Invited Review

Cargo ships routing and scheduling: Survey of models and problems

David RONEN
School of Business Administration, University of Missouri - St. Louis, St. Louis, MO 63121, U.S.A.

Received March 1982

When a ship costs thousands of dollars per day, significant savings can be achieved by proper fleet routing and scheduling. In contrast to vehicle scheduling, relatively little work has been done in ship routing and scheduling. This paper discusses briefly the differences between vehicle and ship routing and scheduling and the reasons for the low attention to ship scheduling in the past. The various modes of operation of cargo ships are described and a classification scheme for ship routing and scheduling models and problems is proposed. A review of ship routing, scheduling and related models is provided. The review is broken down into the following categories: transportation system models, liner operations, tramp shipping, industrial operations and other models. Finally, recent trends in ship scheduling, shortcomings in existing models and requirements from realistic models are discussed.

1. Introduction

The continuous growth of the world population and of its standard of living, combined with depletion of local resources, increases the dependence of the world economy on international trade. Although international seaborne shipping is the major artery of international trade, relatively little research has been done in quantitative aspects of designing and managing seaborne shipping systems. This article tries to shed light on one aspect of seaborne shipping systems, namely routing and scheduling of seaborne cargo transportation.

Transportation scheduling has been widely discussed in the literature but most of the attention has been devoted to scheduling vehicles. A good review of vehicle scheduling problems and models is provided by Clausen [14]. Other modes of transportation, i.e., air, rail and water, have attracted much less attention, and one may wonder why, especially when considering the much larger capital investments and operating costs of those other modes. When a ship costs millions of dollars and its daily operating expenses are tens of thousands of dollars, large benefits may be expected from improving its scheduling process. Several explanations follow for the low attention drawn by ship scheduling problems:

(1) *Low visibility.* In the U.S.A., the major source of research in quantitative methods, ships are a minor transportation mode; most cargo is moved by truck or rail. Moreover, numerous organizations operate fleets of trucks, but very few operate ships. Actually, most of the work reviewed in this paper originated in European countries, which are more dependent on ocean shipping.

(2) *Ship scheduling problems are less structured than standard vehicle scheduling problems.* In ship scheduling there is a much larger variety in problem structures and operating environments.

(3) *In ship operations there is much more uncertainty.* Ships may be delayed due to weather conditions, mechanical problems and strikes (both on board and on shore), and usually very little slack is built into their schedules, due to their high costs. Levy, Lvov and Lovetsky [25] studied schedule performance of merchant ships, and found a probability of 0.3 of meeting a planned quarterly schedule (about 3 voyages). Thus medium term schedules are used as guidelines and are changed very often.

(4) *The shipping market is volatile, international, capital intensive and relatively free – without barriers to entry or regulation of rates.* Thus shipowners

North-Holland Publishing Company
European Journal of Operational Research 12 (1983) 119–126

0377-2217/83/0000-0000/$03.00

take advantage of different national laws and regulations, and therefore capital investment decisions have a much larger effect on the bottom line than operational decisions.

(5) *The ocean shipping industry has a long tradition.* Ships have been around for thousands of years and therefore the industry is conservative and not open to new ideas. Most quantitative models originated in vertically integrated organizations where ocean shipping is just one component of the business.

Several terms must be clarified before proceeding. The term 'shipping' in this article means moving of cargoes by ships. 'Routing' usually has a special meaning in shipping; it usually means weather routing, i.e., choosing a path in the sea between two ports of call in order to minimize the effect of bad weather. Here 'routing' will mean specifying sequences of ports of call to ships. 'Scheduling' is routing with times (or time windows) attached to the calls of the ships in the ports. Short term will mean up to several weeks forward, medium term up to several months, and long term is beyond that.

There are three general modes of operation in shipping: liner, tramp and industrial (Lawrence [24]). These modes are not well defined or mutually exclusive. A ship may be easily transferred from one mode to another and an operator can operate ships in several modes at the same time. A liner operation resembles a bus line – it publishes time tables and competes for cargo. The schedule of liner ships affects the demand for their service (cargo available). Liners usually operate in closed routes and often no voyage origin or destination can be defined because they may load and discharge cargo in each port of call and may never be empty. Moreover, a liner may be scheduled to call in a particular port more than once in a single voyage.

