DISPATCHING PETROLEUM PRODUCTS

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(Received April 1993; revisions received October 1993, June 1994; accepted July 1994)

Petroleum products are distributed worldwide from refineries and lube plants to retail outlets and industrial customers. Proper dispatching of shipments of such products, packaged and in bulk, may result in significant transportation and inventory cost savings. This work examines the variety of operational environments which exist in dispatching petroleum products, and the operations research tools used by oil companies to dispatch such products. In addition, it identifies gaps where additional research is needed.

The oil industry spends billions of dollars annually on the distribution of petroleum products. It is estimated that in the U.S. distribution costs from the refinery to the gas station are around four cents per gallon of gas. With an annual volume of 74 billion gallons (in 1990), that segment alone spends close to three billion dollars. Although the oil industry has been a major source of applications of operations research (especially in vertically integrated oil companies), from exploration through production to distribution, there is a dearth of reports on those applications. Instead, the vast majority of the published work is focused either on the theoretical aspects of the problems encountered or with experiments with models which often are not realistic. The purpose of this paper is to review OR applications in dispatching oil products and to discuss practical aspects and issues in such operations.

The two basic types of "manufacturing" plants that exist in the oil industry are refineries and lube plants. Refineries produce light/white products (gasoline, kerosene, diesel oil, aviation fuel, etc.) which are shipped in bulk to tank terminals (distribution centers) or to industrial customers. Refineries also produce heavy/black products (base stock for lubes, residual oil) which are shipped in bulk to industrial customers and lube plants (Figure 1 outlines the distribution chain of refinery products). Lube plants produce lube oils, greases, and waxes, which are shipped (packaged or in bulk) to distribution centers or industrial customers (Figure 2 outlines the distribution chain of lube products).

This article deals with the dispatching of oil products, the most detailed level of planning in product distribution. Dispatching includes the determination of sources, destinations, timing, composition, and size of shipments, as well as assignment of these shipments to transportation modes and units. The discussion is divided into four parts, corresponding to the four different types of operational environments encountered in practice:

1. light products in bulk from refineries to tank terminals (and industrial customers);
2. light products from tank terminals to retail outlets;
3. bulk lubes (from lube plants to industrial customers); and
4. packaged lubes (from lube plants to retail outlets and industrial customers).

The distribution of heavy products from refineries is similar to the first group above (light products in bulk from refineries), and therefore is not treated separately.

Table I presents the distribution (dispatching) characteristics of the four operational environments. These distribution characteristics dictate available operational alternatives. For example, standardized light products allow exchanges of products between producers, thus increasing the potential number of sources to load the products. Conversely, specialized products cannot be exchanged and may often be made to order. Large volume products are usually shipped in bulk, whereas small volume products are usually shipped packaged. The product characteristics dictate the transportation modes used and the trip characteristics, which may, in turn, necessitate different approaches and models to achieve satisfactory dispatches.

Dispatching petroleum products may involve consideration of transportation and product sourcing costs, operating rules of the transportation units, inventory considerations, customer service policies, and other factors. Transportation fleets are usually not homogeneous in their physical characteristics and costs, and the transportation costs are usually neither linear nor continuous

Subject classifications: Industries, petroleum: products distribution. Transportation, scheduling: distribution of petroleum products.
Area of review: OR PRACTICE.

