# MARITIME CHEMICAL LOGISTICS: IMPORTANCE OF OPTIMIZATION MODELING AND RESEARCH OPPORTUNITIES

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**ABSTRACT**
Despite the prevalence of optimization models in academic literature that address a wide variety of maritime transportation planning problems and the significant cost saving opportunities that these models can offer, their applications in maritime chemical logistics remain few and far between. In this paper, we aim to address the overlook of optimization models by industry practitioners in two ways. First, we present several models developed by our group that can address realistic problems in maritime chemical logistics. Second, we identify and describe future research opportunities in this field. On the whole, several opportunities remain available for improving the decision-making processes in maritime chemical logistics via optimization modeling, and for addressing the practical needs of various stakeholders which include port operators, shipping and chemical companies.

Keywords: maritime chemical logistics, optimization models, research,

## 1. INTRODUCTION

Since the industrial revolution in the late 18th and early 19th century, the contribution of chemical industry to global economic growth is increasingly significant. The global chemical trade which hit more than US$1.24 trillion in 2006 has achieved an impressive 14% average annualized growth between 2000 and 2006 (World Trade Organization, 2007). Correspondingly, the demand for maritime transport and logistics for the chemical industry has also increased over the years. Heideloff et al. (2005) stated that the capacity of ships (300 gross tons and over) that primarily support the global chemical industry and comprise oil, chemical, and liquid gas tankers, grew 3% annually between 2001 and 2005 to reach 368.4 million deadweight ton (dwt) at the beginning of 2005. In addition, the world has also been witnessing a flurry of expansion in chemical terminaling and storage facilities that include the bulk liquid terminals as reported by Markarian (2000) to accommodate the rise in the global demand of chemical products and seaborne chemical trade. Recently, Royal Vopak (2008) have decided to continue the Phase 4 capacity expansion project of their Banyan terminal which is expected to be completed in June 2009. The terminal will then have a total capacity of 1,245,000m$^3$. After officially opened a new tank farm of 380,000m$^3$ at the Fujairah terminal in February 2008, Royal Vopak are now evaluating the feasibility of expanding it by another 1,200,000m$^3$ with construction of new jetties that have four to six docking spaces. Evidently, the growth in the fleet of ships and the expansion of port facilities supporting the chemical industry that take place in tandem with the growth of global chemical industry highlight the importance of maritime transport in global chemical logistics.

Efficient and cost-effective management of maritime chemical logistics is clearly crucial to the financial success of global chemical supply chains, since the logistics costs can be as high as 20% or more of purchasing costs (Karimi et al., 2002). Maritime transportation planning problems in general have attracted the interest of academic researchers since the 1950s. Many of existing optimization models in the literature can address a variety of problems in maritime chemical logistics and they include ship routing and scheduling, fleet sizing and allocation, logistics network design, port or terminal operation planning, etc. Nevertheless, their applications in the industry remain limited. This phenomenon could be attributed to two key reasons. First, many of the industry practitioners are not aware of the availability of such optimization models that can support their decision-making processes. Second, there are practitioners who are aware of their availability but are somehow either intimidated by the underlying mathematical complexity of these models or doubtful of their ability to address their planning problems. Though it is true that majority of existing optimization models are mathematically complex, that should not deter industry practitioners from applying them as end-users, especially if extensive experimental studies have proven problem solving ability of these models. Moreover, given the increasingly complex and competitive business environment in maritime chemical logistics, it is important that major stakeholders like port operators, ship owners, and chemical companies learn the science, not just the art, of running their businesses so that critical decisions can be made systematically and objectively. Clearly, one effective means of making systematic and objective decisions can be accomplished via the application of optimization models.

This paper aims to address the underutilization of optimization models in maritime chemical logistics in two ways. First, we describe planning problems in maritime chemical logistics, and introduce optimizations models developed by our group that address these problems. Second, we identify and describe future research opportunities in each of these problems which will improve the application of optimization models in the industry. On the whole, several opportunities remain available for improving the decision-making processes in maritime chemical logistics via optimization modeling, and for addressing the practical needs of various stakeholders which include port operators, shipping and chemical companies

## 2. ACADEMIC RESEARCH

This section aims to offer readers a brief overview of major research works done by our group that use optimization-based models to address six important transportation planning problems in the realm of maritime chemical logistics. We divide our review into six parts and for each part, we (1) introduce the problem background, (2) describe our optimization-based approach to address the problem, and (3) identify opportunities for further research.