Tramp operation resembles a taxi-cab operation. The ships are sent where cargoes are available and usually the cargo is a whole shipload with a single origin and one or two destinations. Liner and tramp operations are common in shipping companies. The objectives of liner and tramp operations are usually to maximize profits per time unit.

Industrial operation is similar to private truck fleet operation. The owner of the cargo controls the fleet of ships. The ships may be owned or chartered. The primary purpose of an industrial operation is usually to assure transportation services for the organization's cargo and to reduce costs. Ordinarily such fleets are sized below the organization's basic continuing requirements and fluctuations in fleet capacity needs are met by charters from other owners. The objective of an industrial operation is usually to provide the required transportation service at minimal cost.

Ships can be easily chartered (in and out) on an international exchange, and can be bought or sold on the international market. Thus an operator can relatively easily change the size of his fleet, but this process requires time.

At this point it may be worthwhile to point out the major differences between standard vehicle routing and scheduling problems and ship routing and scheduling problems.:

(1) Ships are different from each other in their operating characteristics (capacity, speed), as well as their cost structure. Due to frequent fluctuations in the ship market, even two identical ships may have quite different cost structures.

(2) The scheduling environment depends, to a large extent, on the mode of operation of the ships.

(3) Ships do not necessarily return to their origin.

(4) Higher uncertainty is involved in scheduling ships (more sources of uncertainty and much longer voyages).

(5) Ships are operated around the clock whereas vehicles are usually not operated during the night (except over the road vehicles, such as moving trucks). Thus ships do not have planned idle periods which absorb delays in operations.

(6) Destination of ships may be changed at sea.

This paper reviews ship routing, scheduling and closely related models. First a classification scheme is suggested for ship routing and scheduling problems and models, then a review of models is provided. The review is broken down into several categories: transportation systems models, liner operations, tramp shipping, industrial operations, and other models. Finally, a summary discusses the major problems with existing models and suggests directions for future research.

2. Classification of ship routing and scheduling problems and models

Following is a suggested classification scheme for ship routing and scheduling problems. This classification may help to identify the type of problem faced and existing algorithms to solve it (if any). The structure of the classification is similar to the one proposed by Bodin, Golden, Assad and Ball [8] for vehicle routing and scheduling problems, but it is much more comprehensive.

A *Mode of operation*
  1. Liner
  2. Tramp
  3. Industrial

B. *Loading and discharge times*
  1. Specified (ship scheduling problem)
  2. Time windows
  3. Open (routing problem)

C. *Number of origins*
  1. One
  2. Multiple

D. *Number of discharging ports*
  1. One
  2. Multiple

E. *Number of loading ports per vessel voyage*
  1. One
  2. Multiple

F. *Number of discharging ports per vessel voyage*
  1. One
  2. Multiple

G. *Number of commodities*
  1. One
  2. Multiple

H. *Fleet size*
  1. One vessel
  2. Multiple vessels

I. *Types of vessels*
  1. One
  2. Multiple

J. *Demands (shipment sizes)*
  1. Deterministic
  2. Stochastic
     a. continuous
     b. discrete
  3. Decision variables

K. *Cruising speed as a decision variable*
  1. Yes
  2. No

L. *Fleet size and composition*
  1. Specified-cannot be changed (short term problem)
     a. sufficient
     b. drop cargoes
  2. Can be changed (medium term problem)
  3. Constant over scheduling period
  4. Changes over scheduling period

M. *Port entry constraints on vessels*
  1. Exist
  2. None

N. *Sea route constraints on vessels*
  1. Exist
  2. None

O. *Ports precedence requirements*
  1. Exist
  2. None

P. *Costs*
  1. Fixed costs (operating and capital)
     a. In operation
     b. In layup
     c. Change of status cost
  2. Variable costs
     a. Steaming costs
     b. Port entry charges
     c. Time in ports
     d. Unit shipping cost
     e. Demurrage (cost of vessel's waiting time)

Q. *Objective*
  1. Minimize costs
  2. Maximize profits
  3. Maximize utility

R. *Cargo transshipment*
  1. Allowed
  2. Excluded

S. *Times between events*
  1. Deterministic
  2. Stochastic

T. *Other problem-specific characteristic*

This long list of problem characteristics demonstrates the large variety and complexity of ship scheduling problems. Although the list above is quite comprehensive, it is by no means exhaustive, and every problem may have some additional twists. Not all the numbered sub-categories above are mutually exclusive and a real problem may possess any mix of these characteristics.