0030-364X/95/4303-0379 $01.25

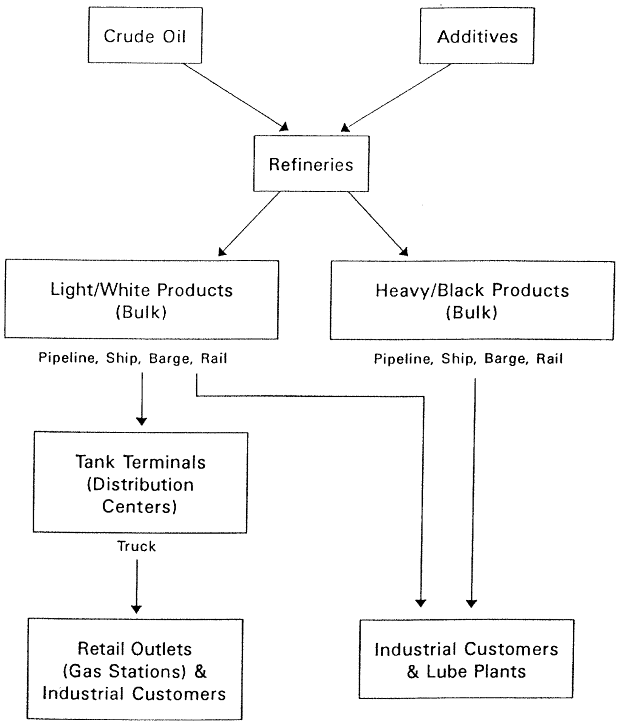

Figure 1. Distribution chain of refined products.

functions of distance or volume, rendering linear programming models inapplicable. This complexity in the dispatching environment resulted in the dominant use of heuristics to derive acceptable dispatches. Due to their flexibility, set partitioning (SP) based optimization models have emerged as the only viable optimization approaches which can address the complexity of transportation dispatching problems (model formulations of SP problems are provided in the Appendix). However, set partitioning models have been hard to solve optimally for problem sizes encountered in daily operations (Bodin 1990). The fast development of computing power, combined with algorithmic developments, have facilitated the recent emergence of set partitioning-based optimization models in operational dispatching systems. Such systems are now in limited use for dispatching oil products.

This work reviews the practice of dispatching products in the oil industry, based on material available in published sources, and the author's own experience. The rest of the paper is organized around the various operational environments. The next four sections address the four operational environments listed above, and the last section discusses general dispatching issues.

1. LIGHT PRODUCTS FROM REFINERIES

Refined light products are shipped in bulk in large quantities from refineries to tank terminals and industrial customers by a variety of modes (ship, barge, pipeline, rail). The operator has several important considerations in dispatching such products:

1. sufficient safety stocks must be maintained at the receiving facilities;
2. product storage requirements should not exceed the available storage capacity at the refineries and terminals;
3. since more than one refinery may be available for loading, the decision at which refinery to source each shipment may be important.

The *shipping slate* is the set of loads to be shipped, along with their timing, origins, and destinations. The above considerations dictate the shipping slate. The familiar inventory routing problem (Dror and Trudeau 1988) addresses only the first consideration above. Due to the significant transit times involved and the connection with production planning at the refineries, the planning horizon usually covers at least several weeks (covering several trips for each vessel, where shipping is by owned and time-chartered vessels). The resulting dispatching problem has two interacting aspects: the inventory considerations (at both ends) and the transportation decisions. A problem that has these two interacting aspects is called a tactical inventory routing problem (Larson 1988).

The significant uncertainty in transportation operations, especially in marine bulk operations (Ronen 1983), requires addressing this problem on a rolling horizon basis (i.e., implementing only immediate decisions and solving the problem again whenever things change from the generated solution). Most major oil companies, as

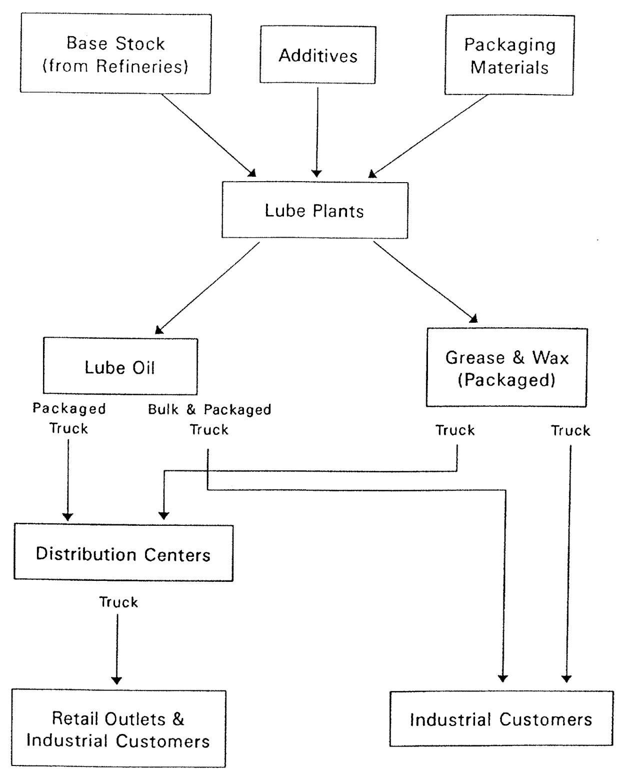

Figure 2. Distribution chain of lube products.

