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Logistics Management in Maritime Transportation Systems

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The efficient routing and scheduling of multi-parcel chemical tankers is a challenging problem for both chemical and shipping industry. To optimally manage complex logistics problem, a novel continuous time precedence-based MILP mathematical formulation is developed to determine the optimal solution to the ship routing and scheduling. The approach aims to determine the assignment of cargos to ships and define the optimal route that each ship should follow to maximize its profit. The MILP-based model is then combined with an iterative algorithm in order to tackle large-scale problems involving a large numbers of ships, ports, and cargos. To illustrate the applicability and importance of the proposed method, a real industrial case study taken from literature is solved with modest CPU times.

1. Introduction

In the current context of a global and very competitive economy, ocean transportation is key issue for logistics in real world chemical supply chains. Today, maritime bulk transport is used for distributing all kinds of products because it is by far the cheapest transportation mode that allows carrying very large loads at low costs. Thus, ocean shipping industry plays a central role in international trade, being responsible for the majority of long-distance shipments in terms of volume. About 75 % of the world trade is transported by sea.

One of the key aspects in the short-term planning of maritime transportation systems is the routing of ships. A maritime carrier aims to minimize the total transportation costs while ensuring that all cargos are transported. Even though the problem can be treated as a multi-ship Pickup and Delivery problem with time windows (m-PDPTW), some additional features must be considered. For each ship, the condition of return to origin port as we known in the conventional vehicle routing problems is not enforced. The ship routes are merely open paths, ending with the last schedule delivery. Different methods on the vehicle assignment problems can be found in Dondo et al. (2008) and Barany et al. (2010).

Jetlund and Karimi (2003) proposed an MILP formulation using variable-length slots and presented a heuristic decomposition to solve the problem defined in this paper. Although such model successfully solved a real problem, new approaches can be developed in order to improve computational times needed to achieve optimal solutions.

This article proposes a novel optimization approach to solve the ship routing and scheduling problem of a fleet of multi-parcel chemical carriers engaged in the transportation of multiple chemicals. A new continuous time precedence-based MILP-based framework is developed to find the optimal solution to the fleet scheduling problem. The objective consists of identifying the cargos that each ship should serve and determines the optimal route that the ship should follow to maximize its profit. The original model can be easily embedded in an iterative algorithm in order to tackle large-scale problems involving a large numbers of ships, ports, and cargos. Such strategy exploits some problem characteristics to significantly reduce the computational effort needed to optimize real-world problems. To illustrate the applicability and importance of the proposed method, a real industrial case study taken from literature is solved with modest CPU times.

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2. Problem description

The routing and scheduling problem of multi-parcel chemical tankers consists of finding the optimal routes for a ship fleet in order to carry multiples cargos at maximum profit while satisfying all problem constraints. A cargo consists of a specified quantity of a given product that must be picked up at its port of loading, transported, and then delivered to its port of discharge. A fleet of ships is utilized for moving the cargos. The ship fleet involves a number of heterogeneous multi-parcel tankers with different properties (sailing speed, total carrying capacity, time charter cost, and port costs). Each ship has a finite load capacity in tonnes that cannot be exceeded. Since cargos on-board must never exceed the maximum carrying capacity, one important property is the volume of each cargo. The ports are interconnected through maritime routes corresponding to sailing segment characterized by a distance-based transportation. Traveling time between two ports can be defined by route length (nautical miles) and the sailing speed of every ship (knots). Vehicle capacities, cargos properties, and port locations are problem data. Every ship can perform pickup and delivery tasks in multiples ports but the number of visited ports must never exceed a maximum amount defined for every ship. The time needed for carrying out loading and discharging operations at each port comprises a fixed inspection time plus a variable time period that directly increases with the total cargo to be loaded/unloaded. For each cargo, the loading and discharging rate (pump capacity) is known a priori. Besides, transhipment cargos have a time interval within pickup service must begin. Such interval is defined by both an earliest pickup time and a latest pickup time. At the beginning of planning horizon, each ship knows the next port to visit and estimated time of arrival at that location.

