EFFICIENT SHORT-TERM SCHEDULING OF REFINERY OPERATIONS BASED ON A CONTINUOUS TIME FORMULATION

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Abstract
The problem addressed in this work is to develop a comprehensive mathematical programming model for the efficient scheduling of oil-refinery operations. Our approach is first to decompose the overall problem spatially into three domains: the crude-oil unloading and blending, the production-unit operations and the product blending and delivery. In particular, the first problem involves the crude-oil unloading from vessels, its transfer to storage tanks and the charging schedule for each crude oil mixture to the distillation units. The second problem consists of the production unit scheduling which includes both fractionation and reaction processes and the third problem describes the finished product blending and shipping end of the refinery. Each of those sub-problems is modeled and solved in a most efficient way using continuous time representation due to relatively small number of variables and constraints. Our last step is to address the integration of these sub-problems by applying heuristic based Lagrangian decomposition iterative methodology. The proposed methodology is applied to realistic case studies and significant computational savings can be achieved compared with existing discrete time models.

Keywords
Oil-refinery, Spatial decomposition, Continuous time formulation, Scheduling.

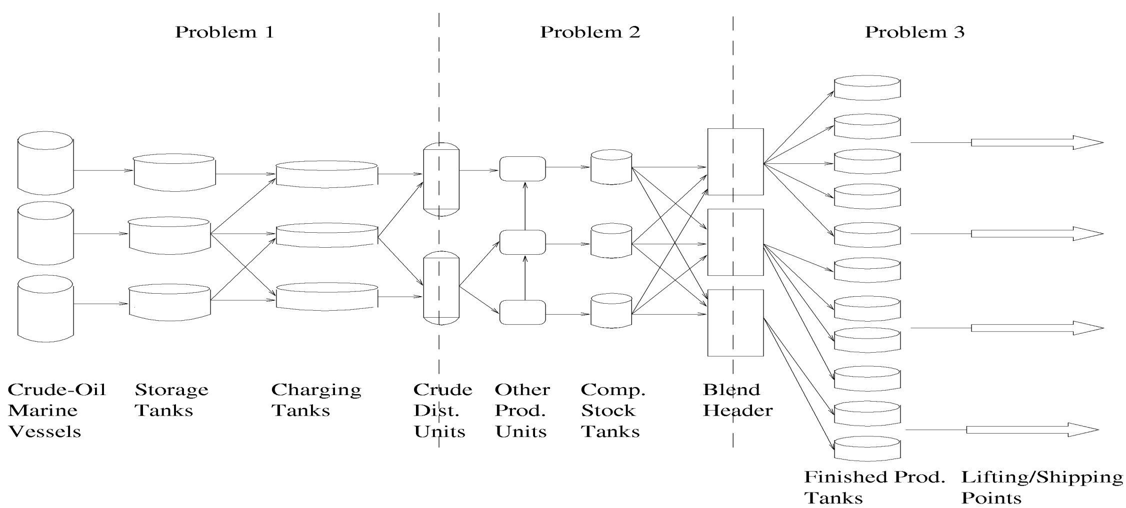

Figure 1: *Graphic Overview of Refinery System*

Introduction

In the literature, mathematical programming technologies have been extensively concerned and developed in the area of long-term refinery planning (Bodington, 1995; Ravi and Reddy, 1998), while short-term scheduling has received less attention.

Refinery planning optimization is mainly addressed through successive linear programming approach, such as GRTMPS (Haverly Systems), PIMS (Aspen Technology) and RPMS (Honeywell Hi-Spec Solutions), while more rigorous nonlinear planning models for refinery production were developed recently (Moro et al., 1998; Pinto et al., 2000). A detailed literature review is not included due to space limitation but can be found in Jia et al. (2002).

The objective of this paper is to propose a new mathematical model that addresses the simultaneous optimization of short-term scheduling problem of refinery operations as stated in section 2. In section 3, the mathematical formulation of problem 1 is presented and then applied to case studies in the following section. The state-task network (STN) representation introduced by Kondili et al. (1993) is used throughout this paper.

