ROUTING AND SCHEDULING OF PARCEL TANKERS: A NOVEL SOLUTION APPROACH

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ABSTRACT
For more than half a century, tanker routing and scheduling problems have also attracted extensive interest from researchers. To date, only one existing tanker routing and scheduling model explicitly accounts for the cargo stowage constraints faced by tanker owners. But the originators of the latter model fail to offer efficient solution methodology that can meet the practical needs of industry practitioners. This paper aims to bridge the research gap in the domain of tanker routing and scheduling in two major ways. First, it introduces a novel solution methodology that can (1) efficiently solve tanker routing and scheduling problem with all key operating constraints, and (2) meet the practical needs of industry practitioners. In addition to highlighting the pros and cons of our tool relative to existing tools, this paper also discusses research opportunities that remain available in this field.

Keywords: parcel tanker, routing and scheduling, optimization, stowage

1. INTRODUCTION

For many years, the US$2.2 trillion global chemical industry has been a key driver of the global economic growth. The global chemical trade which hit more than US$1.24 trillion in 2006 has achieved an impressive 14% average annualized growth between 2000 and 2006 (World Trade Organization, 2007). To support this growing chemical trade, new parcel tankers which primarily ship cargos between chemical processing facilities and manufacturers worldwide have been built in record numbers (Shaw, 2003).

Essentially, a parcel tanker distinguishes itself from other maritime bulk carriers by its multiple independent cargo tanks which enable it to carry multiple liquid cargos simultaneously. To ensure there is no contact between different cargoes, each tank usually has its own cargo handling system which consists of pump and associated piping. Moreover, these pumps and pipes are constructed using materials that are compatible with the cargoes to be handled so that their qualities will not be compromised as a result of their passage through the pumps and pipes. In practice, each cargo handling system is designed to handle a variety of products from light to heavy end products so as to enhance the cargo carrying versatility of the tankers. Clearly, the pipe work associated with these tanks for cargo loading and discharging as well as the cargo loading and discharging arrangement are complex. Thus, all procedures that entail handling of cargoes have to be carried out with great care and precision to both avoid cargo contamination and ensure that cargoes owned by different shippers are kept separated. To ensure incompatible chemical cargoes do not come into contact with each other, parcel tankers are usually constructed with cofferdam (i.e. a space between two tank walls) between adjacent tanks. In addition, cargo tanks of parcel tankers must also be cleaned prior to loading of cargoes to (1) uphold the chemical cargo quality and (2) avoid unwanted chemical reactions that may pose safety hazards.

Due to safety concerns, parcel tanker operators have to contend with two regulatory constraints that are sanctioned by International Maritime Organization (IMO). First, the cargo tanks of parcel tankers must be lined with appropriate coatings that are compatible with the cargoes that they are carrying in accordance with either Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (BCH code) for ships constructed before 1 July 1986 or International Bulk Chemical Code (IBC Code) for those built after 1 July 1986. This is to protect (1) the inner surfaces of cargo tanks from the corrosive properties of chemical cargoes and (2) the cargoes from contamination that arises due to corrosion and accumulated scale on uncoated tank surfaces. Typical coatings in use include epoxy, phenolic resins, zinc silicate, polyurethane and rubber. However, majority of these coatings are not compatible with all chemical cargoes. For example, epoxy coating is compatible with alkalis, glycols, vegetable oils but not with aromatics like benzene and toluene. On the other hand, zinc silicate is compatible with aromatics but not with acids, alkalis and vegetable oils. As such, parcel tankers usually have their cargo tanks lined with a number of different coatings so that they can carry as wide a range of chemical cargoes as possible.

Second, dangerous chemical cargoes that might cause a chemical reaction by mixing must be not be loaded into adjoining tanks as stipulated in the IBC Code and BHC Code. This regulatory stowage restriction is summarized in the U.S. Coast Guard Compatibility Chart that is found in Code of Federal Regulations (CFR) Title 46 Part 150 and many in the shipping community are using it as a guide to identify the incompatible chemical cargoes that cannot be loaded into adjacent tanks. A copy of the compatibility chart is shown in Figure 1 where a box with “X” indicates the possible reaction of the corresponding chemical cargoes and they cannot be carried in adjacent tanks.