The problem goal consists of identifying the cargos that each ship should serve and determines the optimal route that the ship should follow to maximize its profit. The total profit is determined by the revenues from all serviced cargos minus operation costs. Three types of cost are usually considered. First, the time-charter cost. Second, the distance-based transportation cost accounting for the fuel oil consumption. Third, the port charge depending on the capacity of ship and the number of visited ports.

3. Solution strategies

3.1 Exact optimization method

The following notations are used in the proposed MILP-based formulation:

Sets: L (cargos); S (ships); P (ports); OB (cargos on-board at the beginning of planning horizon); IP_s (first port to visit by ship s); LP_p (cargos loaded in port p); DP_p (cargos discharged in port p).

Parameters: $dist_{p,p'}$ (distance in nm between port p and port p'); dr_l (discharge rate of cargo l in tonnes/h); ept_l (earliest time for pickup cargo l); fc_s (cost of fuel per unit distance for ship s); lpt_l (latest time for pickup cargo l); lr_l (loading rate of cargo l in tonnes/h); $pc_{p,s}$ (port cost for ship s at port p); sr_l (revenue for cargo l in US$); tad (inspection time); v_s (sailing speed of ship s in knots); tcc_s (time-charter cost per unit time of ship s); ti_s (arrival time in day of ship s at first port); $vmax_s$ (total carrying capacity of ship s in tonnes); $volume_l$ (volume of cargo l in tonnes).

Variables: $LOAD_{p,s}$ (total cargo loaded on the ship s after completing the service at port p); $PR_{p,p',s}$ (binary variable denoting that port p is visited before/after port p' by ship s); PROFIT (total revenue); $TD_{p,s}$ (accumulated ship travel distance to reach port p); TTD_s (total distance travelled by ship s); TTV_s (total travel time for ship s); $TV_{p,s}$ (arrival time of ship s at port p); $UNLOAD_{p,s}$ (total cargo unloaded from the ship s after completing the service at port p); $Y_{l,s}$ (binary variable denoting that ship s serves cargo l); $X_{p,s}$ (binary variable denoting that ship s visits port p).

On the basis of this notation, the ship routing and scheduling comprise the following constraints:

Each cargo l ∈ L can be fulfilled by just a ship s ∈ S

$$\sum_{s \in S} Y_{l,s} \le 1 \qquad \forall l \in L \tag{1}$$

If some cargo l is assigned to ship s, its loading and discharging port should be visited by s.

$$Y_{l,s} \le X_{p,s} \qquad \forall l \in L, p \in P, s \in S : (((l \notin OB) \cap (l \in LP_p)) \cup (l \in DP_p)) \tag{2}$$

Traveling time and distance to the first port visited for ship s.

$$TV_{p,s} = ti_s X_{p,s} \qquad \forall p \in P, s \in S : p \in IP_s \tag{3}$$

$$TD_{p,s} = ti_s\, 24 v_s\, X_{p,s} \qquad \forall p \in P, s \in S : p \in IP_s \tag{4}$$

If some cargo l is assigned to ship s, its pickup port must be visited before its discharge port.

$$TV_{p',s} \geq TV_{p,s} + \sum_{l' \in L:(l' \notin OB) \cap (l' \in LP_p)} (Y_{l',s}\, volume_{l'}) / lr_{l'} + \sum_{l' \in L: l' \in DP_p} (Y_{l',s}\, volume_{l'}) / dr_{l'} + tad + dist_{p,p'} / (24 v_s) - M_t (1 - Y_{l,s}) \quad \forall l \in L, s \in S, (p,p') \in P : l \notin OB \cap l \in LP_p \cap l \in DP_{p'} \tag{5}$$