Problem Definition

A typical crude-oil unloading system considered here consists of crude-oil marine vessels, storage tanks,

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charging tanks, and crude-oil distillation units, as illustrated in Figure 1. Crude-oil vessels unload crude oil into storage tanks after arrival at the refinery docking station. Then the crude-oil is transferred from storage tanks to charging tanks, in which a crude-oil mix is produced. The crude-oil mix in each charging tank may then be charged into one or more crude-oil distillation units. The lube-oil refinery problem includes three processing stages: extraction, dewaxing and hydrofinishing. The gasoline blending system consists of four pieces of equipment all linked together through various piping segments, flowmeters and valves. They are in order: componentstock tanks, blend header, productstock tanks and lifting ports. Componentstock tanks provide components for the blend header according to the recipes so that different products can be produced and then stored in their suitable productstock tanks. The final step is to lift those products during the specified time periods in order to satisfy all the orders. The key information available from external sources are:

a) key component concentration ranges.
b) yields between feed grades and product grades.
c) recipe of each product which is assumed fixed to maintain model's linearity.
d) amount of product required for each order.
e) minimum and maximum flowrates.
f) capacity limitations of all tanks.
g) types of materials that can be stored in each tank.
h) time horizon under consideration.

The objective is to determine the following variables:
a) starting and end times of tasks taking place at each stage.
b) amount and type of material being produced or consumed at each time.
c) amount and type of material being stored at each time in each tank, so as to minimize the operation cost, maximize the total profit and process all the orders in specific time periods.

The overall problem is first decomposed into three sub-problems as illustrated in Figure 1, and each of those is modeled and solved in an effficient way based on a continuous time formulation. Then, in order to avoid sub-optimalities and infeasibilities, the integration of these sub-problems is addressed by applying heuristic based Lagrangian decomposition iterative methodology. Due to space limitation, only the mathematical formulation and the results of problem 1 is presented in this paper.

Mathematical Formulation

The following assumptions are made in this paper:
a) the times required for CDU mode change are neglected.
b) perfect mixing is assumed in the tanks.
c) the property state of each crude-oil or mixture is decided only by specific key components.

The mathematical model involves mainly material balance constraints, allocation constraints, sequence constraints, and demand constraints. Material balance constraints connect the amounts of material in one unit at one event point to that at the next event point. Allocation constraints set the delivery assignments between two consecutive stages, and the beginning and finishing times of each operation are determined by the sequence constraints. Demand constraints ensure that all the demands will be satisfied during the time horizon.

Material Balance Constraints

$$v(v,n+1) = v(v,n) - \sum_{i \in I_v} b(v,i,n) \quad (1)$$

$$v(i,n+1) = v(i,n) + \sum_{v \in V_i} b(v,i,n) - \sum_{j \in J_i} b(i,j,n) \quad (2)$$

$$v(j,n+1) = v(j,n) + \sum_{i \in I_j} b(i,j,n) - \sum_{l \in L_j} b(j,l,n) \quad (3)$$

$$v(j,k,n+1) = v(j,k,n) + \sum_{i \in I_j} b(i,j,n) * Ds(i,k) - \sum_{l \in L_j} b(j,l,k,n) \quad (4)$$