Table I
Distribution Characteristics of the Different Operational Environments

Operation/Distribution Characteristics	Light (Bulk) Refineries to Terminals	Light (Bulk) Terminals to Outlets	Lubes (Bulk)	Lubes (Packaged)
Products	Standardized	Standardized	Specialized	Specialized
Product Line	Narrow (few)	Narrow	Narrow	Wide (many)
Volume (Storage)	Large	Large	Small	Small
Sources	One/Few	One/Few	One	One
Destinations	Few	Many	Few	Many
Transportation	Specialized	Specialized	Specialized	Common
Backhauls	Occasional	No	No	Yes
Transportation mode	Ship, Pipeline, Rail, Barge	Truck	Truck	Truck
Trips per truck shift	—	Multiple	Multiple	One/Two
Delivery stops per route	One to Three	One to Five	One/Two	Multiple
Mixing of products in same compartment	No	No	No	Yes
Transit time	Days	Hours	Hours	Hours

well as chemical manufacturers, face this type of problem. The same tactical inventory routing problem also exists in the transportation of crude oil to refineries.

The following additional concerns may exist in solving this type of problem, depending on the specific operation:

- Transportation units may have different sizes and compartments (e.g., ships, barges). As such, the timing, sizing, and product composition of shipments may depend heavily on the availability of transportation units and their operational restrictions.
- Facilities shared with other operators (e.g., pipelines, marine terminals) may be unavailable when needed, disrupting planned schedules.
- Cross contamination of products must be prevented when the same line or tank is used for different products.
- On a partially loaded leg of a vessel, the vessel must be loaded in a safe manner to assure stability.
- A vessel may load at more than one refinery.
- Single voyage (spot) charters of vessels may be unavailable.

Additional issues associated with such problems are related to measuring output and costs. For example, how does one compare two alternate dispatches? Two alternate dispatches may have different quantities shipped between the various origin-destination pairs, at different times, by different transportation units. Thus, the output of the transportation system is not the same. Operating costs may often be calculated fairly accurately, but how do you incorporate the value of location and free time of a transportation unit toward the end of the planning horizon? Alternate dispatches may represent different violations of tank topping constraints at the refineries or safety stock constraints at the receiving ends. How should such violations be evaluated?

Several oil companies use linear programming and network models for product distribution planning to determine the shipping slate. A model used by Shell was presented by Zierer, Mitchell and White (1976), and one used by Southland/Citgo was presented by Klingman et al. (1988). Mehring and Gutterman (1990) developed a similar model for Amoco (U.K.), but it was not implemented due to insufficient resources for proper implementation. However, these systems do not deal with dispatching the transportation of the planned shipments. Oil companies usually separate the determination of the shipping slate from the dispatching decisions because these decisions are vested in different departments, and their combined solution is difficult.

Little practical work has been published in the area of tactical inventory routing in the oil industry. Miller (1987) presented an interactive dispatching system, which was developed and used by Ethyl Corporation for dispatching and strategic planning. The system addresses the inventory aspect only at the receiving end (requiring safety stocks there), but does not consider inventory at the sources. It uses heuristics combined with user intelligence and some suboptimization routines to construct a dispatch. In most cases, simple heuristics are used to solve these problems.

Several systems have been developed to address the dispatching side of operations. Fisher and Rosenwein (1989) developed a bulk oil products dispatching system for the Tanker Division of the Military Sealift Command, an operation similar to the ones discussed here. In this system, a specified set of loads is dispatched using a set packing model (**SPK**; see the Appendix) which considers all feasible schedules for each vessel. Bausch, Brown and Ronen (1991) developed a products dispatching system for a given set of loads which uses an elastic set partitioning model (**ESP**; see the Appendix), where all feasible schedules of the vessels are considered. This system quickly provides optimal solutions on a microcomputer. Both systems allow the user to assure that only managerially acceptable schedules will be considered by requiring the user to specify some external control parameters, such as maximal waiting time for loading or maximal length of a ballast leg. These parameters are used to limit the size of the set of feasible schedules. However, within these limitations, all feasible schedules are considered, assuring a feasible solution to the problem. Bausch, Brown and Ronen solved problems with thousands of columns (binary variables) and dozens of rows (vessels and loads), and that system is being used operationally. Fisher and Rosenwein solved problems with up to a thousand columns, but the system has not been used due to changes in personnel (Glassman 1994).