CARGO COMPATIBILITY

REACTIVE GROUPS

Cargo Groups	1. NON-OXIDIZING MINERAL ACIDS	2. SULFURIC ACID	3. NITRIC ACID	4. ORGANIC ACIDS	5. CAUSTICS	6. AMMONIA	7. ALIPHATIC AMINES	8. ALKANOLAMINES	9. AROMATIC AMINES	10. AMIDES	11. ORGANIC ANHYDRIDES	12. ISOCYANATES	13. VINYL ACETATE	14. ACRYLATES	15. SUBSTITUTED ALLYLS	16. ALKYLENE OXIDES	17. EPICHLORONYDRIN	18. KETONES	19. ALDEHYDES	20. ALCOHOLS, GLYCOLS	21. PHENOLS, CRESOLS	22. CAPROLACTAM SOLUTION	
1. NON-OXIDIZING MINERAL ACIDS		x			x	x	x	x	x	x	x	x	x			x	x						1
2. SULFURIC ACID	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	2
3. NITRIC ACID		x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		3
4. ORGANIC ACIDS		x			x	x	x	x				x				x	x						4
5. CAUSTICS	x	x	x	x							x	x				x	x		x	x	x	x	5
6. AMMNONIA	x	x	x	x						x	x	x	x			x	x		x				6
7. ALIPHATIC AMINES	x	x	x	x							x	x	x	x	x	x	x	x	x	x	x	x	7
8. ALKANOLAMINES	x	x	x	x							x	x	x	x	x	x	x		x				8
9. AROMATIC AMINES	x	x	x								x	x							x				9
10. AMIDES	x	x	x			x						x									x		10
11. ORGANIC ANHYDRIDES	x	x	x		x	x	x	x	x														11
12. ISOCYANATES	x	x	x	x	x	x	x	x	x	x										x		x	12
13. VINYL ACETATE	x	x	x			x	x	x															13
14. ACRYLATES		x	x				x	x															14
15. SUBSTITUTED ALLYLS		x	x				x	x															15
16. ALKYLENE OXIDES	x	x	x	x	x	x	x	x															16
17. EPICHLOROHYDRAIN	x	x	x	x	x	x	x	x															17
18. KETONES		x	x				x																18
19. ALDEHYDES		x	x		x	x	x	x	x														19
20. ALCOHOLS, GLYCOLS		x	x		x		x					x											20
21. PHENOLS, CRESOLS		x	x		x		x			x													21
22. CAPROLACTAM SOLUTION		x			x		x					x											22
30. OLEFINS		x	x																				30
31. PARAFFINS																							31
32. AROMATIC HYDROCARBONS			x																				32
33. MISCELLANEOUS HYDROCARBOAN MIXTURES			x																				33
34. ESTERS		x	x																				34
35. VINYL HALIDES			x																			x	35
36. HALOGENATED HYDROCARBONS																							36
37. NITRILES		x																					37
38. CARBON DISULFIDE							x	x															38
39. SULFOLANE																							39
40. GLYCOL ETHERS		x										x											40
41. ETHERS		x	x																				41
42. NITROCOMPOUNDS					x	x	x	x	x														42
43. MISCELLANEOUS WATER SOLUTIONS		x										x											43
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	

Figure 1: Cargo Compatibility Chart from 46 CFR Part 150

Parcel tankers are capital-intensive and their operating cost runs in ten thousands of dollars a day per ship. In an industry which is notoriously cyclical by nature, efficient cargo assignment, routing and scheduling of parcel tankers is crucial to the financial success of a tanker company. Unfortunately, an optimal assignment of cargos, routes and schedules to a fleet of ships requires solving an inherently complex combinatorial problem. This complexity is further accentuated in the tanker sector primarily due to the need to comply the aforementioned two safety regulations (i.e. cargo-tank and cargo-cargo restrictions) imposed on cargo stowage conditions by IMO.