Time-based sequencing constraints

$$TV_{p',s} \geq TV_{p,s} + \sum_{l \in L:(l \notin OB) \cap (l \in LP_p)} (Y_{l,s}\, volume_l) / lr_l + \sum_{l \in L: l \in DP_p} (Y_{l,s}\, volume_l) / dr_l + tad + dist_{p,p'} / (24 v_s) - M_t (1 - PR_{p,p',s}) - M_t (2 - X_{p,s} - X_{p',s}) \quad \forall (p,p') \in P, s \in S : p < p' \tag{6}$$

$$TV_{p,s} \geq TV_{p',s} + \sum_{l \in L:(l \notin OB) \cap (l \in LP_{p'})} (Y_{l,s}\, volume_l) / lr_l + \sum_{l \in L: l \in DP_{p'}} (Y_{l,s}\, volume_l) / dr_l + tad + dist_{p',p} / (24 v_s) - M_t PR_{p,p',s} - M_t (2 - X_{p,s} - X_{p',s}) \quad \forall (p,p') \in P, s \in S : p < p' \tag{7}$$

Distance-based sequencing constraints

$$TD_{p',s} \geq TD_{p,s} + dist_{p,p'} - M_d (1 - PR_{p,p',s}) - M_d (2 - X_{p,s} - X_{p',s}) \quad \forall (p,p') \in P, s \in S : p < p' \tag{8}$$

$$TD_{p,s} \geq TD_{p',s} + dist_{p',p} - M_d PR_{p,p',s} - M_d (2 - X_{p,s} - X_{p',s}) \quad \forall (p,p') \in P, s \in S : p < p' \tag{9}$$

Overall travelling time and distance along the route assigned to ship s

$$TTV_s \geq TV_{p,s} + \sum_{l \in L: l \in DP_p} (Y_{l,s}\, volume_l) / dr_l + X_{p,s}\, tad \quad \forall p \in P, s \in S \tag{10}$$

$$TTD_s \geq TD_{p,s} \quad \forall p \in P, s \in S \tag{11}$$

Time windows constraints. Interval within pickup service must begin.

$$TV_{p,s} \leq LPT_l - 0.5 tad + M_t (1 - Y_{l,s}) \quad \forall l \in L, s \in S, p \in P : l \notin OB \cap l \in LP_p \tag{12}$$

$$TV_{p',s} \geq EPT_l + 0.5 tad + dist_{p,p'} / (24 v_s) + Y_{l,s} volume_l / lr_l - M_t (1 - PR_{p,p',s}) - M_t (2 - X_{p,s} - X_{p',s}) - M_t (1 - Y_{l,s}) \quad \forall (p,p') \in P, s \in S, l \in L : ((p < p') \cap (l \notin OB) \cap (l \in LP_p)) \tag{13}$$

$$TV_{p,s} \geq EPT_l + 0.5 tad + dist_{p',p} / (24 v_s) + Y_{l,s} volume_l / lr_l - M_t PR_{p,p',s} - M_t (2 - X_{p,s} - X_{p',s}) - M_t (1 - Y_{l,s}) \quad \forall (p,p') \in P, s \in S, l \in L : ((p < p') \cap (l \notin OB) \cap (l \in LP_{p'})) \tag{14}$$

Capacity constraints on the load transported by ship s after visit port p.

$$LOAD_{p,s} - UNLOAD_{p,s} \leq v\max_s X_{p,s} \quad \forall p \in P, s \in S \tag{15}$$

$$LOAD_{p,s} - UNLOAD_{p,s} \geq 0 \quad \forall p \in P, s \in S \tag{16}$$

Load-based sequencing constraints

$$LOAD_{p,s} \geq \sum_{l \in L: l \in OB} Y_{l,s} volume_l + \sum_{l \in L:(l \notin OB) \cap (l \in LP_p)} Y_{l,s}\, volume_l \quad \forall p \in P, s \in S : p \in IP_s \tag{17}$$

$$LOAD_{p',s} \geq LOAD_{p,s} + \sum_{l \in L:(l \notin OB) \cap (l \in LP_{p'})} (Y_{l,s}\, volume_l) - M_c (1 - PR_{p,p',s}) - M_c (2 - X_{p,s} - X_{p',s}) \quad \forall (p,p') \in P, s \in S : p < p' \tag{18}$$