The fast development of computing power combined with increased competition and cost pressures in the oil industry may result in progress toward practical solutions for this type of tactical inventory routing problem.

2. LIGHT PRODUCTS FROM TANK TERMINALS

Light products are usually distributed from tank terminals to retail outlets (gas stations) and industrial customers by tanker trucks. There exists a variety of operations in this segment of the distribution chain. The characteristics of a specific operation are affected by the competitive environment, demand density, company policies, laws and regulations, and numerous other factors. The two basic approaches for determining loads are pull system and push system.

In a *pull system* product shipments are triggered by orders placed with the supplier by the receiving end, to be delivered at certain times. The supplier may limit the orders to dictated product quantity combinations, which fit a typical truck compartmentation. For example: 3,500 + 2,000 + 1,800 gallons, or 3,500 + 3,800 gallons, and so on. The ordered quantities may have to be adjusted (within limits) to fit the available trucks, to prevent shipping partially empty compartments. Less than truckload (split) orders require loading two (or more) orders on the same truck and may pose significant complications in filling the truck compartments. However, in certain cases, additional split orders are generated by calling outlets which may need products to fill the truck.

In a *push system* the supplier has to assure that sufficient stock is available at the receiving end, but the shipment timing is flexible, and the shipment size may be a function of its timing. In addition, the ownership of the inventory at the receiving end may affect shipping decisions. If the receiving end owns that inventory, the supplier has a strong incentive to push product to that end. A push system allows better utilization of the truck fleet and more control over the retail outlets than a pull system, because the supplier controls the generation of shipments. Such a system falls in the domain of inventory routing problems (see Dror and Trudeau).

An operator may have at his disposal a mixed fleet of trucks with various physical and economic characteristics. The trucks may have different sizes, compartmentation, and equipment. Owned (or leased) trucks are charged per mile or kilometer, per hour and sometimes per trip (depending on the driver compensation scheme). Dedicated carrier trucks (which may be hired by the day/week/month) may have minimal daily charges. Hired trucks may operate on point-to-point rates or on a cost per delivered volume × distance (kiloliter × kilometer). In view of the varied fleet composition and cost terms, minimizing delivery cost is the appropriate objective. Since dispatching is a short-term planning process, capital costs are not considered explicitly. They are reflected in the owned (or leased) fleet size and mix and in the charges of hired trucks.

A variety of dispatching environments exists, and following is a list of variations which were observed worldwide (USA, U.K., Australia, New Zealand, France, Japan):

- One or several product sources may be used. Each tank terminal may be dispatched separately, or a (metropolitan) area having multiple (alternate) sources may be dispatched together. In the latter case, a customer (retail outlet) may be supplied from different sources, and there may be product cost differentials among the sources. Product exchanges among oil companies allow a company to draw products from multiple sources.
- The supply of certain products may be limited at certain sources.
- Trucks may be available for hire on a short term (daily) basis.
- A truck may perform multiple trips per shift.
- A truck may have from 1 to 13 compartments.
- A truck may have up to 9 (or more) delivery stops on a single trip (multiple-stop trips are usually longer than single-stop trips, and performed in areas with lower demand density).
- A truck may load at more than one source (different products) for a single trip.
- There may be several deliveries to the same location on the same shift (either different products or large quantities).
- Trucks may have no meters to measure the delivered quantity (full compartments are dropped to speed-up delivery). The delivered quantity is the one measured during the truck loading.
- Trucks may be loaded by product volume or weight (the latter provides better utilization of truck capacity). When the product is warm (has low density), larger volume may be loaded on the truck without violating the weight limits.
- Special separation between certain products on a truck may be necessary to prevent product cross contamination in case of wall perforations (double bulkheads/

walls). If such separation is not available, an empty compartment must be left between the products.

