Management of Supplies and Movements of Tank Containers in Chemical Logistics

*I.A.Karimi[1], M. Sharafali[2], H. Mahalingam[3], Arul Sundaramoorthy[3] (**Speaker**)*
[1]Department of Chemical and Biomolecular Engineering
National University of Singapore, Singapore 117576

[2]Department of Management
University of Melbourne, Parkville, Australia, VIC 3010

[3]The Logistics Institute-Asia Pacific
National University of Singapore, Singapore 119260

Abstract

Effective logistics is the key to improving supply chain performance. Tank containers are attractive from the viewpoints of safety, cost, and environment, and are widely used for transporting fluid chemicals. Minimizing the logistics costs arising from the container flow imbalances across the globe and container cleaning is a major issue that chemical companies and affiliated third-party logistics firms face routinely. In contrast to dry containers, this important problem of managing tank containers in global chemical logistics has received no attention. In this paper, we present an innovative, event-based, "pull" approach for the minimum-cost or the maximum-profit scheduling of the transport and cleaning of multi-product tank containers (loaded and empty) given a set of projected shipment orders. We develop and illustrate through examples a novel linear programming formulation that successfully solves large, industrially relevant problems.

INTRODUCTION

Logistics is the glue that binds the entities of a supply chain. More and more businesses have now realized that its effectiveness is critical to the superior performance of the supply chain. For instance, the move towards just in time and agile manufacturing has tremendously increased the impact of the logistics decisions. This is especially true for the chemical industry with its globally distributed plant sites, storage terminals, suppliers, customers, etc. The global transport of chemicals and a variety of other materials (e.g. plant equipment, instrumentation, indirect materials, safety equipment, etc.) is central to its day-to-day operations. Logistics costs (Karimi et al., 2002) can vary from 3.6% of the purchase price for a best-in-class (BIC) site to 20% at the other extreme.

The transport of chemicals by pipelines is ideal. However, this is not always possible. Chemical logistics requires a mix of means such as trucks, trains, ships, barges, tankers, etc. Sea transport is the key to global chemical logistics. Bulk shipping of chemicals occurs in huge volumes, and involves very large crude carriers (VLCCs) and a variety of multi-parcel chemical tankers. The former routinely transport crude oils worldwide (Reddy et al., 2004), while the latter transport clean petrochemical products (CPP) and other chemicals such as vegetable oils (Jetlund and Karimi, 2004). However, there is another equally important segment of chemical logistics, called container shipping.

Containerization refers to the method of distributing materials in a unitized form, namely a container that allows inter-modal or multi-modal transport (one that uses a mix of road, rail, sea, or inland waterways). The most common "dry" containers are 20×8.5×8 feet (called as twenty feet equivalent unit or TEU) and 40×8.5×8 feet (forty feet equivalent units or FEU) boxes. These containers can be seamlessly loaded onto ships, trucks, or rail using appropriate handling machinery. Dry containers carry all kinds of goods including certain solid chemicals, but liquid or gaseous chemicals require special containers, called tank containers. A tank container is simply a cylindrical tank set inside a frame of the standard dry container so that the machinery used for the dry containers can also handle the entire apparatus. This allows the tank containers to be stacked one atop another on ships, loaded on trucks, rail, etc. A tank container offers several advantages over the conventional modes of shipping chemicals such as drums:

1. It is environment-friendly, because it minimizes the spillage during filling/unloading and leakage during transport. It permits the transport of dangerous chemicals in a safe manner
2. It is more cost-effective, because it permits a higher payload as compared to drums stowed in conventional dry containers (43% more volume). Its modular construction, ease of portability, and mechanized modes of handling all contribute to the cost savings.
3. It allows multi-modal transport.
4. It is reliable, secure, and designed to last for 20~30 years.
5. It is cleanable, reusable, and can be placed into alternate commodity service with minimum downtime.
6. Customers who have limited space or wish to avoid the high cost of permanent storage can use it for temporary storage.
7. It can be used for the transport of food-grade items.