### 2.1. Product Pooling Location-Allocation

In practice, producers of liquid chemicals do not share their storage facilities even when their products are similar in terms of quality and storage requirements. These producers usually store their products individually in dedicated storage tanks before they are discharged into chemical tankers for delivery to their respective destination ports. Similarly, these ports are also equipped with storage tanks to receive the cargos from the chemical tankers. The storage tanks at a destination port belong either to an industrial customer who needs the cargos as feedstock for its manufacturing processes or to a third party logistics (3PL) company which manages the storage activities of cargos on behalf of its industrial clients. Even when the storage tanks are owned by 3PL companies, each of them will be dedicated to only one client and not be shared among different clients.

With collaborative logistics being a buzzword in the business world today, the current storage arrangement of liquid chemicals described above has ample room for improvement. Clearly, producers of liquid chemicals with same commercial grades can harness significant cost savings if they share the storage facilities of their products before they are distributed to their respective customers via short and frequent milk runs. This is both technically and financially feasible, especially when (1) these chemicals are manufactured using mature and stable production technologies and (2) their storage requirements are similar, and (3) customers of these producers are in the same vicinity. Such arrangement of pooling chemicals from multiple producers at shared storage facilities prior to their delivery to their respective customers is an excellent example of collaborative logistics. By collaborating with each other in the storage and transportation of chemicals, chemical companies can achieve the economies of scale in storage and distribution costs that cannot be attained individually.

To help potential pooling companies make strategic logistics design decisions for product pooling arrangement, Tong (2003) and Tong et al. (2006) developed a solution strategy which entails a multi-period mixed-integer linear programming (MILP) model and a heuristic. The model serves to determine the optimal product pooling locations, and capacities of terminals while the heuristic generates routes of milk runs that serve the suppliers and customers. The authors also applied their solution approach on a realistic problem of industrial scale which entails determination of methanol pooling location in the Asia Pacific region.

Several extensions of this problem are possible, which would address some practical features. Specifically, one needs to consider multiple products and transport via parcel tankers. This will require a faster and integrated methodology to address routing and location problems. Finally, uncertainty always exists in business data such as demand and freight rates, and models are needed for addressing these.

### 2.2. Routing and Scheduling of Chemical Tankers

World-scale chemical processing facilities in major production centers in the US, Europe and Middle East export a wide range of chemical and petrochemical products to downstream manufacturers worldwide. Earnings of major operators engaged in shipping of bulk liquid chemicals are mainly derived from this deep-sea trade, where fleets of multi-compartment chemical tankers shuttle between major production ports and manufacturers worldwide.

Ships are capital-intensive and their operating cost can run in ten thousands of dollars a day per ship. Whether it is a chemical company that owns and manages a fleet of ships, or a shipping company that manages the fleet and is hired by a chemical company via a third 3PL provider, the ultimate cost of logistics directly affects the cost effectiveness of global chemical supply chains. Efficient routing and scheduling of multi-parcel chemical tankers is therefore a key challenge for both chemical and shipping industries. An optimal assignment of cargos and schedules to a fleet of carriers is a complex combinatorial problem. Nevertheless, many shipping companies still route and schedule their ships manually. Hence, the potential for improving the scheduling process in maritime transportation is considerable. Computer-based decision support systems (DSS) with optimization routines can be valuable to fleet operators in achieving efficient fleet operation, which would eventually benefit the global chemical industry.

To improve the decision-making processes in management of parcel tankers, Jetlund and Karimi (2004) used the slot-based modeling approach (Karimi and McDonald, 1997) to develop a profit maximization MILP model for routing and scheduling parcel tankers engaged in the shipping of bulk liquid chemicals with cargo pickup time-windows. They proposed a heuristic decomposition algorithm that obtains the fleet schedule by repeatedly solving the base formulation for a single ship. Their solution approach is generally applicable to all kinds of carriers engaged in the transportation of multiple commodities, and to transportation systems where frequent schedule updates or a short-term planning horizon is required.

To the best of the authors' knowledge, none of the existing models that address routing and scheduling of chemical tankers account for the operational constraints pertinent ship stability and cargo stowage till the recent publication of our work. Neo et al. (2006) introduced a new routing and scheduling model that accounts explicitly the unique operational limitations of chemical tankers. Essentially their new model which is an extension of single-ship model of Jetlund and Karimi (2004) involves deciding which ports should the ship visit and in which sequence, which cargoes it should pickup and unload, and when, which tanks should each cargo be assigned and when over the entire trip so as to maximize the profit for the ship.