2. LITERATURE REVIEW

Tanker routing and scheduling problems (TRSPs) have also attracted extensive interest from researchers for more than half a century. Recently, Oh and Karimi (2007) highlighted that distinction can be made among these problems in terms of their characteristics. The latter define the problem scope and business operations practice which tend to differ among tanker companies. Problem characteristics in turn contribute to the variations in the types of operating constraints considered in these problems as well as the solution methodologies that have evolved to address them. Generally, there are six basic characteristics that define a TRSP. They include the number of cargo types carried by each tanker, number of vessel types in a fleet, cargo delivery arrangement, time chartering option, demand nature and problem objective. . In some problems such as those of Flood (1954) and Brown et al. (1987), each tanker can only carry single cargo type per voyage, as opposed to multiple cargo types in other works. In addition, the former addressed a homogenous fleet problem where all vessels are of the same type (i.e. single vessel type) with the same cargo carrying capacity. Together with Rao and Zionts (1968) and Sherali et al. (1999), their problems also entail direct shipment of each cargo from its origin to it destination without the tanker visiting other ports for loading or discharging of other cargos. The option of time chartering other tankers to fulfill shipment orders is another characteristic that differentiate TRSPs. Some of the existing models such as those of Rao & Zionts (1968), Brown et al. (1987), Bausch et al. (1998), Sherali et al. (1999) and Brønmo et al. (2007) account for this option while others omit this option. The last two distinguishing problem characteristics are related and they are associated with the nature of shipment orders and problem objective. Most of the earlier models address TRSPs with a set of given shipment orders and with the objective of fulfilling all these orders at minimum costs. In contrast, recently developed models like those of Jetlund and Karimi (2004), Neo et al. (2006) and Brønmo et al. (2007) considered a problem where there are decisions pertinent to selection of shipment orders that are to be fulfilled with the objective of profit maximization. See Table 1 for an overview of differences in problem characteristics among the selected models.

Essentially, there are two approaches of solving TRSPs. One employs pure optimization techniques to determine optimal solutions of problems concerned. Examples of such approach can be found in Appelgren (1971), Brown et al (1987), Bausch et al. (1998), etc. But application of their solution methods in the industry is limited primarily due to excessive computational times needed to solve problems of industrial scale. Due to enormous complexity of TRSPs, the solution time needed to solve them to optimality increases exponentially with problem size. In addition, the application of these methods also tends to be inhibited by specific characteristics of their respective problems. Recall from Table 1 that both Appelgren (1971) and Brown et al (1987) address problems which only have direct shipment of cargos while the problem in Bausch et al. (1998) has a predetermined set of shipment orders.

Table 1: Key Problem Characteristics and Operating Constraints

Authors	Paper Code (PC)	Problem Characteristics: No. of cargo types	No. of vessel types	Direct shipment	Orders to fulfill	Ship time charter option	Problem objective	Operating Constraints: Cargo-Cargo restrictions	Cargo-Tank restrictions	Ship stability	Laycans
Flood (1954)	a	S	S	Y	F	N	1	N	N	N	N
Rao & Zionts (1968)	b	M	M	Y	F	Y	1	N	N	N	N
Appelgren (1971)	c	M	M	Y	D	N	2	N	N	N	Y
Mckay & Harley (1974)	d	M	M	N	F	N	1	N	N	N	Y
Brown et al. (1987)	e	S	S	Y	F	Y	1	N	N	N	Y
Scott (1995)	f	M	M	Y	F	N	1	N	N	N	N
Bausch et al. (1998)	g	M	M	N	F	Y	1	N	Y	Y	Y
Sherali et al. (1999)	h	M	M	Y	F	Y	1	N	N	N	Y
Jetlund & Karimi (2004)	i	M	M	N	D	N	2	N	N	N	Y
Neo et al. (2006)	j	M	M	N	D	N	2	Y	Y	Y	Y
Brønmo et al. (2007)	k	M	M	N	D	Y	2	N	Y	N	Y
Notations: S = Single, M= Multiple, Y = Yes, N = No, F = Fixed, D = Decision Variables, 1= Cost Minimization, 2 = Profit Maximization											

In contrast, the second approach of addressing TRSPs uses heuristics that usually have the capability to derive good solutions of large scale problems in much lesser computational times than the first approach. These heuristics can be found in Mckay and Harley (1974), Sherali et al. (1999), Jetlund and Karimi (2004), and Brønmo et al. (2007) and they tend to meet the basic operational need of tanker companies which typically require short turnaround times to generate good routes and schedules for their fleets. Generally, these heuristics are able to determine good solutions efficiently by (1) novel mathematical formulation that makes problem more tractable (e.g. Sherali et al., 1999 and Jetlund & Karimi, 2004) than other conventional approaches, (2) leveraging the prowess of intelligence-based search algorithms as in Mckay and Harley (1974) and Brønmo et al., 2007). See Table 2 for details of solution approaches of all selected models.

