A model-based disruption management strategy for distributed supply chains

Arief Adhitya[1], Rajagopalan Srinivasan[1, 2], and I.A. Karimi[2]
[1]Institute of Chemical and Engineering Sciences,
1 Pesek Road, Jurong Island, Singapore 627833, Singapore
[2]Department of Chemical and Biomolecular Engineering, National University of Singapore,
4 Engineering Drive 4, Singapore 117576, Singapore

Abstract

Enterprises today have realized the importance of supply chain management to achieve operational efficiency, cut costs, and maintain quality. Uncertainties in supply, demand, transportation, market conditions, and many other factors can interrupt supply chain operations, causing significant adverse effects. These uncertainties motivate the development of decision support systems for managing disruptions in the supply chain. In this paper, we propose a model-based framework for rescheduling operations in the face of supply chain disruptions. A causal model captures the cause-and-effect among all the variables in supply chain operation and is used for identifying the consequences of a disruption. Rescheduling is done by searching a rectifications-graph, which captures all possible options to overcome the disruption effects, based on a user-specified utility function. In contrast to heuristic approaches, the main advantages of the proposed model-based rescheduling method are the completeness of solution search and flexibility of the objective function. The proposed framework is illustrated using a refinery supply chain example.

Introduction

Supply chain management is a key consideration for today's enterprises to increase their operational efficiencies and minimize costs while maintaining quality. Globalization due to the lowered trade barriers has increased competitiveness and put higher pressure on companies' bottom lines. To reduce costs and increase efficiency, strategies such as outsourcing, single sourcing, multi-site production, centralized distribution, etc are employed by companies. This leads to lengthy and complex supply chains, which suffer from the lack of visibility among supply chain entities and vulnerability to disruptions. The lack of visibility hinders supply chain entities from making reliable forecasts, which results in inefficient supply chain operations and increases risks. Risk is the probability of a disruption occurrence in the supply chain operations. The material, information, and finance flows among entities of a complex supply chain are disruption-prone as blockage in any of these would lead to undesirable events like process shutdown, financial loss, under- or over-supply, etc. Hence, supply chain disruption management is crucial.

The literature in the area of supply chain disruption management is limited and no general structured methodology has been proposed to date. Sheffi et al. (2003) describe mechanisms that companies follow to assess terrorism-related risks, protect the supply chain from those risks, and attain resilience. They provide classifications of disruptions, security measures, and ideas to achieve resilience. They report various case studies and interviews with executives of companies. Wilson (2003) focuses only on transportation disruptions. Gaonkar and Viswanadham (2004) propose a conceptual framework to approach supply chain risk problems. They classify supply chain risks in three forms – deviation, disruption and disaster – and noted that supply chains need to be robust in three levels – strategic, tactical and operational. Julka et al. (2002a, b) propose an agent-based framework for modeling a supply chain. In their framework, the behavior of every entity in the supply chain is emulated using an agent that imitates the behaviors of various departments in a refinery. Mishra et al. (2003, 2004) extend this approach to manage disruptions in a refinery supply chain. In the event of a disruption, agents collaborate to identify a holistic rectification strategy using heuristic rules. Adhitya et al. (2005) propose a heuristic-based rescheduling strategy to manage refinery supply chain disruptions. Heuristic approaches lack generality and flexibility; this paper, therefore, proposes a general model-based framework for disruption management in a supply chain.

Problem Statement

Figure 1 shows the refinery configuration. This work is based on the discrete-time formulation of crude oil scheduling by Reddy et al. [9], which considered the unloading of crude oil from large multi-parcel tankers via an SBM (Single Buoy Mooring) line or from smaller single-parcel ships via jetties up to the charging of crude oil to CDUs. Given the optimal operation schedule from the mathematical program by Reddy et al. [9], and the disruptions, generate optimal (or near optimal) new schedule(s) accommodating the disruptions.