Though many of the existing ship routing and scheduling models have been developed for maritime chemical logistics, they possess some shortcomings that adversely affect their application in the industry. First, no existing ship routing and scheduling model comprehensively accounts for all key operating constraints. Practically all existing models account for only some of these constraints and ignore the rest. As such, this limits their application potential in maritime chemical logistics. Second, none of the existing models account for uncertainty in parameters. One reason could be that even the deterministic forms for these models are NP hard problems. However, shipping companies must routinely contend with a wide variety of uncertainties due to weather-induced voyage delays and mechanical problems of vessels, and accounting for these uncertainties is definitely crucial from an industrial standpoint. Thus, a stochastic model with a reasonably practical algorithm, which comprehensively addresses uncertainties will be of significant practical value to most shipping companies. Finally, cargo compatibility and ship stability are also important considerations in maritime chemical logistics and have not been addressed satisfactorily by the existing models.

### 2.3. Scheduling Trans-shipment Operations in Maritime Chemical Transportation

Shipment of chemical cargos can be broadly classified into two main types, namely deep-sea and short-sea shipping. Deep-sea shipping entails transportation of cargos between continents in deep seawater, where large multi-compartment tankers move large volumes of cargos between major ports and manufacturers. In contrast, short-sea shipping focuses transportation of cargos with regional areas. It normally involves smaller multi-compartment vessels that travel relatively short distances between regional ports. When deep-sea carriers arrive at major ports, they not only unload some cargos, but they also directly (ship-to-ship) transfer some cargos to short-sea carriers for further delivery to regional ports. This reduces transport costs, because the fuel and time-charter costs of deep-sea carriers are far greater than those of short-sea carriers. Furthermore, deep-sea carriers often cannot enter shallow destination ports, because of draft limitations. Then, the only way to deliver cargos to regional destinations is by transferring them to the smaller carriers that can access regional ports. The operation of transferring cargos directly (ship-to-ship) from intercontinental deep-sea to regional short-sea carriers or, generally, from one vessel to another is called trans-shipment.

Over the years, the increase in deep-sea and short-sea shipping activities globally and the myriad of mergers, acquisitions, and collaboration are increasing the demand for trans-shipment operations. The main feature that distinguishes the trans-shipment of chemicals from that of other goods is that the transfer must be direct via a hose, making it necessary for both the donor and recipient ships to be engaged in the operation simultaneously. Unlike most other goods or containers that can simply be stored at a port for a period before another ship collects them, a donor ship cannot simply dump a non-containerized chemical cargo at a port and leave, and let the recipient ship collect it some time later. Most ports do not have facilities for such temporary storage. Such a delayed transfer would normally require a 3PL facility and would incur significant additional costs. Moreover, when multiple ships are involved in trans-shipment, multiple trans-shipment operations may overlap in time, queues of ships may develop and congestion may occur. This congestion may lead to delays and subsequent costs, if one does not synchronize and schedule the various requests optimally. Clearly, a careful scheduling is crucial and extremely important under such circumstances for the shipping companies, because ships are highly capital-intensive assets with operating costs. In addition, port costs also increase with the time that a ship spends at a port and can be substantial. Sometimes, even the demurrage of tankers may be important and this can be several thousand U.S. dollars per day. Therefore, there is a tremendous need for systematic scheduling procedures that minimize the total cost of trans-shipment operations.

No optimization model has been developed to address such trans-shipment scheduling problem till recently when Huang and Karimi (2006a) introduced a MILP scheduling model for a general trans-shipment scenario for regional distribution, where multiple large donor-carriers trans-ship bulk liquid cargos to multiple small recipient-carriers at a trans-shipment location. Their model aims to determine the sequence in, the sides (larboard or starboard) from, and the times at which, each recipient ship should receive cargos to minimize the total time-charter costs of all ships. They also presented and compared several alternative formulations of their model. To address large problems, the authors introduced a novel approach which simplifies their rigorous model heuristically using a cargo aggregation assumption. This approach reduces the formulation size tremendously and decreases model solution times by around 2 orders of magnitude, yet gives near-optimal solutions. This heuristic model promises to be very effective for solving large problems of practical interest. Compared to the manual procedures used in practice for such problems, their MILP models promise to reduce the total operation cost by up to 6.32%.

Essentially, further research opportunities in this field are similar to those described in previous section. One entails comprehensive account of realistic operating constraints so as to improve application potential of optimization models. The other one concerns the account of uncertainty induced by weather and mechanical problems of vessels, and development of efficient solution methodologies to address problems with uncertainty.