Table 2: Solution Methods (SM) of Selected Models

PC	SM*	Remarks
a	POM	Applies transportation theory which employs simplex method
b	POM	Employs column generation scheme that involves solving out-of-kilter subproblems
c	POM	Applies branch and bound algorithm with Dantzig-Wolfe decomposition technique
d	H	2 step approach: (1) generates a set of possible schedules and then (2) determines the best one by employing an iterative scheme that solves a linear programming (LP) model
e	POM	2 step approach: (1) generates all possible schedules and then (2) determines the optimal one by solving a SP model
f	POM	Uses Lagrangian relaxation to generate a set of feasible schedules (which include the optimal one) and use a modified Benders' decomposition to determine the optimal one
g	POM	2 step approach: (1) generates all possible schedules and then (2) determines the optimal one by solving a SP model
h	H	Uses a specialized rolling horizon heuristic to solve practical sized problems that are represented by aggregated model
i	H	Uses the slot-based modeling approach and a decomposition-based algorithm
j	POM	Uses commercial solver (CPLEX)
k	H	Uses multi-start local search approach
* POM = Pure Optimization Method; H = Heuristic		

Evidently, many solution techniques that cater to different types of TRSPs have evolved over the years. Nevertheless, majority of them have limited application potential in tanker business world due to omission of key operating constraints faced by tanker owners. To the best of the authors' knowledge, no tanker routing and scheduling models account for the aforementioned two stowage constraints explicitly and concurrently till the publication of Neo et al. (2006). But the latter fail to offer efficient solution methodology that can meet the practical needs of industry practitioners. For example, it took more than five hours to solve their model for a simple single tanker problem. Clearly, this model alone cannot meet the industry needs since tanker owners usually require a much shorter solution time to address a larger scale problem which involves multiple vessels.

In our effort to bridge this application gap, this paper introduces a novel solution methodology that can (1) efficiently solve TRSP with all key operating constraints, and (2) meet the practical needs of industry practitioners. To illustrate effectiveness of our proposed approach, we apply our new solution approach to solve a realistic TRSP of industrial scale. In addition to highlighting the pros and cons of our tool relative to existing tools, this paper also discuss research opportunities that remain available in this field.

3. PROBLEM STATEMENT

Essentially, the TRSP that we are addressing in this paper is similar as the multi-ship problem described in Jetlund and Karimi (2004) and underlying assumptions in both problems are also similar. The key difference in these two problems lies in the account of cargo-tank and cargo-cargo restrictions which are omitted in the model formulation of Jetlund and Karimi (2004). In our effort to make this paper complete and self-explanatory, we describe our TSRP and its assumptions as follows.

We consider a fleet of *S* tankers ($s = 1,2,\ldots,S$) where the following information is known for each tanker *s* at the start of planning horizon: (1) its current location, (2) the set $\mathbf{L_s}$ (loaded) of cargos on board the tanker *s*, (3) cargo stowage plan of these loaded cargoes, (4) the route (i.e. sequence of port visit) and schedule of *s*, and (5) the cargo *j* ($j \in \mathbf{L_s}$) to be unloaded at each port, (6) its total volumetric and weight carrying capacities, (7) its total number of cargo tanks and capacity of each of these tanks. In addition, there is also a set **U** (unloaded) of potential cargos that is available for pick up by any tanker in the fleet. Critical information pertinent to each of these potential cargos *j* ($j \in \mathbf{U}$) are available and they include its pickup port, discharge port, and size in volume and weight. There is also a time window of pickup for each of these potential cargos *j* ($j \in \mathbf{U}$) which is denoted as (EPT_j, LPT_j), where EPT_j is the earliest pickup time and LPT_j the latest pickup time. In the planning horizon which is 4 week long or so, a tanker *s* may serve some or all of the set **U** of potential cargos in addition to those in $\mathbf{L_s}$. **U** also includes the transshipment cargos with assigned time windows for pickup by small ships. A tanker *s* can possibly visit *P* ports ($i = 1, 2, \ldots, P$) which consist of all the pickup and discharge ports of cargoes in $\mathbf{L_s}$ and discharge ports of cargoes in **U**. Whenever a tanker s visits a port *i*, it pays a fixed port charge of PC_{is} which depends mainly on the size/capacity (dwt) of s and the number of berths that it visits. Typically, a ship anchors after arrival at a port and waits for a free berth to load and/or discharge cargos. Before it can berth and before it can leave a port, it must go through inspections. We assume a fixed total inspection time, T_{adm} at any port for all the tankers.