3. Transportation systems models

Ship routing can be viewed in a wider transportation planning context. The design of the transportation system specifies the constraints on the ship routing environment, such as: loading ports, discharging ports, shipment sizes (through size of storage facilities), types of ships, fleet size and combination. Thus, in the long run, ship routing is closely related to the design of the transportation system. Only industrial operations, which are vertically integrated, can relate transportation system design with ship routing. Several examples can be found for design of transportation system where ship routing is a component of the whole system. Conley, Farnsworth, Koenigsberg and Wiersema [15] presented a linear programming model for planning the movement of a homogeneous product from overseas origins to 400 inland U.S. destinations through several discharge ports. The fleet consisted of 50 ships of six types and part of the decision was to assign the ships to routes. The objective was to minimize costs. The problem was simplified by specifying for each case a set of discharge ports and solving it. Further simplification was possible by decomposing the ocean transportation segment from the land transportation segment while taking advantage of the structure of the problem. Näslund [32] presented an analysis of a wood pulp distribution system in Northern Europe with several loading ports and numerous discharge ports. Part of the decision was to select the types of ships to be employed, the unloading ports and the routes of the ships. The objective was to minimize the total transportation costs, from the port of origin to the inland destination. The structure of the cost functions allowed the use of an algorithm similar to the one proposed by Baumol and Wolfe [5] for the warehouse location problem. In this case the location of the discharge ports was selected. The algorithm provides a local optimum but not a global one. Moreover, analytical cost functions are fitted to represent the actual costs, thus detracting from the accuracy of the results.

Mathis [26] discussed an oil supply system where the decision variables were fleet size and mix, sizes of shore tanks and routes of ships. Demands and supplies in the ports were known and transshipment was allowed at discharge ports. Many restrictive assumptions were made, such as: there is only one type of crude, a tanker must remain in its assigned route, sizes of tankers are continuous and analytical approximations are used for cost functions. The objective was to minimize the cost of the system. The problem was formulated as a non-linear integer program and, by taking advantage of the problem's structure, it was solved by a Branch and Bound procedure with Generalized Upper Bounds. The author stated that most oil companies used simulation to attack this problem.

4. Liner operations

Liner operations' revenues depend on the quality of service (frequency, transit time, reliability and other factors) and therefore the availability of cargoes (revenues) depends on the routing and scheduling decisions. Thus in liner operations the operator's objective will be to maximize profits per time unit and not to minimize costs. Due to the large role of uncertainty in liner operations, which stems from a relatively large number of ports of call in a voyage and from cargo availability, the major modelling methods have been simulation and heuristic decision rules.

Datz [17] suggested a simple calculative procedure for scheduling liners and estimating the financial results of a schedule. Neuhof [30] gave a general discussion on the selection of ports of call for liners. Olson, Sorenson and Sullivan [34] presented a deterministic simulation model used in a liner company, operating between the U.S. west coast and Hawaii, for evaluating scheduling decisions. Kydland [22] developed a more elaborate stochastic simulation model for planning purposes. His model uses linear programming in a subproblem to determine the optimal number of ships for providing a specified service frequency.

Almogy and Levin [1] took a more rigorous approach to a narrower problem. They built a stochastic model to decide what cargoes should be selected out of the available cargoes in order to maximize profit per time unit. Their objective function was linear and separable, and they outlined the solution method but did not provide any example. Nemhauser and Yu [29] discussed a model for rail service which may be applicable to liners. They used dynamic programming to find the optimal frequency of service which maximizes profits over the planning horizon when the demand for the service is a function of its frequency and timing.