$$LOAD_{p,s} \geq LOAD_{p',s} + \sum_{l \in L:(l \notin OB) \cap (l \in LP_p)} (Y_{l,s}\, volume_l) - M_c PR_{p,p',s} - M_c (2 - X_{p,s} - X_{p',s}) \qquad \forall (p,p') \in P, s \in S : p < p' \tag{19}$$

$$UNLOAD_{p,s} \geq \sum_{l \in DP_p} Y_{l,s}\, volume_l \qquad \forall p \in P, s \in S : p \in IP_s \tag{20}$$

$$UNLOAD_{p',s} \geq UNLOAD_{p,s} + \sum_{l \in DP_{p'}} (Y_{l,s}\, volume_l) - M_c (1 - PR_{p,p',s}) - M_c (2 - X_{p,s} - X_{p',s}) \qquad \forall (p,p') \in P, s \in S : p < p' \tag{21}$$

$$UNLOAD_{p,s} \geq UNLOAD_{p',s} + \sum_{l \in DP_p} (Y_{l,s}\, volume_l) - M_c PR_{p,p',s} - M_c (2 - X_{p,s} - X_{p',s}) \qquad \forall (p,p') \in P, s \in S : p < p' \tag{22}$$

Upper bounds on the values $Load_{p,s}$ and $Unload_{p,s}$.

$$LOAD_{p,s} - \sum_{l \in L} Y_{l,s}\, volume_l \leq v\max_s (1 - X_{p,s}) \qquad \forall p \in P, s \in S \tag{23}$$

$$UNLOAD_{p,s} - \sum_{l \in L} Y_{l,s}\, volume_l \leq v\max_s (1 - X_{p,s}) \qquad \forall p \in P, s \in S \tag{24}$$

Objective function: maximize the net profit

$$Max \left[\sum_{s \in S} \sum_{l \in L} sr_l Y_{l,s} - \sum_{s \in S} tcc_s TTV_s - \sum_{s \in S} fc_s TTD_s - \sum_{s \in S} \sum_{p \in P} pc_{p,s} X_{p,s} \right] \tag{25}$$

3.2 Iterative algorithm

The logistic problem presented in this work is characterized by a high combinatorial complexity that in many instances exceeds the capabilities of current pure optimization models. Thus, a rigorous MILP-based iterative algorithm was developed in order to tackle problems with a large numbers of cargos, ports, and ships. In this particular problem, the solution strategy can take advantage that the one-ship model (for each ship) and the two-ship model (for two ships in simultaneous) can be solved in few seconds of CPU time. The procedure is described in Figure 1. At the first step, the one-ship problem is solved for each ship. Consequently, the solution generated can be infeasible because a cargo can be served by more than one ship. However, the developed algorithm aims gradually to build a feasible solution. In this way, once a preliminary assignment of cargos to ships has been performed, the procedure identifies the pair of ships having the greatest amount of cargos in common. Then, a two-ship problem is solved to assign disputed cargos to one of the two candidate ships. As new reallocations and port reordering can occur in this phase, once cargos are assigned to a determined ship, the one-ship model for both ships is solved again and the procedure is repeated beginning with the second step. The algorithm is repeated until the ships scheduling becomes feasible and, no cargos are served by more than one ship. When this happened, the procedure is stopped and the best routing and scheduling of every ships is given as solution.