The objective of our TRSP is to maximize the expected total profit of the tanker company over the planning horizon by (1) selecting the cargos that the fleet should serve subject to all relevant constraints, and (2) deriving the cargo stowage plan as well as the route and schedule of every tanker in the fleet. The total profit is revenue arising from the service of cargos minus the port costs, time charter cost, tank changeover costs and fuel costs of all tankers. We also make the following assumptions to simplify the problem or to estimate some parameters:

(1) Each tanker capacity is constrained only by its total volume or deadweight in tonnes.
(2) Every tanker belongs to a certain class based on its deadweight capacity. We estimate port cost as the average cost of approaching a port for the ships of the respective class.
(3) Speeds of each tanker *s* in ballast and laden voyages are constant at v_s^B and v_s^L nautical mile per hour (nm/h) respectively.
(4) There are four main fuel oil consumption rates to consider for each tanker *s* and they are linear functions of time spent at sea, time spent at port during cargo loading, time spent at port due to cargo unloading, time spent on tank cleaning respectively. At ports where there are both cargo loading and unloading activities, the fuel consumption rate is assumed to be average of the consumption rates at port during cargo loading and loading.
(5) Loading and discharge times are given by the total cargo volume or weight transferred divided by the relevant pump rates. The resulting service time is a conservative measure, as a carrier sometimes would be able to load and/or discharge multiple cargos at the same time. In other words, we do not model the actual port operations in detail. This is also reasonable for a planning model and also because as a ship may spend as much as 40% of its total time waiting at ports rather than in actual port operations.
(6) Inspection time before berthing and that before leaving the port are both $0.5T_{adm}$ for every tanker.
(7) Once a tanker loads a cargo, it must deliver that cargo. It cannot transship that cargo to another vessel.
(8) Cargo deliveries have no due-dates.
(9) Any vessel instability that arises due to cargo stowage can be adequately rectified by filling the ballast tanks to their respective appropriate levels.

To this end, it is important to highlight three key features of our TRSP which not only distinguish it from other problems but also make it more computationally challenging to solve. First, our problem accounts for different voyage speeds for each tanker based on whether the latter is in laden or ballast voyage. This reflects more realistically of the industry practice where the ballast speed is usually higher than the laden speed (i.e. $v_s^B > v_s^L$). Second, our TRSP also represents the fuel consumption of vessels more realistically by having consumption rates which differ according the vessel activities. In contrast, all existing TRSPs in literature do not have such detailed representation of fuel consumption rates. A more realistic representation of the fuel consumption is clearly crucial in the current business environment where bunker fuel constitutes 40-90% of a vessel daily operating costs and fuel prices have risen by almost 300% over the last three years. Third, our TRSP does not restrict the number of visits by each tanker to any port over a given planning horizon. In the TRSPs of Jetlund and Karimi (2004) and Neo et al. (2006), the authors limit the number of visit to any port by a vessel to a maximum of one.

4. NOVEL SOLUTION FRAMEWORK

Due to confidentiality reasons, we cannot disclose the technical details of our new solution framework to any external party. As such, we will not present or describe any details of the algorithmic steps involved in our solution framework in this paper. Instead, we only highlight the key features of our new novel solution approach which allow it to solve TRSPs of industrial scale efficiently and meet the practical needs of industry practitioners.

Essentially, our new methodology entails an implicit enumeration algorithm that aims to generate good cargo-tanker combinations, and their corresponding routes and schedules, feasible cargo stowage plans. It also involves one final step of solving a set-partitioning model who aims determine the best (in terms of overall profit) cargo-tanker combinations, and the corresponding cargo stowage plan, route and schedule of each tanker of each tanker. The novelty of our new solution approach stems primarily from the ability of a heuristic to determine a good cargo stowage plan, a good route of and schedule of a tanker by enumerating only a fraction of all possible permutations.