The latest work on liner scheduling is by Boffey, Edmond, Hinxman and Pursglove [9]. They built an interactive computer program, which may use heuristics, to schedule container ships over the North Atlantic. Their article provides a good description of a realistic ship scheduling problem environment. They used a greedy heuristic to generate schedules but report that managers prefer the package without the heuristic part, where schedules are generated manually and the model is a calculative one.

5. Tramp shipping

Very little work has been done in scheduling or routing tramp shipping. The reason may be the large number of small operators in the tramp market. Many large shipping companies usually see the tramp market as a secondary one, mainly due to the uncertainty in ship employment availability, and operate ships in tramp trades when they are either very profitable or when they do not have better occupation for the ships. One major exception is in refrigerated ships, where most of the cargoes are highly seasonal and in large quantities, and therefore most of the world reefer fleet is operated in tramp.

Refrigerated shipping provides the only work on ship scheduling in tramp shipping. Appelgren [2,3] described a typical problem of a tramp operator: the problem is to assign an optimal sequence of cargoes to each vessel in a given fleet during a given time period. Each cargo has a loading time window; size, type, origin and destination ports and loading and discharge times. Each vessel has its operational characteristics, initial position and an expected daily marginal revenue from optional cargoes that are not known but may become available for loading during the planning period. All contracted cargoes must be loaded, whereas optional cargoes may be rejected. A ship may carry only one cargo at a time (i.e., a single loading port in a voyage) but a cargo may be discharged in several ports. The objective is to maximize the revenue of optional cargoes minus the additional voyage and fuel costs. In the initial article [2] a linear programming model is formulated for the problem and is solved by Dantzig–Wolfe decomposition. The subproblems are network flow problems solved by dynamic programming, and the master problem is a linear binary problem solved as LP. Thus, integer solutions are not guaranteed. The purpose of the second paper [3] is to modify the solution procedure and guarantee integer solutions. This is done by solving the master problem by a branch-and-bound algorithm. The simple structure of the master problem LP allows one to combine the branch-and-bound algorithm with the Dantzig–Wolfe decomposition.

6. Industrial operations

Industrial operations, where the owner of the cargo controls the ship, abound in shipping of bulk and semi-bulk commodities, such as: oil, ore, coal, grain, lumber, pulp, citrus, bananas, sugar, potash and phosphate rock. The ship scheduling problem most widely discussed was presented by Dantzig and Fulkerson [16]. They considered a tanker scheduling problem where dates of loading and discharge are specified and the objective is to minimize the number of tankers to meet that fixed schedule, assuming a single loading and a single discharge port per tanker voyage. All the tankers are identical. The problem was solved as a transportation problem and the tankers' schedules were derived from the solution. Flood [18] dealt with the same problem from a different aspect. He assumed a given size fleet and minimized the total distance in ballast (empty) of the tankers by solving a transportation problem. Minimizing the distance in ballast will minimize the operating expenses under these assumptions. Briskin [11] extended the problem to the case in which several discharging ports are allowed. He first clustered unloading ports together and used the transportation method to schedule the tankers, and then used dynamic programming to determine the schedule of each vessel through its cluster of unloading ports. Bellmore, Bennington and Lubore [6] further extended the problem by allowing a mix of different types of tankers and allowing partially loaded tankers. Every delivery date was specified within a certain time interval. The authors defined utility associated with every delivery and tried to maximize the total utility by solving a mixed integer linear program. The utility of a delivery represents the desirability of that delivery and the cost of the delivery. Empty legs and placing each tanker in service have negative utilities. They suggested a possible approach for solution by decomposition with a branch-and-bound algorithm and network subproblems. However, no application or results have been presented.

McKay and Hartley [27] added realistic dimensions to the above tanker scheduling problem by considering multiple products and excluding entry of certain ports by certain tankers due to draft or length limitations. They allowed multiple loading ports in a voyage, and tried to minimize the operating costs of the tankers plus the costs of buying the products at the loading ports. The problem was formulated as a large mixed integer linear problem where the integer variables are the route selection variables (acceptable routes are prespecified). The problem was solved as a linear program with a specialized rounding procedure for the integer variables. This last formulation is the most realistic one but no optimal solution is assured.