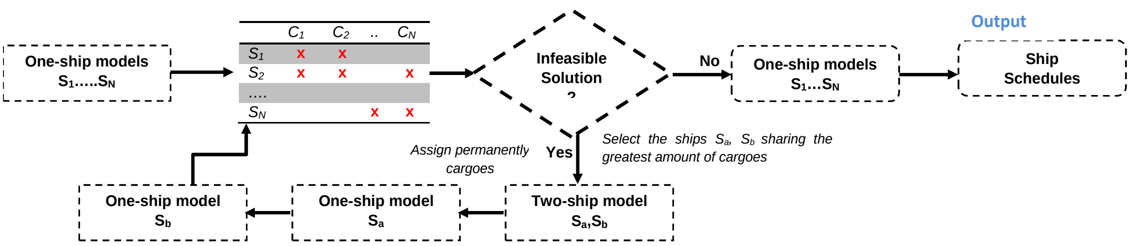

Figure 1: The MILP-based algorithm

4. Case study and computational results

The applicability and effectiveness of the proposed formulation are illustrated by effectively coping with a real industrial case study involving 10 ships, 36 ports, and 79 cargos, where 37 cargos correspond to already on-board ships and the remaining 42 are new potential cargos. Such example was previously tackled by Jetlund and Karimi (2003). Based on real data provided by the company, we assume tad=6h for all ports, $lr_l=dr_l=200$ tn/h, and $v_s=13$ knots. Figure 2 shows the Asia Pacific Region where all the ports are located. Information related to ship characteristics is given in Table 1, while Table 2 provides the load/discharge ports, volumes, service revenues, and time windows for all cargos. The example was solved with a modest computational effort by using a DELL PRECISION T5500 Workstation with six-core Intel Xeon Processor and the modelling language GAMS and CPLEX 12.2 as the MILP solver.

Table 1: Ship properties

Ship	Size (dwt)	Cost (US$/day)	First Port	Arrival Time (day)
1	11,000	9,000	2	1.62
2	11,000	9,000	29	1.875
3	11,000	8,000	3	0.083
4	8,200	8,000	11	3.625
5	8,200	7,000	36	1.573
6	5,800	7,000	28	1.323
7	5,800	7,000	30	2.865
8	5,800	7,000	26	3.750
9	5,800	7,000	13	2.031
10	6,000	7,000	24	0.367

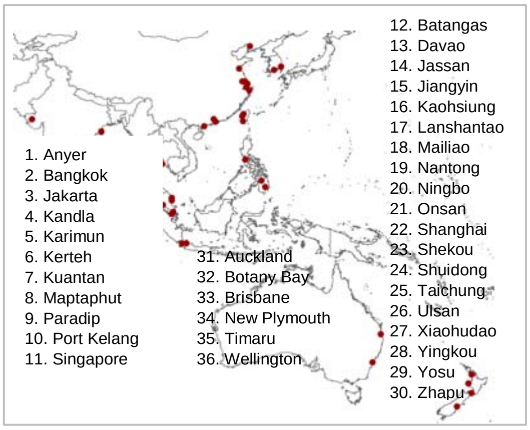

Figure 2: Asia pacific region

Table 2: Load/discharge ports, volume, shipping rates, and time windows for all cargos

Nº	Ports	Tn.	$/tn	TW	Nº	Ports	Tn.	$/tn	TW	Nº	Port	Tn.	$/tn
1	5-24	950	47.50	8-12	27	11-4	500	26.25	1-8	53	29	850	42.50
2	5-23	596	50.00	8-12	28	11-4	500	26.25	1-8	54	26	300	40.00
3	5-25	1049	30.00	8-12	29	11-4	300	26.25	1-8	55	26	300	40.00
4	5-16	700	40.00	8-12	30	5-8	500	32.00	8-12	56	3	2086	35.50
5	5-22	501	40.00	8-12	31	5-8	1000	32.00	8-12	57	5	3000	40.00
6	5-2	2092	30.00	8-12	32	5-2	250	32.00	8-12	58	36	500	61.50
7	5-14	1000	45.00	8-12	33	11-6	350	68.57	8-13	59	35	500	61.50
8	5-1	1011	28.00	8-12	34	7-2	500	40.00	14-18	60	34	50	61.50
9	5-20	1400	36.00	6-10	35	7-2	200	40.00	14-18	61	31	50	61.50
10	5-10	500	60.00	6-10	36	21-9	6000	48.30	4-8	62	28	5359	18.00
11	26-20	995	34.00	9-12	37	26-17	300	30.00	4-8	63	19	1001	36.00
12	26-20	678	34.00	9-12	38	26-22	600	30.00	4-8	64	20	650	40.00
13	26-22	1000	34.00	9-12	39	33-16	1100	52.37	7-11	65	15	1050	40.00
14	26-22	505	34.00	9-12	40	33-22	2700	52.37	1-11	66	22	2000	26.00
15	26-19	1000	36.00	9-12	41	33-30	4500	52.37	7-11	67	22	500	26.00
16	26-19	315	36.00	9-12	42	33-25	150	52.37	7-11	68	13	800	75.00
17	11-23	2700	25.00	4-8	43	2	315	40.00	-	69	12	350	85.71
18	11-23	350	25.00	4-8	44	2	315	40.00	-	70	12	300	83.33
19	11-13	600	25.00	4-8	45	2	315	40.00	-	71	12	300	21.60
20	11-32	800	56.00	0-6	46	2	199	40.00	-	72	18	2000	21.60
21	7-22	800	37.50	5-10	47	7	1490	32.50	-	73	16	1300	21.60
22	7-22	300	37.50	5-10	48	11	455	30.00	-	74	12	300	83.33
23	7-26	400	37.50	5-10	49	11	105	30.00	-	75	24	731	42.50
24	7-26	700	38.50	5-10	50	11	509	30.00	-	76	24	488	42.50
25	7-22	1000	37.50	5-10	51	3	210	71.46	-	77	27	1000	40.00
26	11-4	1000	26.25	1-8	52	3	210	71.46	-	78	27	1000	26.00
										79	27	850	26.00