- Order product quantity adjustments (to fit truck compartments) may, or may not, be permitted (within specified limits). On the one hand, it is undesirable to ship air (empty volume), on the other hand, customer order quantities should not be changed drastically (may result in product shortage or insufficient storage space at the receiving facility).
- Specified delivery time windows may, or may not, be followed. The time windows may be hard or soft, wide or narrow, and a delivery may have more than one time window.
- First/last load (in the shift) may be assigned on a first-come, first-served basis (too many customers want their load at the beginning or end of the day).
- Balancing workload among drivers (hours and number of trips) may be necessary due to pay scale structure or labor contract requirements.

A dispatcher must try to minimize the cost of delivery while taking into account all the relevant considerations, and satisfying the customers, management, and the truck drivers. However, usually the dispatcher is not even aware of the delivery costs involved, and tries to find an acceptable dispatch. In a large metropolitan area, several hundred orders may be dispatched daily, using dozens of trucks and half a dozen sources. By now it should be clear that no single dispatching model can address the variety of existing problems (see Bisschop 1988).

The various characteristics of the systems discussed in this section are presented in Table II. Bell et al. (1983) present a push system for distribution of industrial gases which was used by Air Products and Chemicals, an operation similar to distribution of light oil products from a single source, except that it distributes each product separately. The system was based on a mixed integer programming model which considered a subset of all feasible routes and was solved by Lagrangian relaxation to within 0.5–2% of optimality. In the mid-1980s, as the business evolved, the computational part was replaced by heuristics, but the user interfaces were retained (Brinker 1994). Golden, Assad and Dahl (1984) discussed a push system with elaborate heuristics for delivery of liquid propane to customers, but no implementation experience was documented.

Brown and Graves describe a single-source dispatching system used by Chevron U.S.A. to ship light products from tank terminals to customers. The system evolved into a multiple source dispatching system used by Mobil Oil Corp. (Brown et al. 1987). This system uses

Table II
Characteristics of Tanker Truck Dispatching Systems

Characteristic	Bausch et al. (1995)	Bell et al. (1983)	Brown et al. (1987)	Brown & Graves (1981)	Franz & Woodmansee (1990)	Golden et al. (1984)
Delivery system	Pull	Push	Pull	Pull	Pull	Push
Product	Lube oil	Industrial gases	Gasoline	Gasoline	Gasoline	Heating oil
Fleet	Mixed	Mixed	Mixed	Mixed	Mixed	?
Objective	Minimum cost	Maximum value	Minimum cost	Minimum cost	Minimum cost	Minimum cost
Sources per dispatch	One	One	Multiple	One	Multiple	One
Technique	Elastic set partitioning	Lagrangian relaxation	Heuristics + network	Heuristics + network	Expert system	Heuristics
Limited supply	No	Yes	Yes	No	Yes	?
Carrier trucks	Yes	?	Yes	Yes	Yes	?
Multiple trips per truck	Yes	?	Yes	Yes	Yes	Yes
Multiple stops per trip	No	Yes	Yes	Yes	No	Yes
Compartments per truck	Multiple	N/A	Multiple	Multiple	Multiple	N/A
Number of products	Multiple	One	Multiple	Multiple	Multiple	One
Separation between products	Yes	N/A	Yes	Yes	Yes	N/A
Loading at several sources	No	No	No	No	?	No
Multiple deliveries to same location	Yes	Yes	Yes	Yes	?	?
Product quantity adjustment	No	Yes	Yes	Yes	?	Yes
Delivery time windows	Limited	Yes	Limited	Limited	Yes	No
Balancing workload	Yes	?	Yes	Yes	Yes	?
Orders per dispatch	Dozens	Hundreds	Hundreds	Hundreds	?	?
Trucks per dispatch	Several	Dozens	Dozens	Dozens	Several	Several
In current use	Yes	Partially	Yes	Yes	No	No

?—not known
N/A—not applicable

network models combined with heuristics. Ronen (1992) has shown that in the single-source case the solutions are usually within 1% of an optimal lower bound.

Franz and Woodmansee (1990) describe a (heuristic) rule-based decision support system for a regional oil company (jobber) which buys light products from other oil companies and delivers them to the customers (retail outlets), but that system has not been implemented yet (Franz 1993).