Laderman, Gleiberman and Egan [23] discussed a ship routing problem that may be faced either by a tramp shipping company or by an industrial operation. During the shipping season in the great lakes an operator is committed to ship specified quantities of bulk commodities between specific pairs of ports (loading and discharge ports). The shipments are made in shiploads of a single commodity. The operator has a fleet of ships of various characteristics, and the objective is to minimize the number of ships required to satisfy the shipping commitments. The problem was solved by a linear programming model, which assigns ships to trips, while rounding resulting non-integer number of trips. Whiton [39] introduced further practical handling capacity constraints to the same problem. A very similar problem was analyzed by Rao and Zionts [35]. They added the possibility of chartering ships if needed, and their objective was to minimize the chartering costs plus the operating costs of the ships. (The operating cost of a ship was assumed proportional to its operating time.) Rao and Zionts used a column generating algorithm with out-of-kilter subproblems in order to reduce the size of the linear programming problem.

Ronen [36] analyzed a short term ship routing problem. His problem was to assign a set of shipments (defined by their sizes and destinations) available at a single origin to an available fleet, at minimal fleet operating cost. The ships could differ in their operating characteristics and cost structure, and all fleet related costs were considered. The problem was formulated as a mixed integer non linear problem and several routing algorithms were compared on a set of realistic problems. It turned out that biased random generation of routes gave results very close to optimal.

Two interactive ship scheduling systems have been presented recently. Stott and Douglas [37] presented a calculative-evaluative decision support system for scheduling bulk carriers with a medium term linear programming model to assign ships to voyages. The model allows voyages with backhauls and different types of ships, but requires specification of voyages in advance. The model tries to minimize the operating costs while meeting loading quantities, and allows chartering of ships in and out. Baker [4] described an interactive vessel scheduling system for a problem similar to the vehicle scheduling problem. The system schedules vessels for distribution of petroleum products from a single refinery to many delivery points. A linear programming model is used for voyage selection (non integer values are rounded) and a network model is used to determine the quantities of products shipped.

7. Other models

In this section models which do not clearly belong in the former sections will be discussed. Schechter [38] presented a ship routing problem which is similar to the vehicle routing problem. He dealt with collection of cargoes from several ports to a central transshipment point and used a heuristic opposite to that of Clarke and Wright [13]. He began with one vessel making all the pickups and added vessels until he achieved a solution accounting for the vessel capacity constraint. Total distance of the vessels was minimized and all vessels returned to the origin. A somewhat similar problem was discussed by Johannson [20]. A tanker had to deliver oil to many ports in Iceland. Each port had a demand and given storage capacity. He used a heuristic based on dynamic programming to determine the 'optimal' route.

Levy, Lvov and Lovetsky [25] presented an interactive fleet scheduling system in the USSR for a centralized unit which controls several shipping companies. An integer programming model is included in their system. McKenzie [28] suggested, on an economic basis, a global control system of ship traffic and scheduling, similar to the air traffic control system.

Scheduling of tugs and barges was discussed by O'Brien and Crane [33] and Bratley and Florian [10]. These problems are somewhat different from ship scheduling because tugs and barges are not a single unit.

Norman [31] discussed scheduling vessels through the Panama Canal – a highly specialized problem which resembles production scheduling problems.

Stochastic aspects of ship scheduling were addressed by Berten [7] who gave a stochastic description of ship dispatching, and by Koenigsberg and Lam [21] who analyzed queueing aspects in a relatively small system of liquid gas carriers operating in closed cycles between a small number of terminals.

A commercial medium and long range Fleet Scheduling Programme (FSP) was described by Cheshire [12] and Hayman [19]. The description is general and does not provide any details about mathematical procedures used, but optimization is claimed.

8. Summary

Ship routing and scheduling problems are varied and complex. The high uncertainty associated with ship operations confines the applicability of deterministic models to long and medium term planning. Thus medium term schedules are used as guidelines and must be updated often. Actual scheduling is done with the fleet and cargoes available for loading at the moment. The recent trend towards computerized interactive scheduling systems, which are used mainly to evaluate alternative schedules, demonstrates the complexity of the problem and the limited applicability of existing mathematical programming models to operational ship routing and scheduling.