A major challenge that the companies using tank containers face arises due to the imbalance of product supply and demand, and hence an imbalance in the container flows across different regions. There exist major flows of loaded containers from the production centers towards the various demand centers globally. However, equivalent flows of products from the demand centers, which can enable the return of the emptied containers to the production centers, often do not exist. As a result, empty containers accumulate at the demand centers, which must be "repositioned" to the production centers. For instance, a company in the Asia-Pacific region ships loaded containers predominantly to western destinations, resulting in an accumulation of the empty containers in the U.S. and other European destinations. Unless the company brings back these empty containers to the Asia-Pacific region, it may not have enough empty containers for reuse. This incurs cost, as ships do not carry empty containers free. The estimated cost of repositioning an empty container can vary from US$400 to US$800 per container. Some freight forwarders actually impose a surcharge (usually around US$300) for the empty container over and above the freight transport charge of the loaded one. The problem is further exacerbated by the need to clean the tank containers before reuse with the cleaning depots located away from the production centers, and the varied and stringent transport requirements of different chemicals. Similar imbalances of container flows exist even among different U.S. regions. Clearly, a systematic study and optimization of multi-product tank container movements and related activities such as cleaning are crucial for reducing chemical logistics costs. Ensuring timely supplies of empty containers to production sites, shipping of loaded containers, cleaning and storage of emptied containers, and repositioning of empty containers to suitable places in anticipation of product orders must be done optimally to minimize the total logistics costs. This paper takes a comprehensive look at this important problem of tank container management.

In this paper, we address the container management problem from the perspectives of three companies:

(a) A chemical company that owns, or leases on a long-term basis, tank containers and manages them for its logistics needs.

(b) A third-party logistics (3PL) or fourth-party logistics (4PL) firm (e.g. Cendian) that either owns or leases containers, and manages them for its client chemical companies. Some chemical companies do not consider the packaging and transportation of chemical products as their core competencies, and are reluctant to invest in facilities and manpower. They prefer to outsource to 3PL and 4PL firms who manage their logistics activities.

(c) A container company (e.g. Stolt-Nielson) that owns containers, and undertakes the responsibility to deliver the chemical cargo as specified by its customers (chemical companies). In many cases, it also provides tank containers for chemical storage to various clients based on spot or contract requests.

We use the term "container operator" or simply operator to describe all of the above companies. Although our primary interest is in the tank containers used in shipping chemicals, the methodology presented here applies even to the containers used in shipping general dry cargos. This is why we use the terms container and tank container interchangeably.

A typical container movement starts with the receipt of an order by the operator from a chemical plant site (the origin site) for a required number of empty containers to deliver the chemicals by some delivery date at a destination site. The operator then has to decide from where to source the empty containers, when and how to deliver them to the origin site where they are loaded with the chemical cargo, when and how to transport the loaded containers to the destination site where they are unloaded, and where to clean and reposition the emptied containers. The repositioning may involve bringing the emptied containers back to where they started, diverting them to nearby areas that need them, or storing them at appropriate depots that can clean them and supply them to other sites in future.

PROBLEM DESCRIPTION

For the global container movements, we assume that the transportation network consists of depots, seaports (or simply ports), and sites. A site is a facility that receives empty (loaded) containers, and loads (unloads) them. It can be a manufacturing, supplier, 3PL, loading, retail, distribution, or customer facility. A depot is a facility that receives empty containers from other depots or sites, cleans and stores them, and then sends them to sites or other depots as and when needed. A freight forwarder usually picks the loaded (empty) containers from a site (depot) and ships them to another site (depot). A site may or may not hold empty containers for a limited time. A site-to-site container movement in general involves three transportation legs. Normally, a land-based leg takes the containers from an origin site to an origin seaport, then a sea-based leg takes them to a destination seaport, and lastly another land-based leg takes them to a destination site. Of course, the same may also apply to a site-to-depot or depot-to-depot movement of an empty container.

Let D be the number of depots ($d = 1, 2, \ldots, D$) and S be the number of sites ($s = 1, 2, \ldots, S$). We assume that the operator knows the current state of the system at time zero. In other words, it knows the empty-container inventories at various depots and sites, and the containers (loaded or empty) that are in transit and their target destinations. At present, the operator has O known, consolidated orders ($o = 1, 2, \ldots, O$) for empty containers from various sites. Each order o has four attributes:

i. Origin site (m): the site that has placed the order for empty containers and will load them after receiving
ii. Destination site (n): the site that will receive the loaded containers
iii. Order quantity (NC_o): the number of containers that site m has requested in order o.
iv. Due date (DD_o): the time at which the loaded containers must reach site n

By a consolidated order, we mean that multiple orders with identical *m, n* and DD_o are lumped into a single bigger order. The operator (or the company that owns the containers) aims to devise a detailed schedule of container movements that minimize the total operating cost. This involves:

1. Assigning the depots or sites from which to send empty containers to the origin site for each order, fixing the numbers of such containers, and setting the times at which they should leave.
2. Setting the number of containers that the operator should spot-lease for each order, if it is unable to fill the order with its own containers.
3. Selecting the depots or sites that should receive the containers released by the destination site for each order, fixing the numbers of such containers, and setting the times at which they should reach.
4. Computing the minimum cost of container movements required to fill all the O orders.