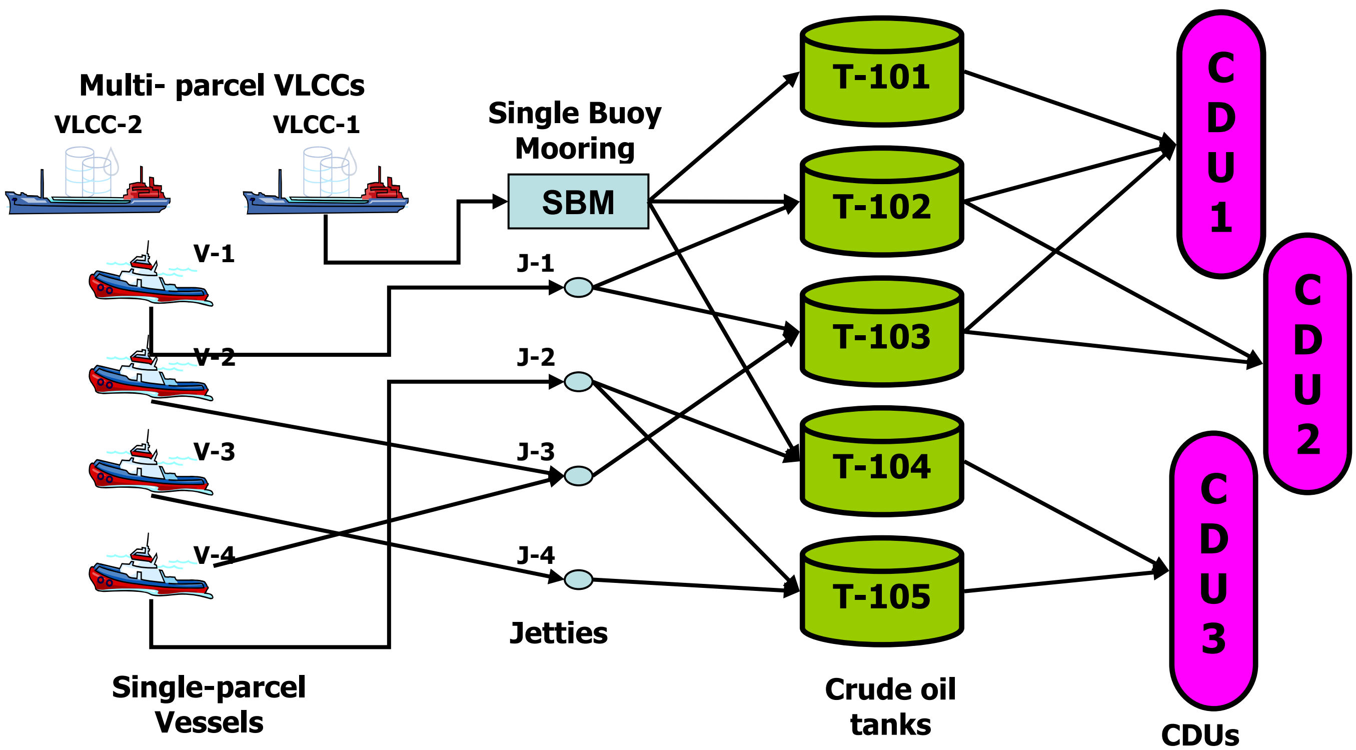

Figure 1: Schematic of refinery configuration in a typical marine-access refinery

Methodology

The key element of the proposed framework is a causal model of the supply chain operations. The model consists of modules which represent the supply chain entities. Each module consists of nodes which represent the supply chain variables related to that particular entity. Nodes are interconnected by arcs, which represent the cause-and-effect relationships between the variables they connect. Disruptions to the supply chain can be imposed on the causal model. They may lead to undesirable consequences such as infeasible supply chain operations, insufficient inventory, production shortfall, unfulfilled demand, etc., which are modeled as violations of limits in the causal model. These violations are identified by using the causal model to propagate the effects of disruptions, by tracing the cause-and-effect relationships starting from the disrupted nodes to other nodes as dictated by the connections (arcs).

Once the violations are identified, rectification options are searched using the rectifications-graph, which captures all possible options to overcome the disruption effects, based on a utility function (for example: minimum costs, minimum changes in the operations schedule, earliest rectifications, etc). The rectifications-graph is generated based on the causal relationships captured in the causal model. In contrast to heuristic approaches, the main advantages of the proposed model-based method are generality, completeness of solution search and flexibility of the utility function. Capabilities of the proposed framework are illustrated using a refinery case study.

Case Study

We consider the case for a refinery with 3 CDUs, 6 crudes, 8 tanks, 2 crude categories, one 3-parcel VLCC, and three single-parcel vessels arriving in a five-day horizon (15 eight-hour slots) and two disruptions: tank unavailability and a vessel delay. Table 1 shows the vessel arrival schedule. Figure 2 shows the optimal operation schedule and its tank volume profile. Table 2 lists the two disruptions.