Only a few models, or computerized systems, for short term scheduling were found. Essentially the short term scheduling problem boils down to three questions: where to send empty ships?, where to send loaded ships?, and what cargoes to load on what ships? The answers to these questions may change frequently with changes in the fleet operating environment. The relation between the medium term schedule (the plan) and the short term schedule (the execution of that plan) is blurred by the operational uncertainty which is usually not accounted for in the medium term plan. This relation, which is complicated by the binary aspect of scheduling problems (is the specific ship at the right place on the planned time, or not?), is not well understood, and requires further analysis.

The objective of ship routing and scheduling is not always clear cut, especially in tramp shipping where not all cargoes available are known in advance. Liner operations try to maximize profit per time unit in the long run but may divert from this objective in the short run in order to gain market share. Industrial operations try to minimize costs as long as they are engaged in intra-corporate service, but once they look for backhauls for other parties they face problems similar to tramp shipping. When cost minimization is the objective, all relevant cost components should be taken into account, including port entry charge, cost of loading and discharge times, and demurrage.

The ship scheduling problem becomes more realistic when two additional decision variables are considered: the cruising speed and the shipment sizes. The fuel consumption of a motor ship, which may cost tens of thousands of dollars a day, depends on the third power of its speed and is a major component of the operating costs. Thus the cruising speed should be considered when a schedule is determined. Shipment sizes may often vary in a given range, especially in industrial operations, and such variations allow larger flexibility for the human scheduler than for a mathematical model which does not account for them. A further realistic aspect may be instilled by trying to avoid ports on weekends, when cargo handling operations do not take place.

Fleet routing and scheduling problems cannot be disconnected from fleet size and mix decisions since the latter impose constraints on the former, at least in the short run.

Most of the published research in ship routing and scheduling has been performed in industrial operations carrying bulk commodities (oil or ore), and very little has been done in other areas. Even in industrial operations the existing models are limited to medium term scheduling and do not address many realistic aspects of ship scheduling problems. When a ship costs tens of thousands of dollars a day, large cost savings can be realized by proper scheduling of a fleet, but realistic models are needed to achieve those savings.

References

[1] Y. Almogy and O. Levin, Parametric analysis of a multistage stochastic shipping problem, *IFORS, OR 69: Proc. Fifth International Conference on OR* (Tavistock, London, 1970) 359–370.

[2] L.H. Appelgren, A column generation algorithm for a ship scheduling problem, *Transportation Sci. 3* (1969) 53–68.

[3] L.H. Appelgren, Integer programming methods for a vessel scheduling problem, *Transportation Sci. 5* (1971) 64–78.

[4] T.E. Baker, Interactive vessel scheduling at Exxon, Presented at CORS/TIMS/ORSA Joint National Meeting, Toronto, 1981.

[5] W.J. Baumol and P. Wolfe, A warehouse location problem, *Operations Res. 6* (1958) 252–263.

[6] M. Bellmore, G. Bennington and S. Lubore, A Multivehicle tanker scheduling problem, *Transportation Sci 5* (1971) 36–47.

[7] B. Berten, Mathematical description of stochastic processes for dispatching ships, *Seewirtschaft 5* (1973) 99–101 (in German).

[8] L. Bodin, B. Golden, A. Assad and M. Ball, The state of the art in the routing and scheduling of vehicles and crews, College of Business and Management, University of Maryland, College Park, MD, Working Paper MS/S No. 81-035 (1981).

[9] T.B. Boffey, E.D. Edmond, A.L. Hinxman and C.J. Pursglove, Two approaches to scheduling container ships with an application to the North Atlantic route, *J. Operational Res. Soc. 30* (1979) 413–425.

[10] P. Bratley and M. Florian, Scheduling newsprint deliveries made by tugs and barges, *Proc. NATO Conference on the Application of Operations Research to Transport Problems* (Western Periodicals Co., North Hollywood, CA, 1972) 203–214.

[11] L.E. Briskin, Selecting delivery dates in the tanker scheduling problem, *Management Sci. 12* (1966) B224–233.

[12] I.M. Cheshire, Most profitable scheduling of bulk cargo fleets, *Norwegian Shipping News 11C* (1972) 40–41.

[13] G. Clarke and J.W. Wright, Scheduling of vehicles from a central depot to a number of delivery points, *Operations Res. 8* (1964) 568–581.