Capacity Constraints

$$v(i,n) \le Vmax(i), \forall i \in I, n \in N \quad (5)$$

$$v(j,n) \le Vmax(j), \forall j \in J, n \in N \quad (6)$$

Allocation Constraints

$$\sum_{j \in J_l} z(j,l,n) \le 1 \quad (7)$$

$$y(i,j,n) + \sum_{l \in L_j} z(j,l,n) \le 1 \quad (8)$$

$$x(v,i,n) * Vmin \le b(v,i,n) \le x(v,i,n) * Vmax \quad (9)$$

$$y(i,j,n) * Vmin \le b(i,j,n) \le y(i,j,n) * Vmax \quad (10)$$

$$z(j,l,n) * Vmin \le b(j,l,n) \le z(j,l,n) * Vmax \quad (11)$$

Demand Constraints

$$\sum_{l \in L_j} \sum_{n \in N} b(j,l,n) = DM(j) \quad (12)$$

Sequence Constraints

$$Ts(v,i,n) \ge Tarr(v) * x(v,i,n) \quad (13)$$

$$Tf(v,i,n) \le H \quad (14)$$

$$Ts(i,j,n+1) \ge Tf(j,l,n) - H * (1 - z(j,l,n)) \quad (15)$$

$$Ts(j,l,n+1) \ge Tf(i,j,n) - H * (1 - y(i,j,n)) \quad (16)$$

$$Ts(j,l,n+1) \ge Tf(j,l',n) - H * (1 - z(j,l',n)) \quad (17)$$

$$\sum_{n} \sum_{j \in J_l} (Tbf(j,l,n) - Tbs(j,l,n)) = H \quad (18)$$

Beginning - Ending Time Consideration

$$Ts(v,i,n) - H * (1 - x(v,i,n)) \leq Tst(v,i,n) \leq Ts(v,i,n) \quad (19)$$

$$Tst(v,i,n) \leq H * x(v,i,n) \quad (20)$$

$$Tf(v,i,n) - H * (1 - x(v,i,n)) \leq Tft(v,i,n) \leq Tf(v,i,n) \quad (21)$$

$$Tft(v,i,n) \leq H * x(v,i,n) \quad (22)$$

Duration Constraints

$$(Tf(v,i,n) - Ts(v,i,n)) * fmin \leq b(v,i,n) \leq (Tf(v,i,n) - Ts(v,i,n)) * fmax \quad (23)$$

$$(Tf(i,j,n) - Ts(i,j,n)) * fmin \leq b(i,j,n) \leq (Tf(i,j,n) - Ts(i,j,n)) * fmax \quad (24)$$

$$(Tf(j,l,n) - Ts(j,l,n)) * fmin \leq b(j,l,n) \leq (Tf(j,l,n) - Ts(j,l,n)) * fmax \quad (25)$$

Objective Function

$$cost = cs * \sum_v \sum_{i \in I_v} \sum_n (Tst(v,i,n) - Tarr(v)) + cu * \sum_v \sum_{i \in I_v} \sum_n (Tft(v,i,n) - Tst(v,i,n)) + ct * \sum_i \sum_n v(i,n)/NE + cb * \sum_j \sum_n v(j,n)/NE \quad (26)$$

Constraints 1) - 3) express that the volumes of crude-oil or oil mix in vessels or tanks at event point (n+1) is equal to that at event point (n) adjusted by any amounts fed from previous stage or transferred to next stage. Simimlarly, constraint 4) states that the amount of component (k) in charging tank (j) at event point (n+1) is equal to that at event point (n) adjusted by any amounts transferred from storage tanks or charged to the CDU. Constraints 5) and 6) impose volume capacity limitations for storage and charging tanks. According to constraints 7) and 8), at most one CDU (l) can be charged by charging tank (j) at one time and vice versa, and charging tank (j) cannot charge CDU and be fed by storage tank at the same time. Constraints 9) - 11) force binary variables x(v,i,n), y(i,j,n) and z(j,l,n) to be 1 if b(v,i,n), b(i,j,n), and b(j,l,n) are not zero, respectively, otherwise, they are equal to zero. These constraints are required in order to maintain the one-to-one assignment of the amounts being transferred and the corresponding binary variables. Constraint 12) states that the demand of crude-oil mix (j) should be met by the total amount of crude-oil mix being lifted from a charging tank (j). The requirement that each vessel can start unloading crude-oil only after its arrival and must empty its cargo before the end of the time horizon is expressed through constraint 13) and 14), respectively. Constraints 15) and 16) are introduced to express that each charging tank (j) can either be fed from storage tank (i) or charge CDU (l) at any event point (n). Constraint 17) states that charging tank (j) should start charging CDU (l) after the completion of charging other CDUs in previous event points. Since each CDU (l) must be operated continuously, the total operation time of each CDU (l) should be equal to the time horizon (H). The starting and end times of unloading of vessel (v) are essentially $Tst(v,i,n) = Ts(v,i,n) * x(v,i,n)$ and $Tft(v,i,n) = Tf(v,i,n) * x(v,i,n)$ that involve bilinear terms (continuous * binary). By applying Glover's transformation (constraints 19) - 22)), linearity can be preserved. Constraints 23) - 25) express that the volume of crude-oil or mix being transferred should be between the limits of [duration time * fmin] and [duration time * fmax]. The objective is to minimize the total operating cost. The first term in eqn 26) is the sea waiting cost, and the second term represents the unloading cost. The total inventory levels of storage tanks and charging tanks are approximated by $\sum_i \sum_n v(i,n)/NE$ and $\sum_j \sum_n v(j,n)/NE$ respectively, which essentially are the sums of inventory level of tanks at each event point divided by the total number of event points.