### 2.4. Scheduling Tanker-Lightering Operations in Crude Oil Transportation

In marine transportation of crude oil, fully loaded large crude oil tankers such as Very large crude carrier (VLCC) and Ultra Large Crude Carrier (ULCC) usually cannot pass through shallow channels or dock at shallow ports due to shallow drafts, narrow entrances, or small berths. Under such circumstances, small vessels are employed to unload a part of the crude oil from the tanker at offshore deep sea in order to reduce its draft and enable its entry into a shallow channel or port. Subsequently, both the tanker and the small vessels travel to the refinery port to deliver the crude oil. The direct ship-to-ship transfer of crude oil from large tankers to small vessels in order to lighter the tankers is called tanker lightering. The large tankers that require lightering are called ship-to-be-lightered (STBL). The small vessels that unload crude oil from an STBL and deliver to the destination ports are called service ships (SS). Apparently, tanker lightering scheduling problem is a special case of the general transshipment problem described in the previous section. However, the former has one distinguishing characteristic that differs from that of the general transshipment problem. While the latter normally involves small vessels making single voyages and then all carriers (large and small) continuing to their next destinations, the tanker lightering operation may involve multiple voyages of the SSs within the planning horizon. Therefore, the travel times of SSs between refineries and lightering locations, the discharge operations of SSs at the refinery ports outside the lightering locations, etc. are important considerations in the problem.

Though a lightering operation incurs additional cost, it offers two advantages to a refinery. First, tanker lightering helps reduce the time-charter costs or demurrage of large tankers (STBL), which can be of the order of US$100,000 per day, by reducing their waiting times for unloading. It also helps reduce inventory costs at the refineries by ensuring on-time delivery of crude oils. Second, tanker lightering gives flexibility to crude supplies. For instance, SSs enable faster delivery, as multiple vessels can simultaneously discharge crude to different tanks, and deliver parts of the crudes to the refineries that need them urgently, before an STBL reaches them. During congestion, tankers may easily spend days awaiting lightering service and demurrage costs may pile up rapidly. Because of such extremely high economic stakes, effective scheduling of lightering operation is crucial for minimizing logistics costs by reducing the waiting times of STBLs and increasing the utilization of SSs.

Unlike other existing models, Huang and Karimi (2006b) developed two new, continuous-time, slot-based MILP models that addressed a general and realistic form of the tanker-lightering scheduling problem with several realistic and practical features ignored by previous work. These features include possibility of multi-compartment service vessels picking up different crude parcels during one voyage and making multiple visits to different STBLs during one voyage, options of selecting crudes to lighter, accounting for the impact of crude densities, demurrage and time-charter costs, etc. Based on their numerical evaluation using literature examples in Lin et al. (2003), the authors noted that their reduced slot-based continuous-time formulation appears to be tighter, simpler, and faster than an existing event-based formulation by Lin et al. (2003) for a slightly different version of the tanker-lightering problem. To reduce solution time required to solve large problem, the authors simplified their rigorous model slightly by means of some intuitive heuristic simplifications. A study was also carried out by the authors to demonstrate the significant reduction of solution time that can be achieved by the simplified model.

Several significant issues remain unaddressed and they offer opportunities for future work on tanker-lightering scheduling problem. First, existing models addressed only a static version of the problem, where all parameters and data are fixed and known. In real life, operational disruptions do occur unexpectedly. As such, it is crucial that models can be enhanced in terms of industry realism by considering the inherent uncertainties in estimated travel times. Second, practically all existing tanker-lightering scheduling models assumed stationary lightering, i.e. the STBLs do not move, while being lightered. Mobile tanker-lightering operation is also used in practice, where both SSs and STBLS travel at a slow speed during the lightering, which would also be a useful variation of the problem addressed by existing models.

### 2.5. Scheduling Tank Container Movements for Chemical Logistics

When chemical companies seek to transport their liquid products in quantities much smaller than the parcel sizes of chemical tankers, they usually turn to container ships. For this, the chemical producers have to store or pack their liquid cargos into tank containers prior to their loading onto container ships. In essence, a tank container is a cylindrical tank set inside a frame of the standard dry container which comes in two standard sizes, namely 20x8.5x8 ft and 40x8.5x8 ft. A major challenge that the companies using tank containers face arises from the imbalance of product supply and demand which results in an imbalance in the container flows across different regions. There are major flows of loaded containers from the production centers toward 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. As a result, there are major flows of loaded containers from the production centers toward the various demand centers globally. This container imbalance problem is further exacerbated by the need to clean the tank containers at various globally distributed cleaning depots before reuse and with the depots often located far away from the production centers. Clearly, significant cost savings can be derived from a systematic study and optimization of multiproduct tank container movements and related activities (such as cleaning) so that there are (1) timely supplies of empty containers to production sites, (2) systematic transfer of used containers to cleaning depots after service, and (3) optimal repositioning of clean and empty containers to suitable places in anticipation of product orders.