Bisschop (1988) gives "an indication of the basic approach, which Shell was exploring for this type of problem, consisting of a combination of a set partitioning algorithm with tabu search. He provides some experimental results for a problem with 80 delivery points, but no further information is available.

Delivery of light products from terminals to customers is somewhat similar to collection of crude oil from small producing wells by trucks and delivering it to pipeline inlets (see Russell and Challinor 1988).

Set partitioning models are a natural candidate for this type of problem. However, the large combinatorial size of the resulting problems (many millions of potential binary columns), and the lack of good rules which could be used to trim the size of the problems, often render this approach unattractive.

3. BULK LUBES

Lube plants blend base stocks and various additives to create products. Some of these products are delivered in bulk to large customers (e.g., car manufacturing plants, ships) by tanker trucks. Dispatching these tanker trucks is similar to dispatching light products from tank terminals (see Section 2), but the scale of the operation is usually much smaller. Only several trucks may be involved and a relatively small number of orders must be delivered from a single lube plant. The products may be blended to order and must be delivered fairly quickly due to lack of storage tank space at the lube plant (other products are packaged after blending and are stored in a warehouse). Alternate sourcing of orders is usually not considered because lube plants are usually far away from each other. The tanker trucks are usually dedicated for lube oils and are either owned or under a long-term contract. A truck usually delivers products to a single location and returns to the plant to load the next order. Due to the small size of this trucking market, additional trucks (on a temporary basis) are usually not available. Some customer locations may be of the "keepful" type (where the supplier assures that the location will not run out of product), and the inventory there must not fall below a minimal level (e.g., car assembly plants).

Because such operations are small, a set partitioning model with exhaustive enumeration of all feasible schedules for each truck is implementable. Such a model may result in problems with several hundred columns, where each column represents an alternate schedule for a truck, and can be solved to optimality quickly on a microcomputer (see Bausch, Brown and Ronen 1995). Such a dispatching system has been implemented recently by Mobil Oil Corp., and is used daily for several lube plants. The characteristics of this system are included in Table II.

4. PACKAGED LUBES

Dispatching packaged lubes, greases and wax is similar to dispatching other packaged goods. A lube plant may blend a variety of products, common products may be distributed regionally, but specialty products may be shipped far away, because they are often produced only in a single plant. The products are usually shipped by truck. Because lube plants are usually far from each other, each plant is dispatched separately, and each customer is assigned to a single source. The products are packaged in a variety of packages (drums, pails, cases), which may be mixed in a truck compartment. Backhauls of packaging materials, empty packages, and materials for production may be available for trucks which return to the source. Truck routes may consist of multiple stops, a truck may perform multiple trips per day, or a route may extend over several days. It is possible to deliver certain orders early if it is economical to do so (customer service guidelines usually do not allow late delivery).

A mixed fleet of trucks, with different sizes, equipment, operating rules, and costs may be available to the dispatcher. An efficient assignment of the shipments to the trucks may be hard to find but may save delivery costs (a conservative estimate of such savings is 5%; see Assad 1988). Owned (and leased) trucks may be constrained to stay within a certain radius around the source to assure their availability for the following day. Long-haul carrier trucks usually do not return to the source, and may be assigned several deliveries in the same geographical direction. Orders may be given to common carriers for delivery at known costs. Other shipping alternatives may exist (e.g., pool distribution points), and each alternative has its own costs and operating rules.

A variety of software packages is available for dispatching packaged goods, but most of them are based on heuristics and try to minimize miles, hours, or the number of trucks used. Characteristics of various software packages were analyzed by Golden, Bodin and Goodwin (1986). The fast developments in this area have caused this work to become a bit dated. An annual directory of logistics software which includes a listing of such packages is compiled by Andersen Consulting (Haverly, Smith and Gutman 1992). However, availability of a mixed fleet invites dispatch cost minimization, which few packages employ.