Through our experimental studies that were based on industrially realistic data, we are able to demonstrate that the aforementioned heuristic can (1) derive optimal route and schedule of a tanker in more than 98% of randomly generated problems, and (2) derive a feasible cargo stowage plan that satisfies the cargo-cargo, cargo-tank restrictions and meets the business needs of tanker owners. More importantly, this heuristic is also able to arrive at a solution to a given TRSP using minimal time which is in terms of seconds on a desktop PC.

Leveraging on the heuristic's ability to determine good route and scheduling, cargo stowage plan of a tanker efficiently, we strategically employ it in our new solution framework to iteratively generate good cargo-tanker combinations with the corresponding stowage plans, routes and schedules of tankers. With this set of cargo-tanker combinations and their respective stowage plans, routes and schedules of tankers, our solution framework will then proceed to solve a set partitioning (SP) model which has the objective of maximizing the total profit of the fleet of tankers over the given planning horizon. Essentially, the SP model has two constraints. One ensures that each of the pending cargos ($j \in \boldsymbol{U}$) can only be assigned to at most one tanker while the other ensures that each tanker s is assigned to only one route and schedule.

5. CASE STUDY

To illustrate effectiveness of our proposed approach, we apply our new solution approach to solve a realistic TRSP of industrial scale. Basically, the problem is similar to the one described in Jetlund and Karimi (2004) where it consists of 10 tankers (5,800-11,000dwt, 10-12 cargo tanks), 42 pending cargos to be picked up by tankers, 37 onboard cargos at time zero and 42 ports. However, our TRSP is more complex primarily due to two main reasons. First, it includes cargo stowage decisions with account of cargo-cargo and cargo-tank restrictions. Second, our TRSP accounts for tank cleaning time requirements which are dependent on the order of cargo changeovers. In contrast, the TRSP in Jetlund and Karimi (2004) does not include these decisions, restrictions and requirements. As such, we randomly generate additional data to account for cargo-cargo and cargo-tank restrictions, as well as tank cleaning time requirements. Due to the sheer size of this extra data set, we are unable to present them all fully in tabular formats. The readers may obtain the full data for this problem by contacting the corresponding author.

We code our new solution methodology in Visual C++ and then use it solve the aforementioned problem. We ran our program on a Windows XP desktop PC with Pentium 4 (2.4 GHz) processor and 256MB RAM. In less than 20 minutes, the program is able to determine the cargo-tanker combinations, cargo stowage plans, routes and schedules of all tankers which offer good total profit to the tanker company over the given planning horizon. Table 3 presents the solution overview which includes the number of route/schedule/stowage (r/s/s) plans generated, profit of r/s/s plan selected by solving the aforementioned SP model, onboard cargos (at time zero) and new cargos (based on selected r/s/s plan) of every tanker in the problem. Figure 2 also shows the routes and schedules of all tankers in the problem based on the solution derived by our new solution methodology. For illustration purpose, we also present the cargo stowage plan of tanker S1 based on its selected r/s/s in Table 4. For example, cargo C6 (which is loaded and unloaded by S1 during its fourth and tenth port of visit) is stowed in tank T11 and T12 in parcels of $851.4 m^3$ and $859.1 m^3$ respectively.

From the above discussion, it is clear that our new solution methodology offers a practical and efficient approach to address TRSP in two major ways. First, the proposed approach does not require advanced computing hardware to execute the underlying algorithmic procedure. Moreover, it requires minimal time to determine a good and feasible solution which satisfies all key operational constraints faced by tanker operators.