SOLUTION METHODOLOGY

As in most scheduling problems, time representation is the key. In this work, we use a novel event-based representation that treats time as continuous. Batch process scheduling literature has used continuous-time representation in several forms. These include variable-length slots with (Lim and Karimi, 2003) and without (Ku and Karimi, 1988) fixed events, and variable events without slots (Gupta and Karimi, 2003). In contrast to the many scheduling problems in which it is impossible to fix the possible event times *a priori*, the present problem is unique in that it permits, with the aforementioned assumptions and simplifications, a continuous-time representation in which we can fix all possible event times *a priori*.

Our methodology comprises two phases. In the first phase, we generate a chronologically ordered super list of possible instances at which container (empty or loaded) movements (events) may occur. We also identify the types of movements that may occur at each such instance. In the second phase, we use these super lists of times and events to develop a linear programming (LP) formulation whose solution will pick the events that minimize the schedule cost.

NOVEL LP FORMULATION

As a prerequisite to our formulation, we process the events and event times as follows. We discard all the events with negative event times, and their associated event times. We then sort all the event times in the chronological order, and remove the duplicate entries. This gives us a strictly increasing super list of event times at which the various events may occur. We use t_0 (= 0) < t_1 < … < t_{k-1} < t_k < t_{k+1} < … < t_K to denote this ordered super list of event times. Next, we identify all the events that may possibly occur at each t_k ($k \geq 0$) in the list. For each such event, we assign a specific variable (x, y, u, v, and w) to denote the number of containers involved in the event as follows:

x_{dmjk} ($j \leq k$): the number of empty containers leaving depot d at t_j to reach site m at t_k
y_{nejk} ($j \leq k$): the number of empty containers leaving site n at t_j to reach depot e at t_k
u_{smjk} ($j \leq k$): the number of empty containers leaving site s at t_j to reach site m at t_k
v_{mnjk} ($j \leq k$): the number of loaded containers leaving site m at t_j to reach site n at t_k
w_{mnjk} ($j \leq k$): the number of leased (from the spot market) containers in v_{mnjk}

In the above, x, y, and u involve the operator-owned containers only. Since each order o has unique sites m and n, a known container requirement NC_o, and known times $t1 = DD_o$ and $t2$, we get v_{mnjk} ($j \leq k$) = NC_o for ($t_j = t2$, $t_k = t1$) and zero otherwise. Thus, all v_{mnjk} ($j \leq k$) are known and not variables in this basic formulation. Lastly, we use DI_{dk} to denote the number of empty containers at time t_k in depot d and SI_{sk} to denote the same at site s.

Because the x-variables represent the empty containers leaving a depot d, and the y-variables represent those entering d, a container balance for a depot d at t_k yields,

$$DI_{dk} = DI_{d(k-1)} + \sum_{s}\sum_{j\le k} y_{sdjk} - \sum_{s}\sum_{j\ge k} x_{dskj} \tag{1}$$

with a capacity restriction, $DI_{dk} \le DI_d^U$.

In contrast to a depot, a site can also send/receive containers to/from the depots, sites or spot market. Therefore, the following container balance at a site s involves all the variables:

$$\begin{aligned} SI_{sk} = SI_{s(k-1)} &+ \sum_{d}\sum_{j\le k} x_{dsjk} + \sum_{n\ne s}\sum_{j\le k} u_{nsjk} + \sum_{m\ne s}\sum_{j\le k}(v_{msjk} - w_{msjk}) \\ &- \sum_{d}\sum_{j\ge k} y_{sdkj} - \sum_{m\ne s}\sum_{j\ge k} u_{smkj} - \sum_{n\ne s}\sum_{j\ge k}(v_{snkj} - w_{snkj}) \end{aligned} \tag{2}$$

with a capacity restriction, $SI_{sk} \le SI_s^U$.