Although a vast body of literature deals with routing and scheduling of vehicles for delivery of packaged goods (see Assad), barely any of it is specific to petroleum products. Bausch, Brown and Ronen (1995) designed a dispatching system for packaged goods which is used daily by Mobil Oil Corp. That system uses an elastic set partitioning model with a column generator which generates only good potential schedules for each truck. A minimal cost dispatch is provided quickly for a fleet with multiple types of trucks. Problems with up to several dozen trucks and several hundred orders, resulting in tens of thousands of columns, are solved on a mainframe. The system has been operational for about three years, saving about a million U.S. dollars annually in transportation costs.

5. DISPATCHING ISSUES

The success of dispatching systems depends, to a large extent, on several additional factors. Several oil companies have centralized their product dispatching operations during the last decade, and have reaped significant benefits in reductions of dispatching personnel, uniform delivery policies, and better management control over dispatching operations. Similar centralization has taken place in various segments of the transportation industry (e.g., railroads) and is facilitated by the fast development of computers and telecommunications. However, some oil companies have chosen to leave their dispatching operations decentralized, claiming better local responsiveness to customer needs.

A dispatching system consists not only of dispatching models and algorithms, but requires user interfaces (both on the input and output sides), various data files with the associated data base interfaces, and data management routines. Major roadblocks may be encountered in acquiring two types of external data: geographical data and carrier rates. Geographical data are required to calculate travel distances, times and the related costs, and are becoming more readily available with the development of Geographical Information Systems. External carrier rates (and their related operating rules) may pose a major headache, especially for trucks, due to their complexity, sheer number, and frequent changes. Some simplification of such rates may be necessary to facilitate their inclusion in a computerized dispatching system. Assad (1988), Bodin (1990), and others have encountered similar implementation experience.

Dispatching is often an act of balancing multiple objectives. The primary objective in such a short-term planning activity is usually variable delivery cost minimization. Additional objectives may be balancing workload among transportation units, minimizing violations of service guidelines, and not shipping too much too early (in order not to "starve" the controlled fleet in the future). However, even total cost minimization is not always simple. Often different organizational units are measured on different types of costs. Dispatching effectiveness is usually measured on transportation costs, but when alternate sourcing of products is feasible, and there are product cost differences among the sources, it may be worthwhile to draw cheaper products from farther sources, thus increasing transportation costs and reducing product (and total) costs. The benefits from such alternate sourcing usually depend on the mix of orders, transportation units, and product availabilities for the specific dispatching instance. In cases where load sizes may be adjusted to fit the available transportation units, minimizing total cost of delivery is not necessarily the appropriate measure of effectiveness. In such cases, one has to look at delivery cost per unit of product, or delivery cost per distance weighted unit of product.

Because an operator seldom uses a uniform fleet, an effective dispatching system should account for the differences among the available transportation units (differences in cost, size, equipment, etc.), and be based on cost minimization. Furthermore, because dispatching is an operational function, a dispatching system must provide a reliable dispatch quickly, even in the presence of minor data problems. Due to the numerous considerations involved in dispatching, some of which are unforeseen and, therefore, cannot be programmed into a dispatching system, a dispatching system should be designed to support the dispatcher, not to replace him/her. Manual overrides should be possible, and the dispatcher should be able to see the cost impact of his/her changes, thus increasing the user's confidence in the system. A timely dispatch with visibility of the associated costs is probably the largest contribution of computerized dispatching systems.

Significant progress has been achieved during the last decade in dispatching products in the oil industry. In certain dispatching environments mathematically optimal dispatches are becoming a reality, whereas in others only good solutions (with known bounds) are possible. The next development step should be integrated solutions to real-life inventory routing problems, which take into account the interaction between the two aspects of such problems (inventory and transportation). The fast development of computing power and solution algorithms will most likely facilitate such evolution in the not too distant future.

APPENDIX

Model Formulations

A1. Set Partitioning

The formulation of a set partitioning (**SP**) model is as follows.

Indices

$i = 1, \ldots, n$ transportation units (vessels/trucks);
j = an alternate schedule;
$j \in J(i)$ schedules requiring transportation unit i;
$k = 1, \ldots, m$ tasks to be performed (shipments/orders);
$j \in J(k)$ schedules performing task k.

Data

C_j = the cost of entire schedule j (a function of the transportation unit and the tasks in that schedule).

Decision Variables

$y_j = 1$ if schedule j is selected; 0 otherwise.