[14] C.O. Clausen, Vehicle routing algorithms for local delivery at naval supply centers, Unpublished M.S. thesis, Naval Postgraduate School, Monterey, CA (1981).

[15] J.H. Conley, R.S. Farnsworth, E. Koenigsberg and U. Wiersema, A linear programming approach to the total movement of a homogeneous product, *Transportation Sci. 2* (1968) 289–302.

[16] G.B. Dantzig and D.R. Fulkerson, Minimizing the number of tankers to meet a fixed schedule, *Naval Res. Logist. Quart. 1* (1954) 217–222.

[17] I.M. Datz, Planning tools for ocean transportation-ship scheduling, *Norwegian Shipping News* (1968) 1064–1069.

[18] M.F. Flood, Application of transportation theory to scheduling a military tanker fleet, *Operations Res. 2* (1954) 150–162.

[19] C. Hayman, Fleet scheduling – Best by computer, *Seatrade* (April 1972) 65–66.

[20] K. Johannson, A heuristic approach to the multi-discharge routing problem, Unpublished Ph.D. dissertation, Illinois Institute of Technology (1969).

[21] E. Koenigsberg and R.D. Lam, Cyclic queue models of fleet operations, *Operations Res. 24* (1976) 516–529.

[22] F. Kydland, *Simulation of Liner Operations* (Institute for Shipping Research, Bergen, 1969).

[23] J. Laderman, L. Gleiberman and J.F. Egan, Vessel allocation by linear programming, *Naval Res. Logist. Quart.* (1966) 315–320.

[24] S.A. Lawrence, *International Sea Transport: The years Ahead* (Lexington Books, Lexington, MA, 1972).

[25] V.D. Levy, S.P. Lvov and S.E. Lovetsky, Man–machine system for merchant fleet operation scheduling, *Proc. 7th International Symposium on Transportation and Traffic Theory*, Kyoto, 1977 (Institute of Systems Science Research) 823–836.

[26] S.J. Mathis, Jr., Synthesis of a crude oil supply system: A nonconvex network problem, Unpublished Ph.D. Dissertation, Case Western Reserve University (1972).

[27] M.D. McKay and H.O. Hartley, Computerized scheduling of seagoing tankers, *Naval Res. Logist. Quart. 21* (1974) 255–264.

[28] J.S. McKenzie, The routing of ships, *J. Transportation Econom. Policy* (May 1971) 201–215.

[29] G.L. Nemhauser and P.L. Yu, A problem in bulk service scheduling, *Operations Res. 20* (1972) 813–819.

[30] B. Neuhof, The ship line decision problem on ports of call, *Hansa 23* (1974) 2013–2017 (in German).

[31] R.J. Norman, An algorithm for the scheduling of vessels through the Panama Canal, Unpublished M.S. thesis, Naval Postgraduate School, Monterey, CA (1973).

[32] B. Näslund, Combined sea and land transportation, *Operational Res. Quart. 21* (1970) 47–59.

[33] G.G. O'Brien and R.R. Crane, The scheduling of a barge line, *Operations Res. 7* (1959) 561–570.

[34] C.A. Olson, E.E. Sorenson and W.J. Sullivan, Medium range scheduling for freighter fleet, *Operations Res. 17* (1969) 565–582.

[35] M.R. Rao and S. Zionts, Allocation of transportation units to alternative trips – A column generation scheme with out-of-kilter subproblems, *Operations Res. 16* (1968) 52–63.

[36] D. Ronen, Scheduling of vessels for shipment of bulk and semi-bulk commodities originating in a single area, Unpublished Ph.D. Dissertation, The Ohio State University (1979).

[37] K.L. Stott, Jr. and B.W. Douglas, A model-based decision support system for planning and scheduling ocean-borne transportation, *Interfaces 11* (1981) 1–10.

[38] J. Schechter, A minimum cost vessel routing model applied to the U.S. Trust Territory of the Pacific Islands, *Maritime Studies and Management 3* (1976) 195–204.

[39] J. C. Whiton, Some constraints on shipping in linear programming models, *Naval Res. Logist. Quart.* (1967) 257–260.