Since the number of containers spot-leased for a given order cannot exceed the total number of containers in that order, we have the upper bound, $w_{mnjk} \le v_{mnjk}$, $j \le k$. Eq. 2 essentially ensures that the spot-leased containers never enter the inventory at any site. These containers simply appear at the origin site for loading and disappear from the destination site after unloading. Thus, they cannot remain in the system for future use.

Towards the end of the scheduling horizon, an emptied container may stay put at its destination site in order to avoid the cost of moving back to a depot. To prevent this behavior, we require that all containers eventually return to the depots. Therefore,

$$\sum_{d} DI_{d0} = \sum_{d} DI_{dK} \tag{3}$$

Finally, the scheduling objective is to minimize the total cost of managing the containers, which is given by:

$$\begin{aligned} C = &\sum_{d}\sum_{s}\sum_{k}\sum_{j\ge k} x_{dskj}XC_{dskj} + \sum_{s}\sum_{d}\sum_{k}\sum_{j\ge k} y_{sdkj}YC_{sdkj} + \sum_{s}\sum_{n\ne s}\sum_{k}\sum_{j\ge k} u_{snkj}UC_{snkj} + \\ &\sum_{m}\sum_{n\ne m}\sum_{k}\sum_{j\ge k} v_{mnkj}VC_{mnkj} + \sum_{m}\sum_{n\ne m}\sum_{k}\sum_{j\ge k} w_{mnkj}WC_{mnkj} + \sum_{s}\sum_{k<K} h_s SI_{sk}(t_{k+1} - t_k) \end{aligned} \tag{4}$$

where, WC_{mnkj} is the total cost (the lease cost plus the cost of transporting back if needed) for leasing one empty container from the spot market at site m and time t_k, XC_{dskj} is the cost of sending one empty container from depot d at time t_k to reach site s at time t_j, YC_{sdkj} is the cost of sending one empty container from site s at time t_k to reach depot d at time t_j, UC_{snkj} is the cost of sending one empty container from site s at time t_k to reach site n at time t_j, and h_s is the cost of holding one empty container at site s for a unit time. Note that the transportation costs for the empty and loaded containers are different. Even though the cost of moving the loaded containers is fixed, eq. (4) includes it for the sake of consistency. In fact, as discussed later, it becomes essential to include that cost for some extensions.

Eqs. (1)–(4) comprise our novel LP formulation. Note that most variables included in the formulation are zero, because only the variables that correspond to possible events exist. Thus, even though we have used sums over all possible time indexes, not all variables will exist in the formulation. As long as the data for container demands are integers, all variables will assume integer values in the optimal solution. Note that we did not assume any pre-specified scheduling horizon. The last possible event fixes the scheduling horizon in our approach. In this way, the horizon allows all containers to return to the depots.

A glance at the constraints of our LP reveals that the coefficients of the variables are 1, 0, or –1, and hence the coefficient matrix is fully unimodular. Then, from the proof of Bazaara and Jarvis (1977), the integrality of an optimal solution to the above LP is guaranteed.

EXAMPLE

To demonstrate the use of our model on a large problem, we selected arbitrary locations in China, and generated data using their latitude and longitude information. We randomly created 50 depots, 65 sites, and 500 orders to model a real scenario. We used the standard "Great Circle" formula [22] and the relevant data from [10] to compute the distances between location pairs. Then, we used a basic transport cost (US$/km) and speed (km/h) to compute the transport times (h) and costs (US$) for all location pairs. However, we assumed a minimum transport time of six hours, zero initial inventories at the sites, and a mark up for the transportation cost of loaded containers. In this example, the transport costs for loaded containers varied from $100 to around $2000. Finally, we generated the orders, their four attributes (origin site, destination site, number of containers, and due date), and initial inventories at the depots randomly.

We used a FORTRAN program to generate the various events and times, the associated cost information, and the input files for GAMS 20.7. This example has a scheduling period of 824 h (34 days). Its LP involved 176,359 variables, 93,267 constraints, and 487,230 nonzeros. Its solution took 8538 iterations and 40.11 s of CPU time using CPLEX 7.5 on a Dell workstation with dual Intel Xeon 2.8 GHz processors and 2 GB RAM. The presolve step of CPLEX 7.5 reduced the original LP drastically by eliminating 11397 constraints and 15677 variables, and making 60262 substitutions. The reduced LP had 21608 constraints, 100420 variables, and 200774 nonzeros, which represents reductions of roughly 77%, 43%, and 59% in constraints, variables, and nonzeros respectively. The optimal cost for all container movements was $7,440,912 (~$7.5 million).