Karimi et al. (2005) were among the first to undertake a comprehensive study of this important short-term tank container management problem. They used an innovative, event-based, “pull” approach to develop a novel linear programming formulation for the minimum-cost or maximum-profit scheduling of the transport and cleaning of multiproduct tank containers (loaded and empty) given a set of projected shipment orders in the short-term. The authors also illustrated the application potential of their models by using it to solve large and industrially relevant problems with key practical considerations such as alternate ship schedules, delivery time windows, and intermodal transport routes.

Ample research opportunities do exist in this area. One key extension is to address uncertainty in container demand orders and a solution methodology for the stochastic model. This is important, because most requests for quotes on containers must be confirmed or agreed to weeks in advance with competitive rates and changes and cancellations can occur easily.

### 2.6. Contract Selection and Tank Allocation in a Terminaling and Storage Facilities

Due to the need to reduce their capital expenditure associated with the logistics facilities and to focus on the core competency of chemical manufacturing, chemical companies are increasingly outsourcing a variety of their logistics activities to 3PL firms in recent years. One key service provided by the 3PL firms to chemical companies is short-term to long-term storage of petrochemical and chemical products. Typically, these 3PL firms own tank storage facilities or tank storage terminals that are located at strategic ports such as Singapore, Rotterdam, etc., where clusters of chemical companies operate in the vicinity. A typical third-party storage terminal may have more than a hundred tanks with a total storage capacity of 150,000 $m^3$ storing a variety of chemicals with varying storage specifications. The tanks in a storage terminal normally have different sizes and characteristics to cater to the variety of storage requirements. Together with the variety of contract orders raised by the chemical clients, which are likely to differ based on storage requirements and time spans, it is clear that the optimal allocation of tanks to contract orders is a complex combinatorial issue.

No model has addressed this problem until recently, when Tay et al. (2005) presented three multi-period MILP models for selecting contracts and allocating tanks to contracts in a typical storage terminal with the objective of profit maximization. For managing larger facilities, the authors proposed two heuristics. They also illustrated their models and algorithms with a case study of industrial scale where the heuristics give comparable solutions that are roughly 8-9% lower than the optimum solution. On one hand, they show the advantage of rigorous optimization, while on the other, they show that even these heuristics could represent significant savings compared to the manual procedures used in the chemical logistics industry.

Like previous problem, the research in this field is still in its infancy and several opportunities exist from revenue management to facility design. One of them, as highlighted by Tay et al. (2005), entails the representation of a more realistic tank allocation problem via an account of tank maintenance requirements. Another research opportunity may also be in the form of accounting for uncertainty in business parameters such as forecasted contract orders for storage tank space. This is especially crucial when the problem involves a relatively long planning horizon and a stochastic programming approach would be more appropriate to determine the optimal tank allocation decisions.

## 3. CONCLUSION

In the modern economic era, it is crucial for all chemical companies, ship and port owners to have sound strategic, tactical, and operational business plans that give them a competitive edge to survive in such turbulent business environment. However, the formulation of good business plans can no long rely solely on the experience of individuals, especially in the complex marketplace of shipping and chemical industry. Together with the wide variety of complex operating constraints in maritime chemical logistics, good business decisions are no longer intuitive, and ad hoc, myopic, or simplistic decision-making processes can be imprudent. In such a complex business environment, it is important that chemical companies, ship owners, and port owners learn the science, not just the art, of running their businesses so that decisions can be made systematically and objectively. One scientific way of running business can be accomplished by employment of optimization models in critical decision-making processes. With the prevalence of optimization models that can support and improve these processes, it is critical that business operators which include chemical companies, ship and port owners are truly aware of these models and understand the benefits of applying them in their organizations. To achieve that, we have described in this paper several practical problems in the maritime chemical logistics which can be addressed using optimization techniques developed by our group and have also identified several opportunities for improving the decision-making processes in maritime chemical logistics with their unique operating characteristics and constraints in mind. We have also used realistic case studies to illustrate the merits of our optimization-based solution approaches which have potential of benefiting major stakeholders of maritime chemical logistics significantly.

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