Case Studies: Results and Comparisons

Four examples are studied with the data obtained from Lee et al. (1996). Example 1 deals with a small size problem, while Example 4 presents a problem with 3 vessels, 6 storage tanks and 4 charging tanks that constitute an industrial size problem. As shown in Table 1, the proposed MILP formulation results in much smaller models in terms of constraints, continuous and binary variables. Consequently, the solutions of those examples are much easier and require less CPU time. Note that for the industrial size problem (problem 4), the proposed formulation can be solved efficiently using 9818 nodes and 92.75 CPU seconds.

Example	Var.	0-1 Var.	Const.	Obj.	Nodes	Iterations	CPU time
1	139	24	364	221.56[1]	56	1,313	0.38
1(Lee et al.)	192	36	331	217.667	208	1,695	17.1
2	341	56	921	342.88	2,843	102,172	43.90
2(Lee et al.)	4,566	70	825	352.55	10,525 (904)[2]	331,493 (21148)	4,158.8 (287.9)
3	273	42	731	274.05	153	3,465	0.97
3(Lee et al.)	581	84	1,222	296.56	>8,993 (2,519)	>515,541 (60,663)	>7744 (1,089.4)
4	509	100	1,345	372.94	9.818	269.259	92.75
4(Lee et al.)	N/A (991)	N/A (105)	N/A (2,154)	N/A (420.99)	N/A (5,011)	N/A (157,883)	N/A (4,372.8)

1 No direct comparison can be made since the objective obtained by the proposed methodology corresponds to and approximation of the reported value due to the continuous nature of the formulation

2 Results in parenthesis are obtained with the use of SOS1 and priority

Table 1: *Computational results and comparisons for problem 1*

Summary and Future Directions

In this paper, a continuous-time formulation was presented for the short-term scheduling of refinery operations. It is shown that the resulting model can be solved efficiently even for realistic large-scale problems. The main advantage of the proposed approach is the full utilization of the time continuity. This results in smaller models in terms of variables and constraints since only the real events have to be modeled. In contrary, discrete time formulations which are commonly used for refinery operations result in excessive number of variables and constraints due to unnecessary time discretization.

Work is currently performed that involves the integration of all three different problems (Figure 1) and will be the subject of future publication.

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Nomenclature

Indices

i = storage tanks
j = charging tanks
k = key components
l = CDUs
n = event points
v = vessels

Sets

I_j = storage tanks which can transfer crude oil to charging tank j
I_v = storage tanks which can be fed by vessel v
J_i = charging tanks which can be fed by tank i
J_l = charging tanks which can charge CDU l
L_j = CDUs which can be charged by charging tank l
V_i = vessels which can feed crude oil to tank i

Parameters

cb = inventory cost of charging tanks per volume per day
cs = sea waiting cost per day
ct = inventory cost of storage tanks per volume per day
cu = unloading cost per day
DM(j) = demand of crude mix from charging tank j
Ds(i,k) = concentration of component k in the crude oil of storage tank i
fmax = maximum volume flow rate
fmin = minimum volume flow rate
NE = total number of event points
Tarr(v) = arrival time of vessel v
Vmax(i) = maximum capacity of storage tank i
Vmax(j) = maximum capacity of charging tank j

Variables

b(v,i,n) = volume of crude oil that vessel v unloads into storage tank i at event point n
b(j,l,k,n) = volume of component k that charging tank j charges into CDU l at event point n
Tf(v,i,n) = end time of vessel v unloading crude oil into storage tank i at event point n
Tft(v,i,n) = time that vessel v finishes unloading crude oil into storage tank i
Ts(v,i,n) = starting time of vessel v unloading crude oil into storage tank i at event point n
Tst(v,i,n) = time that vessel v starts unloading crude oil into storage tank i
v(v,n) = volume of crude oil in vessel v at event point n
v(j,k,n) = volume of component k in charging tank j at event point n
x(v,i,n) = binary variables that assign the beginning of v unloading crude oil to i at event point n
y(i,j,n) = binary variables that assign the beginning of i transferring crude oil to j at event point n
z(j,l,n) = binary variables that assign the beginning of j charging crude oil mix to l at event point n

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