Note that the 8245 containers moving over a month in this example are representative of the scale of operation of a typical big container company that moves about 100,000 containers per year or 8300 per month. We observe that the depots alone satisfy 260 orders (~50%), while the sites satisfy 126 orders (~25%). The operator needs to lease only a few (202 or ~2.5%) containers from the spot market. The depots and sites combine to satisfy most of the remaining orders.

Container utilization is a key concern in container management. One metric for this is the average time-utilization of a container, which is the percent time that a container spends on an average not idling in the inventories of depots or sites. Mathematically, we can write this as,

$$\rho = \lim_{T \to \infty} \frac{1}{NT} \sum_{i=1}^{N} \int_0^T Z_i(u)\,du$$

where, N is the number of containers in the system, T is the total operation time, and $Z_i(t) = 1$, if a container i is in use at time t, and zero otherwise. For this example with a finite time horizon, the above expression reduces to,

$$\rho = 1 - \frac{\sum_{k=0}^{K-1} \left[(t_{k+1} - t_k) \left(\sum_d DI_{dk} + \sum_s SI_{sk} \right) \right]}{t_K \sum_d DI_{d0}}$$

The above gives us ρ = 0.25 (or 25%) for this example. The actual utilization will be slightly higher, because the containers do not have orders in this example towards the end of the scheduling horizon and they are simply waiting at the depots. In a dynamic situation, new orders will arrive to use them continuously during subsequent scheduling runs.

Since the orders demand 8245 containers and the operator leases only 202 containers from the spot market, the optimizer fulfills most orders by using and reusing the operator-owned 1260 containers. In other words, as we would expect, the optimizer uses a container more than once during the scheduling horizon. We define container turn as the number of times a container is used during the horizon. We can compute this metric of container utilization as,

$$\tau = \frac{\text{Containers ordered} - \text{Containers spot-leased}}{\text{Containers in the system}}$$

Note that we subtract the spot-leased containers in the above, as the system uses a spot-lease container only once. For this example, $\tau \approx 6$. In other words, each container owned by the operator turns (up for work!) roughly (8245-202)/1260 or six times during the scheduling horizon. The higher the container turn, more effective the use of the containers, but it is clear that this metric increases with the scheduling horizon. Therefore, a better metric would be the one that is normalized with respect to time, i.e. container turn per unit time. We can compute this as τ / t_K. For this example, this is approximately 0.2 /day or one turn every five days. One could also define other metrics such as cost per container or profit per container.

CONCLUSION

We have presented an important problem of tank container management in global chemical logistics, which has received little attention in the literature. The two-step, event-based, demand-driven, deterministic methodology presented in this paper is novel and simple. The ability to handle order-specific and time-dependent information is a major advantage of our approach. Because it involves an LP whose size reduces massively during the preprocessing step of a commercial LP algorithm such as CPLEX, it helps solve the large, industrial-scale problems swiftly. This is extremely important, because in most cases, it is impossible to predict all future shipment orders precisely. Changes, additions, cancellations, etc. in orders and data always occur, and the user must generate schedules repeatedly using the updated information in an extremely dynamic business environment. For example, it is common for ship schedules to change at short notice. A simple way to address the change in ship schedules is to re-solve the entire problem incorporating the new ship schedule information in the model and taking into account the present status of the empty/loaded container positions. In this case, the formulation will not change, even if some customers cancel their earlier orders. However, the best way to address uncertainties is through stochastic formulations. One approach is stochastic programming that would still keep the formulation a LP, but would require solving a series of LPs. The other popular approach is robust optimization, where the goal is to find a "good" solution that would be robust enough or a solution that would be insensitive to uncertainties in the input parameters. We hope to address this need in a future communication.

Lastly, it is noteworthy that our methodology also applies directly to the management of the widely used dry containers with minor modifications. We believe that the proposed methodology is more compact and uses fewer variables than the existing network modeling approach for managing dry containers. We expect this to result in a computational advantage for our approach. However, we hope to report more on this comparison in a future communication.

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