Table 3 shows the schedule used by the shipping company while details about the new solution are given in Table 4 and illustrated in Figure 3. The new schedule improves profits by approximately 40 % with regards to actually used by the company. Moreover, significant profits are obtained with regards to other approaches that have tried to solve the same problem.

Table 3: Company's Schedule

Ship	Served Cargos	Profit
1	1-5,9,10,43-52	19,442
2	36, 53-55	102,155
3	26-29, 56	-36,577
4	17-19, 21-25, 57	81,350
5	39-42, 58-61	168,478
6	62	70,777
7	63-67	104,666
8	11-16, 39, 40	32,454
9	68-74	125,289
10	6, 30-35, 75-79	126,600
Total Profit		***794,634***

Table 4: New Schedule

Ship	Served Cargos	Profit
1	1-2, 5, 9, 17-19, 21-22, 25, 43-52	185,311.51
2	36, 53-55	112,436.56
3	56	62,722.40
4	6, 10, 30-35, 57	129,507.74
5	40-41, 58-61	174,839.34
6	62	70,772.22
7	63-67	104,683.82
8	11-16, 38, 40	48,613.48
9	68-74	118,945.02
10	75-79	110,054.68
	Total Profit	***1,117,887***

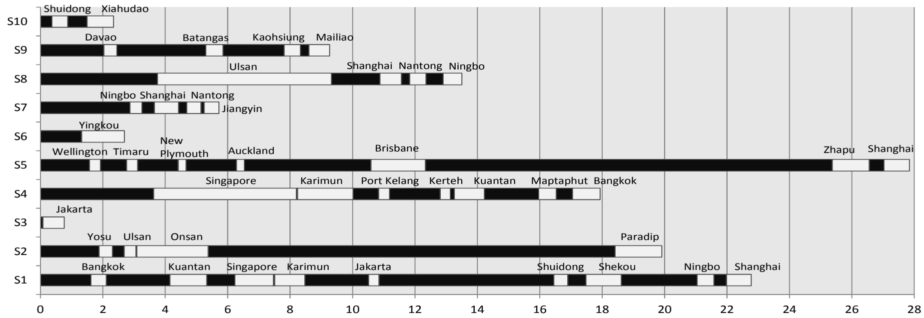

Figure 3: Ship Schedules

5. Conclusions

This paper has presented a new continuous time precedence-based MILP mathematical formulation to the efficient routing and scheduling of multi-parcel chemical tankers. The optimization approach is then combined with and iterative strategy in order to tackle large-scale problems involving a large numbers of ships, ports and cargos. To illustrate the applicability and importance of the proposed method, a real industrial case study of a multi-national shipping company that operates a fleet of ships in the Asia Pacific Region is solved with modest CPU times. Significant improvements in company's profits are obtained with regards to solutions given by other approaches that have tried to solve the same problem.

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