arrives. If this is feasible, the scheduler would also need to increase the CDU-charging rate in later periods such that the demand (or production target) for the horizon is met. A 30% wider operating range of CDU 3 will obviate a shutdown and allow production targets to be met. Alternatively, the CDU could be charged with a non–Group 2 crude if it is capable of processing a wider range of crude properties.

Scheduling decisions

Observation 4. Scheduling operations at the middle of the equipment's range improves resilience because there is more room to adjust the rates when required. However, because optimal operations are typically at the limits, there is a trade-off between optimality and resilience.

Observation 5. Longer scheduling horizons improve refinery reschedulability; however, the computation time required for original scheduling will increase sharply.

- Illustration: From the previous illustration of the case of delay beyond Time 11, it is possible that as the result of a maximum CDU throughput constraint, there is not enough time in the scheduling horizon to make up for the lost CDU throughput arising from the reduced charging rate in the earlier periods. If the scheduling horizon is longer, there is more room to make up for the lost production.

Supply chain design and disruption management capabilities

Observation 6. A nimble supply chain with access to alternate geographically distributed suppliers is more resilient.

- Illustration: In the previous scenario, if there is inadequate inventory to maintain operations, emergency crude could be procured from a nearby proximal supplier.

Observation 7. The earlier a disruption is detected, the higher the success of rescheduling. Timely detection of disruption requires fast, unhindered information flow among supply chain constituents and supply chain monitoring and disruption management systems.

- Illustration: If the parcel delay is known earlier, the CDU-charging rate can be reduced early to preserve Group 2 crude and avoid CDU shutdown.

In summary, higher inventory, hardware redundancy, wider operating range, longer scheduling horizon, midrange operation, and earlier detection of disruption would improve the refinery's resilience to disruptions.

Conclusions

One element in recovering from supply chain disruptions is rescheduling operations. In this article, a heuristic rescheduling strategy has been proposed to manage refinery supply chain disruptions. The motivations for heuristic rescheduling arise from the time-consuming nature of total rescheduling and instability of optimal schedules to changes in problem data. Because rescheduling is usually time critical and changes in configuration undesirable in the short term, a heuristic strategy that minimizes both rescheduling time and configuration changes even at the expense of suboptimality is justified. Our approach uses a block preservation strategy for rescheduling. The originally developed optimal schedule forms the basis for rescheduling. This schedule is decomposed into operation blocks that are preserved by the rescheduler to the extent possible to generate a new schedule that is feasible in the face of the disruption. The proposed strategy has been shown to work well for all the disruptions considered. It can also be directly extended to cover other disruptions such as limited transfer rates, parcel volume, and crude quality changes.

The proposed heuristic rescheduling approach has several advantages: most notably it requires much less time to generate efficient schedules compared to total rescheduling. Furthermore, the method will generate a number of feasible schedules rather than just one; the user can therefore select a schedule using an integrated graphical environment and account for factors that cannot be easily quantified. The method also minimizes configurational changes, which are generally undesirable. Another potential benefit is that the method can provide insights for full optimization, by limiting the search space based on the schedules generated.

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