Table 3: Solution Overview of Case Study

Tanker ID	Number of r/s/s generated	Profit of selected r/s/s ($)	Onboard cargos (time zero)	New cargos
S1	267	93,222.7	C43,C44,C45,C46, C47,C48,C49,C50, C51,C52	C6,C10,C30,C31,C33,C34,C35
S2	97	102,053.0	C53,C54,C55	C36
S3	122	61,985.9	C56	-
S4	169	120,203.0	C57	C1,C2,C4,C17
S5	12	44,986.8	C58,C59,C60,C61	C41
S6	83	70,770.6	C62	-
S7	107	103,308.0	C63,C64,C65,C66, C67	-
S8	61	-40,892.0	-	-
S9	71	163,033.0	C68,C69,C70,C71, C72,C73,C74	C12,C12,C13, C14
S10	115	108,997.0	C75,C76,C77,C78, C79	-
	Total	827,668.0		

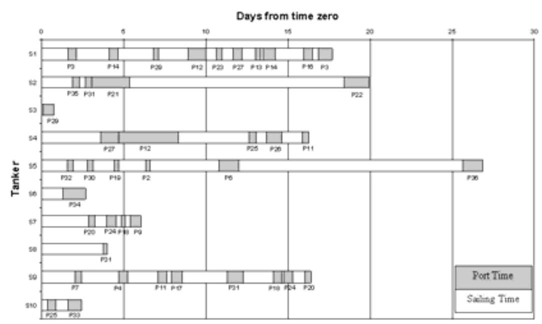

Figure 2: Routes and Schedules of Tankers

Table 4: Cargo Stowage Plan of Tanker S1 in Case Study

Tank ID	Cargo																
	C6	C10	C30	C31	C33	C34	C35	C43	C44	C45	C46	C47	C48	C49	C50	C51	C52
T1	0.0	0.0	0.0	0.0	0.0	480.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	316.9	0.0	0.0
T2	0.0	0.0	0.0	0.0	0.0	0.0	119.2	0.0	0.0	0.0	0.0	0.0	251.2	0.0	0.0	0.0	0.0
T3	0.0	0.0	578.0	0.0	0.0	0.0	0.0	191.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	176.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T5	0.0	0.0	0.0	668.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	137.2
T6	0.0	527.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	122.8	0.0	0.0	0.0	0.0	0.0	0.0
T7	0.0	0.0	0.0	0.0	253.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	119.0	0.0
T8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.1	0.0	0.0	0.0
T9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
T11	851.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	985.5	0.0	0.0	0.0	0.0	0.0
T12	859.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	201.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PN*	4	4	4	4	6	8	8	0	0	0	0	0	0	0	0	0	0
DN*	10	5	9	9	7	10	10	1	1	1	1	2	6	6	6	3	3

* PN and DN denote the pickup and discharge port number of a cargo respectively. They represent the order of the port in a port visit sequence where the cargo is loaded and unloaded respectively. Cargos which are onboard at time zero will have pickup port number equal to zero.

6. CONCLUSION

This paper makes some primal and significant contributions towards research on tanker routing and scheduling primarily via the introduction of a novel solution framework that can address TRSP of industrial scale and with account of key operational constraints faced by tanker owners. These constraints include those pertinent to cargo pickup time windows, cargo stowage conditions and tank cleaning requirements. It is also important to highlight the proposed algorithmic procedure can be conveniently modified for evaluation purposes or to accommodate to preferences of tanker owners. For example, tanker owners may want to evaluate the impact of assigning specific cargos ($j \in \mathbf{U}$) to specific tankers on their bottom-lines. Or they may have preferences on the available tonnage supply at specific regions at specific time intervals of the future so that their tanker companies will be in a better position to capitalize on the potential spot chartering opportunities that have been identified. In both such incidents, the need or preference of the decision-makers can be easily accommodated with only minor modifications of few algorithmic steps in our proposed solution methodology. To the best of the authors' knowledge, a solution methodology with all the abovementioned features for routing and scheduling of tankers does not exist in the literature.

Nevertheless, improvement opportunity remains available in this field, particularly in the area of solution methodology development. Clearly, there are other extensions of the TRSP addressed in this paper which are relevant to the tanker industry and which need to be addressed. Some of these industrially relevant problem extensions include (1) addition of bunking decisions, (2) encompassing ballast water allocation decisions to manage ship stability, and (3) treatment of vessel speeds as decision variables, which are based on laden weight of a voyage to manage fuel consumption. Inevitably, these extensions complicate the problem drastically and require the development of new solution approaches which may differ from our proposed solution framework. However, these extensions do offer exciting research opportunities which can significantly enhance decision-making processes of tanker companies in their tasks of routing of scheduling of tankers.

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