Table 1: Vessel arrival schedule

Parcel	Crude	Volume	Arrival Time
1	2	10	2
2	6	100	2
3	1	100	2
4	4	90	2
5	2	125	4
6	5	125	4
7	3	100	6

Tank	1		2		3		4		5		6		7		8	
	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	10	1	100	3	20	5						
2					90	2	10	2			-20	2	-20	2	-32.5	1
3									80	4	20	6				
4	-20	1	-20	1	-20	1	-20	1	-20	1	-20	1	-20	1	-7.5	2
	-20	2	-20	2	-20	2	-20	2	-20	2						
5									10	4	105	6			-25	2
6											105	5	100	7		
7					-20	3	-3.2	3	-3.2	3	-3.2	3	-3.2	3	-3.2	3
8							-16.8	3	-16.8	3	-16.8	3	-16.8	3	-16.8	3

Tank	9		10		11		12		13		14		15	
	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
3														
4	-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
6	-50	3	-50	3	-50	3	-30	3	-20	3	-20	3	-20	3
7														
8														

Tank	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	250	230	210	220	320	340	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

Figure 2: Optimal schedule and tank volume profile for the case study

Table 2: Disruptions

No.	Disruptions
1	Parcel 7, scheduled to arrive at time 6, is delayed. New arrival time is time 8.
2	Tank 7 will be unavailable for five periods starting from time 6.

Due to disruption 1, Parcel 7 cannot be unloaded into Tank 6 as it is charging CDU 3 from period 9 onwards. This leads to out-of-crude situation in Tank 6 and the schedule becomes infeasible. Figure 3a and 3b are the new schedules generated with their tank volume profiles. Table 3 compares the objective value of the schedules. As shown in Table 3, there is only a small profit loss in the new schedules as compared to the original schedule.

Tank	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
	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	-20	3	-20	3	10	1	100	3	20	5			-3.2	3	-3.2	3	-3.2	3	-3.2	3										
2					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									80	4	20	6																		
4	-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									10	4	105	6			-25	2	-25	2	-25	2	-25	2	-25	2	-25	2	-25	2	-25	2
6											105	5					100	7			-50	3	-50	3	-50	3	-30	3	-20	3
7					-20	3	-3.2	3	-3.2	3	-3.2	3	TANK UNAVAILABLE																	
8							-16.8	3	-16.8	3	-16.8	3	-16.8	3	-16.8	3	-16.8	3	-16.8	3										

Tank	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	250	230	210	220	320	340	340	336.8	333.6	330.4	327.2	327.2	327.2	327.2	327.2	327.2
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	155	125	105
7	100	100	100	80	76.8	73.6	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4
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

Figure 3a: New schedule 1 and the corresponding tank volume profile

Tank	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
	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	-20	3	-20	3	10	1	100	3	20	5																				
2					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									80	4	20	6																		
4	-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									10	4	105	6			-25	2	-25	2	-25	2	-25	2	-25	2	-25	2	-25	2	-25	2
6											105	5					100	7			-50	3	-50	3	-50	3	-30	3	-20	3
7					-20	3	-3.2	3	-3.2	3	-3.2	3	TANK UNAVAILABLE																	
8							-16.8	3	-16.8	3	-16.8	3	-20	3	-20	3	-20	3	-20	3										

Tank	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	250	230	210	220	320	340	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	155	125	105
7	100	100	100	80	76.8	73.6	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4	70.4
8	250	250	250	250	233.2	216.4	199.6	179.6	159.6	139.6	119.6	119.6	119.6	119.6	119.6	119.6

Figure 3b: New schedule 2 and the corresponding tank volume profile

Table 3: Objective value of the schedules

Schedule	Profit
Original	1,849
New schedule 1	1,841
New schedule 2	1,842

Concluding Remarks

The prevalence of uncertainties in supply chain operations has motivated the development of simulation models and decision support system for managing disruptions in the supply chain. In this paper, a model-based approach for rescheduling supply chain operations in response to disruptions has been developed. In the proposed approach, the cause-and-effect relationship between all possible supply chain operations is modeled using a causal model. The consequences of any disruption are manifested as violations in the model. Different options to overcome these violations are generated and captured in the rectifications-graph. The best one that optimizes a pre-specified utility function is proposed as the new schedule.

The rectifications-graph is a map of all possible rectification solutions. While seeking rectifications, modification of variables are propagated and new violations are detected. A new schedule is proposed only when all violations have been rectified. Hence, all proposed schedules are guaranteed to be feasible and correct. Since all the decision variables in the schedule are included and each variable can be modified as needed, all possible rescheduling solutions can be obtained using the proposed approach. In this sense, the model can be said to be complete. This completeness is the main advantage of the proposed model-based method over the heuristic approach. The flexibility in using various utility functions (minimum number of changes, maximum profit, etc) is another major advantage since it provides the user the freedom to choose the one which suits each situation the best. The proposed model-based method thus generalizes the previously reported heuristic-based rescheduling method and overcomes its shortcomings.

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