Model Formulation (SP)

$$Z = \text{Min} \sum_j C_j y_j \tag{1}$$

subject to

$$\sum_{j \in J(i)} y_j = 1 \quad \text{for each transportation unit } i, \tag{2}$$

$$\sum_{j \in J(k)} y_j = 1 \quad \text{for each task } k, \tag{3}$$

$$y_j \in \{0, 1\} \quad \text{for each schedule } j. \tag{4}$$

Constraints (2) seek one schedule for each transportation unit and constraints (3) seek to perform all tasks.

A2. Elastic Set Partitioning

In elastic set partitioning (**ESP**) violation of the constraints is permitted at a penalty which is added to the objective function.

Additional Notation

$\underline{d}_i, \bar{d}_i$ = the lower and upper constraint violation penalties for transportation unit i;

$\underline{s}_k, \bar{s}_k$ = the lower and upper constraint violation penalties for task k;

$\underline{\delta}_i, \bar{\delta}_i$ = the elastic (constraint violation) variables for transportation unit i;

$\underline{\sigma}_k, \bar{\sigma}_k$ = the elastic (constraint violation) variables for task k.

Model Formulation (ESP)

$$Z = \text{Min} \sum_j C_j y_j + \sum_{i=1}^{n} (\underline{d}_i \underline{\delta}_i + \bar{d}_i \bar{\delta}_i) + \sum_{k=1}^{m} (\underline{s}_k \underline{\sigma}_k + \bar{s}_k \bar{\sigma}_k) \tag{5}$$

subject to

$$\sum_{j \in J(i)} y_j + \underline{\delta}_i - \bar{\delta}_i = 1 \quad \text{for each transportation unit } i, \tag{6}$$

$$\sum_{j \in J(k)} y_j + \underline{\sigma}_k - \bar{\sigma}_k = 1 \quad \text{for each task } k, \tag{7}$$

$$y_j \in \{0, 1\} \quad \text{for each schedule } j, \tag{8}$$

$$\underline{\delta}_i, \bar{\delta}_i \in \{0, 1\} \quad \text{for each transportation unit } i, \tag{9}$$

$$\underline{\sigma}_k, \bar{\sigma}_k \in \{0, 1\} \quad \text{for each task } k. \tag{10}$$

Constraints (6) seek one schedule for each transportation unit, where a lower violation represents total idleness of the unit (at a penalty representing the idleness cost) and an upper violation incurs a high schedule disruption penalty. Constraints (7) seek to perform all tasks; a lower violation represents a common carrier shipment (where permissible, at the appropriate cost), and an upper violation results in a high disruption penalty. The disruption penalties are assigned large numerical values to prevent such disruptions from occurring.

A3. Set Packing

Set packing (**SPK**) maximizes the "profit" from using the available transportation units (in comparison with performing the tasks by common carriers).

Model Formulation (SPK)

$$Z = \text{Max} \sum_j C_j y_j \tag{11}$$

subject to

$$\sum_{j \in J(i)} y_j \leqslant 1 \quad \text{for each transportation unit } i, \tag{12}$$

$$\sum_{j \in J(k)} y_j \leqslant 1 \quad \text{for each task } k, \tag{13}$$

$$y_j \in \{0, 1\} \quad \text{for each schedule } j, \tag{14}$$

where C_j is the "profit" (or savings) resulting from using the transportation unit instead of shipping the loads by a common carrier. That "profit" consists of the common carrier charges for the loads involved, minus the marginal cost of using the transportation unit to deliver these loads.

A4. Summary

The **SP** formulation is more rigid and requires all tasks to be performed by the set of available transportation units. The **ESP** and **SPK** models are more flexible and recognize the availability of common carrier, optional loads, and idleness of vessels (via the cost coefficients). Although these additional alternatives may be added explicitly to the **SP** model, they increase the size of the problem. The **ESP** and **SPK** models are similar in their approach, but the **ESP** model is more explicit in the consideration of common carriers, idle vessels, and optional loads (their costs are spelled out in the objective function).

ACKNOWLEDGMENT

The author thanks Dr. Richard Powers of Insight, Inc. for the idea and encouragement for this work, Mr. Dan Bausch of Insight, Inc. for sharing his experience, and the associate editor and two anonymous referees for their constructive criticism.

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